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Assessment of the production potential of an emerging *Artemia* population in the Aral Sea, Uzbekistan

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ABSTRACT

The objective of this study was to provide information on the developing parthenogenetic *Artemia* population in the Uzbek part of the Aral Sea, and to assess its potential for commercial exploitation. A sampling campaign was designed for abiotic factors (temperature, salinity, transparency) and *Artemia* population parameters at least once monthly in the period March–October of the years 2005–2007.

By 2007 salinity in both basins had increased to values above 100 g l^{-1}. Moreover, by 2007, desiccation had rendered the eastern Aral basin practically inaccessible for sampling or cyst harvesting. The volume of the western basin remained considerable, given its depth, with a relatively accessible shoreline. Average *Artemia* population parameters (e.g. adult abundance<0.5 adults l^{-1}; 10–25 cysts $brood^{-1}$; cyst abundance<5 and 10 cysts l^{-1} for the western, resp. eastern basin) were low compared to *Artemia* sites of commercial importance. A gradual gain in population size in the western basin was observed over the period 2005–2007. The data further suggest that the low *Artemia* productivity is not genetically determined, but is largely the result of food limitation. The western basin may approach the threshold where a small-scale commercial operation is justified.

1. Introduction

The dramatic decline in the volume of the Aral Sea, a terminal lake in the territory of Uzbekistan and Kazakhstan, since the 2nd half of the previous century, has received worldwide attention in scientific and popular literature (Micklin, 1988, 1996, 2007; Micklin and Aladin, 2008). While the lake level has seen regressions in archeological and historical times (Boroffka et al., 2006; Le Callonnec et al., 2005), the present drop of its water level started in the 1960s and is caused by diversion of inflows from the Amu Darya and Syr Darya rivers for the benefit of agriculture, industry and water supply of urban areas. The hydrology of the Aral Sea has recently been studied in detail (Crétaux et al., 2005; Zavialov et al., 2009) and water resource management strategies have been proposed, but have met with limited success (Heaven et al., 2002). As a consequence, in the period 2000–2010 the Aral Sea has been increasingly divided into distinct water bodies (i.e. eastern and western basins of the main Aral Sea, the so-called Large Aral, and the Small Aral Sea in the northern Kazakhstan region), presently leaving the western basin of the Large Aral as the only open water body of importance on Uzbek territory. Water management construction projects in the area of the Small Aral have resulted in a stabilization or even partial restoration of former salinity levels combined with the reintroduction of vertebrate fish species (Aladin et al., 2005). However, these projects have had virtually no beneficial impact on the Large Aral (Fig. 1).

Ecological changes in the Aral Sea have resulted in disappearance of the fish stocks upon which the neighboring human communities formerly depended for their sustenance and employment, whereas before the 1960s annual fish catches amounted up to 44,000 tons annually (Aladin et al., 1998). The contemporary eastern and western Aral basins are hypersaline water bodies with total elimination of fish and invertebrate species of fresh, brackish water, or marine origin (Williams and Aladin, 2006). Changes in the biotic composition of the Aral Sea have been monitored in detail since the 1960s, and have been extensively documented in Russian-language journals (see overview in Mirabdullayev et al., 2004). Since the 1990s multiple international scientific studies have described the Aral ecosystems in their transition from an oligohaline into a hypersaline water body, including the gradual colonization of the open part of the lake by a parthenogenetic *Artemia* population (Aladin and Potts, 1992; Aladin et

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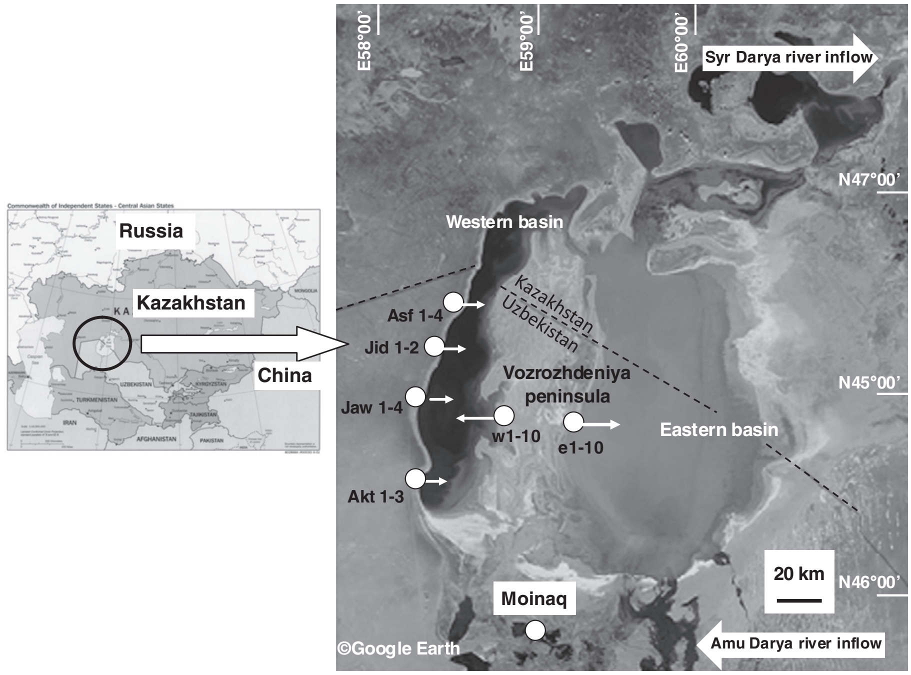

Fig. 1. Sampling sites within the western and eastern Aral basins. White dots correspond with on-shore access points, from where off-shore transect sampling (arrows) was done. Left: index map of Central Asia.

al., 1998; Andreev et al., 1992a,b; Filippov, 1997; Filippov and Komendantov, 1996; Friedricht and Oberhansli, 2005; Mirabdullayev et al., 2004).

The brine shrimp *Artemia* is an essential component of aquaculture production worldwide, as the larvae (nauplii) hatching out of its cysts are the most commonly used live food item in marine larviculture. Global demand for *Artemia* cysts is on the order of approximately 2000 tons per year (Dhont and Sorgeloos, 2002). The Great Salt Lake (GSL), Utah, USA, is still the main supplier of *Artemia* cysts on the world market but the unpredictability of these GSL harvests in terms of quantity and quality (Lavens and Sorgeloos, 2000) is a strong incentive to explore alternative resources.

Local records collected over a two decade period from the 1980s through the 1990s reported the existence of a local parthenogenetic *Artemia* population in coastal shallow water bodies adjacent to the former Aral Sea bed, and in small lakes and pools on the nearby Ustyurt Plateau, west of the Aral Sea (Mirabdullayev et al., 2004). At the end of the 1990s *Artemia* presence was occasionally recorded in the Aral Sea itself near the NE coast of the former Vozrozhdeniya Island (now a peninsula; Joldasova et al., 1999). As salinity increased, *Artemia* has become the dominant zooplankton species in the Aral Sea since 2000 (Mirabdullayev et al., 2004). This progressive colonization and the assessment of the available cyst stocks were addressed by Arashkevich et al. (2009) who collected zooplankton data between 2002 and 2006. This study, however, was restricted to the western Aral basin, and the assessment of the temporal variation of the population was based on a yearly autumn sampling program.

The assessment of the potential development and management of an Aral Sea *Artemia* resource, which could provide some degree of economic recovery to the Aral region through sustainable management strategies, was the subject of a NATO Science for Peace Project (SfP 980859, 2004–2007). The objective was to provide systematic and frequent biological and ecological information on the developing *Artemia* population in the Aral Sea, to compare it with other *Artemia* populations of the world and to use it to assess its potential for commercial exploitation. The following questions were addressed in this study: 1) to what extent has the *Artemia* population colonized the Aral Sea, and 2) is the emerging *Artemia* population sufficiently robust and productive for economically beneficial commercial exploitation? For this purpose, an extensive sampling campaign was organized to collect information on the abiotic conditions, primary production and the *Artemia* population. The results of the primary production study are the subject of a separate publication (Marden et al., unpublished results) and will not be discussed here in detail.

2. Materials and methods

2.1. Site description and sampling sites

The sampling program included the western and eastern Aral basins within Uzbekistan as existing in 2005–2007. The former fishing harbor of Moinaq was used as point of departure for sampling expeditions (Fig. 1). A number of points on the shore were defined, which could be reached over land without too many logistic problems, and where there was relatively easy access to open water. From these access points on the shore, samples were taken along transects off-shore (Table 1, Fig. 1).

Sampling expeditions were planned to be conducted monthly from March to October in the years 2005–2007 (Table 2). During peak periods of reproduction, multiple sampling expeditions per month were conducted but due to harsh weather conditions or technical problems (hazards with transport vehicles over the rough terrain were not exceptional) not all expeditions could be completed successfully or some planned expeditions had to be canceled. Due to the decreasing lake elevation in the eastern Aral basin and the resulting extensive expanses of mud, sampling of the eastern basin could not be completed in 2007. An effort was made during each sampling expedition to sample the entire set of designated sites. Weather and logistic conditions sometimes precluded a completely successful sampling program.

2.2. Abiotic parameters

Salinity, water temperature, and transparency were measured at each sample location. Temperature was measured using either a mercury or digital thermometer (calibrated by the manufacturer), and

Table 1
List of sampling sites in western and eastern Aral basins, with their geographical characteristics.

Access on-shore	code of sampling site	Aral basin	Depth (m)	Site coordinates
Peninsula	w10	West	5.2	44°50′923 N 58°36′797 E
Peninsula	w9	West	4.7	44°51′173 N 58°37′517 E
Peninsula	w8	West	4.1	44°51′429 N 58°38′181 E
Peninsula	w7	West	3.4	44°51′718 N 58°38′833 E
Peninsula	w6	West	2.8	44°51′921 N 58°39′538 E
Peninsula	w5	West	2.2	44°52′133 N 58°40′245 E
Peninsula	w4	West	1.8	44°52′387 N 58°40′895 E
Peninsula	w3	West	1.4	44°52′666 N 58°41′546 E
Peninsula	w2	West	0.9	44°52′969 N 58°42′199 E
Peninsula	w1	West	0.5	44°53′313 N 58°42′871 E
Peninsula	e10	East	1.8	44°50′506 N 59°25′029 E
Peninsula	e9	East	1.8	44°50′660 N 59°24′274 E
Peninsula	e8	East	1.7	44°50′833 N 59°23′549 E
Peninsula	e7	East	1.6	44°51′004 N 59°22′812 E
Peninsula	e6	East	1.6	44°51′135 N 59°22′060 E
Peninsula	e5	East	1.3	44°51′255 N 59°21′319 E
Peninsula	e4	East	1.2	44°51′226 N 59°20′521 E
Peninsula	e3	East	1.1	44°51′174 N 59°19′751 E
Peninsula	e2	East	0.8	44°51′056 N 59°18′862 E
Peninsula	e1	East	0.4	44°50′980 N 59°18′015 E
Ust-Yurt	Asf-1	West	19.0	45°57′336 N 58°16′511 E
Ust-Yurt	Asf-2	West	24.0	45°57′148 N 58°18′146 E
Ust-Yurt	Asf-3	West	20.5	45°56′380 N 58°19′559 E
Ust-Yurt	Asf-4	West	23.5	45°53′585 N 58°19′002 E
Ust-Yurt	Jid-1	West	22.0	45°31′227 N 58°14′274 E
Ust-Yurt	Jid-2	West	39.5	45°31′299 N 58°15′534 E
Ust-Yurt	Jaw-1	West	42.0	45°05′302 N 58°20′401 E
Ust-Yurt	Jaw-2	West	20.0	45°04′547 N 58°22′120 E
Ust-Yurt	Jaw-3	West	12.5	45°04′094 N 58°23′341 E
Ust-Yurt	Jaw-4	West	39.5	45°01′255 N 58°29′066 E
Ust-Yurt	Akt-1	West	24.0	44°31′337 N 58°17′545 E
Ust-Yurt	Akt-2	West	39.5	44°29′070 N 58°16′539 E
Ust-Yurt	Akt-3	West	20.0	44°29′456 N 58°15′320 E

salinity by means of a temperature-corrected refractometer, calibrated for zero with distilled water. Water transparency was measured with a 20 cm black and white Secchi disk.

2.3. Artemia sampling and enumeration

Artemia were collected by means of a 50 cm-diameter plankton net with a mesh size of 150 µm and an aspect ratio of 1:5, with a removable sampling cup located at the distal net end. Vertical plankton net hauls were taken from the bottom of each site (eastern Aral basin), or at a depth of 1, 4, 6, and 12 m for the western basin sites, depending on the total depth for the particular site (Table 2). Two plankton net hauls were taken at each depth and the contents were combined in the sample bottle. The contents of the two pooled samples were filtered sequentially through sieves with mesh sizes of 850, 500, and 120 µm respectively. Filtered *Artemia* were re-suspended in a known volume of water and the suspension was sub-sampled for the actual count. If the samples could not be counted within 24 h of collection they were stabilized with 4% formalin solution and stored until enumeration could be executed (within 48 h). Generally the volume of the sub-sample was 1% to 100% of the re-suspended sample depending upon the density of the *Artemia* in the suspension. Constant aeration was applied to mix the sample thoroughly prior to sampling and counting. *Artemia* were counted according to their age-class as nauplii, meta-nauplii, juveniles, pre-adults, and adults. Cysts were also isolated and counted. Brood sac contents of gravid females were grouped according to the presence of cysts or nauplii and the entire brood sac contents were counted. If possible 30 females per site and per depth were used for the brood sac counts. Reproductive mode (oviparity or ovoviviparity) was recorded.

Table 2
Number of successfully completed expeditions for the western and eastern Aral basin in the period March 2005-October 2007.

Month	Western basin			Eastern basin		
	2005	2006	2007	2005	2006	2007
March	1	0	0	1	0	0
April	1	1	0	1	2	0
May	0	1	0	0	1	0
June	2	1	1	2	1	0
July	1	0	1	0	0	0
August	2	2	1	2	2	0
September	1	0	1	1	0	0
October	1	0	0	1	0	0
Yearly total	9	5	4	8	6	0
Grand total	32					

2.4. Statistics

ANOVA analysis was performed, after testing of assumptions of normal distribution and homogeneity of variances, on *Artemia* population parameters allowing for comparison of productivity of the eastern versus the western basin. Significance of differences between means was calculated by the Tukey's test. The significance level was set as $P \leq 0.05$.

3. Results

3.1. Abiotic factors

3.1.1. Salinity

Average yearly salinity in the western basin increased from 87.6 g l^{-1} in 2005 to 103.1 g l^{-1} in 2007, while the average yearly salinity in the eastern basin was 96.0 g l^{-1} in 2005 and 90.5 g l^{-1} in 2006. Although there were some depth-related differences, the depth profiles did not reveal a definable chemocline in the Aral Sea (Table 3). Within each year, however, there were distinctly different patterns of salinity flux between the two basins. The larger, and substantially deeper, western basin showed a relatively consistent increase in salinity, while the eastern, shallow basin demonstrated pronounced within-year salinity fluctuations (Fig. 2). The trend from 2005 to 2006 in the eastern basin was one of decreasing salinity during 2005 and increasing salinity during 2006. Substantial inflow during 2005 in the eastern basin from the Amu Darya resulted in a decrease from a high of 126 g l^{-1} to the lowest measurement of 67 g l^{-1} in the southern region of the eastern basin (i.e. the region under most immediate influence from Amu Darya inflow). In the western basin we recorded an increase from 82.2 g l^{-1} in May 2005 to a high of 109.2 g l^{-1} in September 2007.

3.1.2. Water temperature

Due to the much greater thermal mass of the western basin the temperature increased slowly in the spring and then maintained its warmer temperature into October (Fig. 3). The eastern basin gained and lost thermal energy more rapidly than the western basin; e.g. in the eastern basin the March temperature was already 7 °C while in the western basin it was just above 0 °C. In both basins summer water temperature exceeded 25 °C with some peak measurement of 28°C to 29 °C.

Though the deep sites were not always easily accessible and the data thus present considerable gaps, a notable thermocline was observed in the western basin: water temperature in sites below 20 m of depth never exceeded 10 °C and remained above 2 °C in early March, and most likely throughout the winter (Fig. 4). Surface temperatures cooled to below zero in the winter and were recorded at −1 °C for some sample locations in March 2005.

Table 3
Salinity ($g\,l^{-1}$) for the open water of the western and eastern Aral basins. Values are mean and standard deviation (S.D.) of all observations per year (see Tables 1 and 2); max. = maximal value observed.

	Year	Western basin			Eastern basin		
		Mean	S.D.	Max.	Mean	S.D.	Max.
Salinity ($g\,l^{-1}$) at 1 m depth	2005	87.6	4.7	105.0	96.0	14.5	116.0
	2006	94.3	3.2	102.0	90.5	20.7	126.0
	2007	103.1	4.4	110.0	–	–	–
Salinity ($g\,l^{-1}$) at maximal depth	2005		4.6	108.0	100.7	13.2	118.0
	2006	95.6	3.7	104.0	93.3	19.4	128.0
	2007	100.3	4.2	110.0	–	–	–

3.1.3. Water transparency

Transparency readings indicated substantially greater transparency in the western basin (as high as 7.8 m) than in the eastern basin (maximum recorded 1.9 m). A comparison of transparency between the two basins was only possible during 2005 (Table 4) due to the diminished depth of the eastern basin in 2006 and 2007; during 2006 and 2007 the eastern basin was so shallow that Secchi depth measurements were likely influenced more by suspended sediment particulates than by algal abundance.

3.2. Artemia population

3.2.1. Abundance and age class distribution of active (non-cyst) stages

Parthenogenetic *Artemia* was the dominant zooplankton species in both western and eastern basins. During winter the active life stages of *Artemia* were completely absent, while the encysted embryos were the only ontogenetic stage found within the open waters. When the water temperature increased to above 5 °C during spring the first free-swimming stages of *Artemia* were found in the water column. Due to the substantially larger thermal mass of the western Aral basin, active stages of *Artemia* were not found in this water body until April and adults were not collected until May. Active stages of *Artemia* were found in the eastern Aral basin as early as March (Fig. 5). Peak abundances of nauplii, juveniles, and pre-adults were reported during May for the eastern basin. In contrast, peak abundances for juveniles and pre-adults in the western basin were found in July, with the naupliar stage showing a maximum abundance during May (Fig. 5). Adult peak abundance for either the western or eastern basin occurred in either August or September (Fig. 6).

Generally, within the water column of the eastern basin the abundance counts for *Artemia* were 2 to 10 times greater than those in the western (Table 5). The highest average monthly abundances for *Artemia* found in the western basin were: 4.20 nauplii l^{-1}, 0.69 juveniles l^{-1}, 0.33 pre-adults l^{-1} and 0.38 adults l^{-1}, whereas these values were 22.43 nauplii l^{-1}, 3.05 juveniles l^{-1}, 4.19 pre-adults l^{-1} and 0.47 adults l^{-1} in the eastern basin. In May 2006 peak abundance of almost all ontogenetic stages was observed in the eastern basin. The average abundance of adults during June, July, August, and September in the western basin (0.08 adults l^{-1}) was significantly lower (ANOVA, $P<0.05$) compared to the eastern basin (0.20 adults l^{-1}). No male *Artemia* were observed in any of the samples collected.

3.2.2. Fecundity

There were no significant differences (ANOVA, $P>0.05$) in brood size between *Artemia* populations located in the western or eastern basin (Table 6). Gravid females were first observed in the eastern basin when the water temperature at 1 m depth was 8.5 °C and at 11.0 °C in the western basin. For oviparous females, the highest average brood sizes per sample location were recorded in September 2007 from the western basin (61.0 cysts brood^{-1}) and in September 2005 from the eastern basin (55.0 cysts brood^{-1}). The highest average yearly brood size for the eastern basin was 22.9 cysts brood^{-1} (2005) and 24.9 cysts brood^{-1} for the western basin (2007). Ovoviviparous reproduction was observed throughout the summer months and maximum average monthly brood sizes for ovoviviparous females were 34.0 nauplii brood^{-1} (June, eastern basin) and 25.3 nauplii brood^{-1} (July, western basin).

The frequency distribution of brood sizes for females (nauplii or cysts) collected from each basin indicates that per capita reproductive potential of females is similar for both basins of the Aral Sea (Fig. 7). The range of brood sizes is generally greater for the western basin,

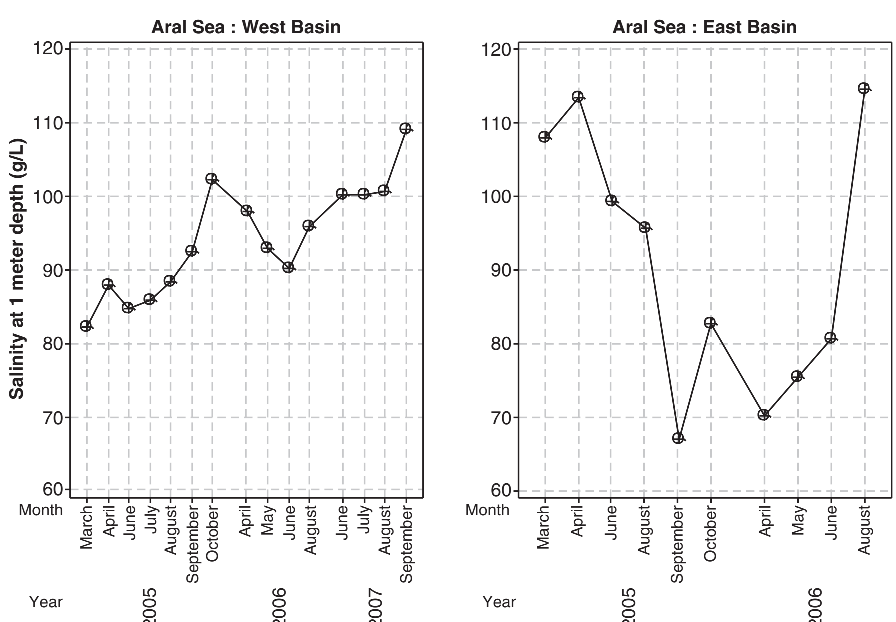

Fig. 2. Salinity fluctuations ($g\,l^{-1}$) in the open water (at 1 m depth) of the eastern and western Aral basins based on averages of all monthly observations throughout 2005–2007 (see Tables **1** and **2**).

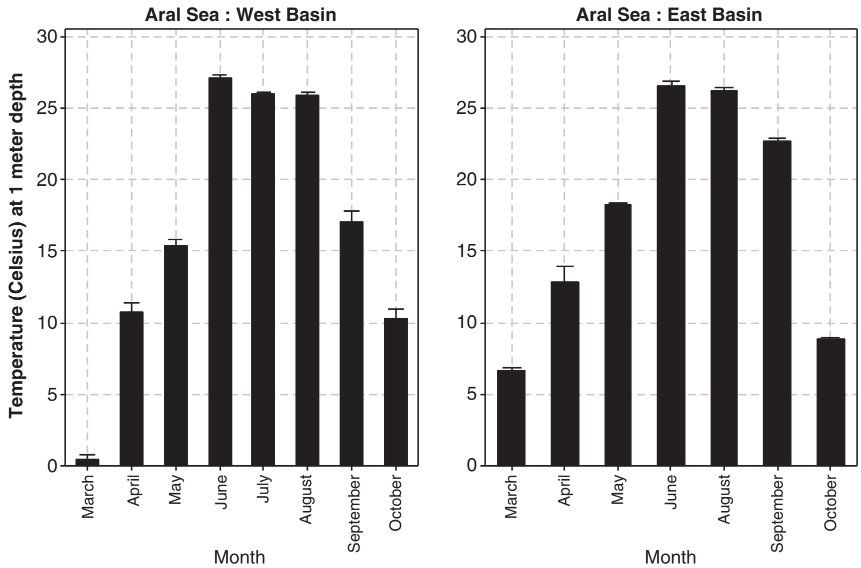

Fig. 3. Average monthly water temperature (taken 1 m depth from surface) in eastern and western Aral basins based on all observations throughout 2005–2007 (see Tables **1** and **2**). Bars are one standard error from the mean.

though there was no significant statistical difference (ANOVA, P > 0.05) in the brood sizes between the two basins.

3.2.3. Cyst abundance in water column

There was a demonstrable increase in cyst accumulation in the water column throughout the summer months with the highest abundance being observed in the fall (Fig. 8). Although the highest concentrations of cysts per liter from the eastern basin did occur in September (2005) and August (2006), there were similar values during other months (e.g., March, May, and June). Monthly average cyst abundance in the western basin was below 1 cyst l^{-1} each spring and then increased to 4–6 cysts l^{-1} in the late summer and fall months (Fig. 8). Actual cyst counts per sample were 0.2–39.0 cysts l^{-1} with an overall average of 6.3 cysts l^{-1} in the eastern basin, with the corresponding values 0.1–15.0 cysts l^{-1} and 1.9 cysts l^{-1} for the western basin.

Cyst abundance was compared across sample site depth category as well. As compared to the overall average of 6.3 cysts l^{-1} in the eastern basin, with a depth less than 3 m, the average values for each depth category in the western basin across the entire study were: 1.8 cysts l^{-1} (<3.0 m), 1.1 cysts l^{-1} (3.0–6.0 m), 2.0 cysts l^{-1} (6.1 m–20.0 m) and 2.3 cysts l^{-1} (>20.0 m), and these values were not statistically different (ANOVA, P > 0.05).

4. Discussion

4.1. Abiotic conditions

At the time of sampling, the eastern and western basins behaved as two virtually separated water bodies. The total volume, shallow depth, inflow of Amu Darya, ground water input, and large surface area/volume ratio rendered the eastern Aral basin subject to more pronounced short-term changes in abiotic conditions when compared to the western basin where changes in hydrochemistry, transparency, and temperature are damped by its larger volume, as reflected in the salinity and temperature fluctuations (resp. Figs. 2 and 3) over the course of the project. The eastern basin, which had an average depth of approximately 1 m at the time of sampling (Zavialov et al., 2009), warmed considerably more rapidly in the spring than the western, affecting the growth and reproduction of the respective *Artemia* populations. The observation of a thermocline in our study (Fig. 4) is congruent with Arashkevich et al. (2009), who similarly report a thermocline occurring between 15 and 20 m below the surface for the western basin. Depth in the eastern basin was so low in 2006 and 2007 that comparison of transparency values between both basins could only be done for 2005 (Table 4). Transparency of the open water (which can be used as indirect assessment of phytoplankton density in absence of a grazing *Artemia* population) in the western basin was substantial and suggested limited algal growth. Transparency depths for the eastern basin showed little fluctuation, though the greatest visual depth occurred in the late summer at a time that corresponds with peak *Artemia* abundance. However, due to the shallow nature and hence contribution of non-algal turbidity to transparency values in the eastern basin, reliable comparison between both basins is difficult.

4.2. Artemia population

Parthenogenetic brine shrimp were found in both the eastern and western Aral basins, with some notable differences and many similarities between the two populations. In both basins the cysts were the only ontogenetic stage observed in the winter months. Due to its more rapid warming up in spring, *Artemia* nauplii were observed as early as March in the eastern basin, whereas this was not before April in the western basin; this difference between both basins persisted throughout the production season for the older ontogenetic stages (Figs. 5 and 6). The eastern Aral basin was consistently more productive per unit volume than the western: abundances of all age categories of *Artemia* were higher in the eastern than in the western basin (Table 5).

Survival and reproductive success of *Artemia* are influenced by multiple biological, physiological, chemical, and physical factors (Lenz, 1987; Lenz and Browne, 1991; Melack and Jellison, 1998; Vanhaecke et al., 1984). Of the many influential factors in *Artemia* reproductive success, temperature and salinity have been demonstrated to exert a pronounced impact (Browne et al., 1988; Wear and Haslett, 1987). Browne and Wanigasekera (2000) characterized parthenogenetic *Artemia* as a niche specialist relative to other species of *Artemia* in being more selective in terms of temperature–salinity combinations allowing maximal reproduction. Consequently, conditions in the Aral Sea at the

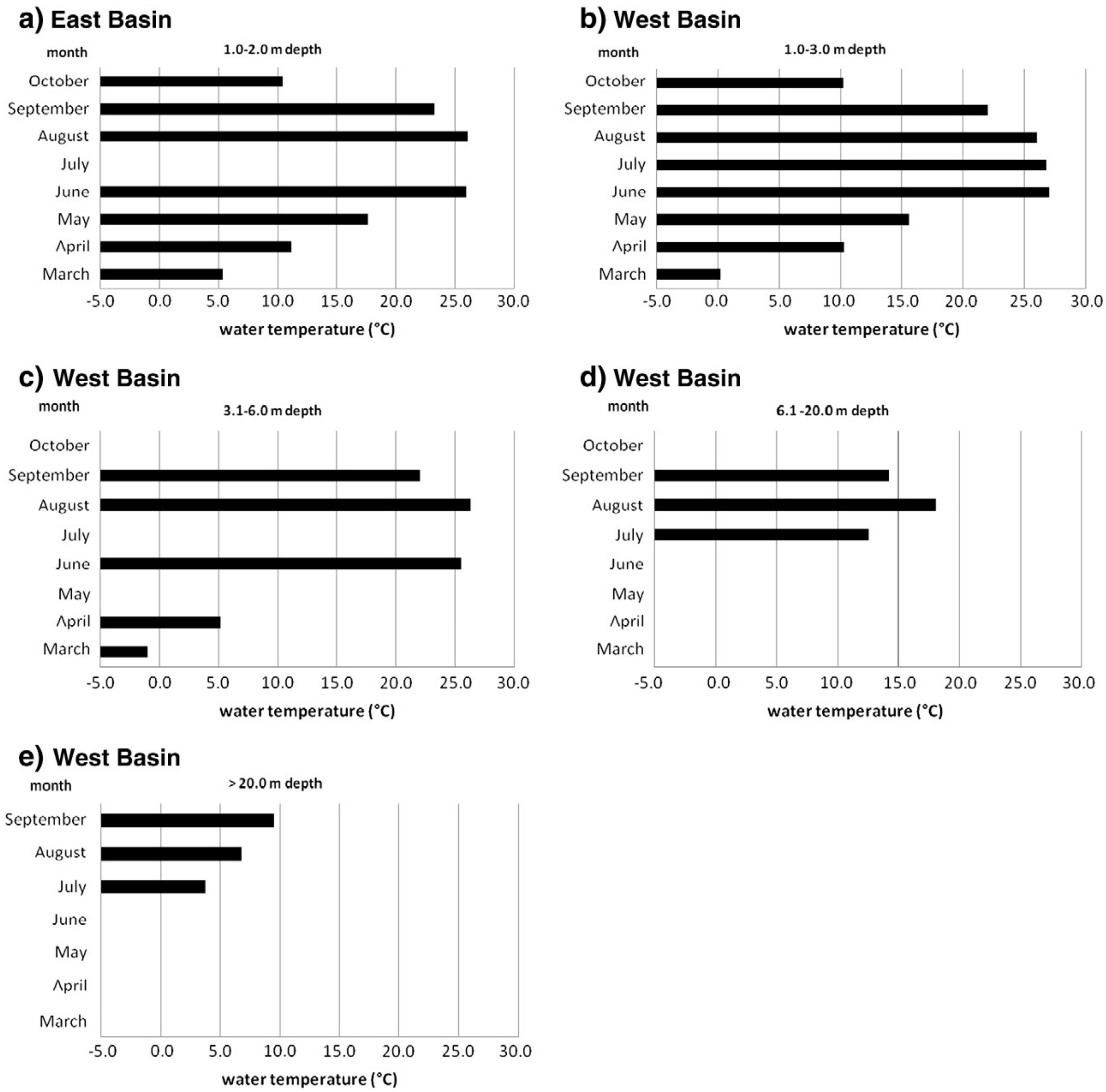

Fig. 4. Monthly average water temperature (°C) of the eastern and western Aral basins across sample depth categories.

Table 4
Average monthly transparency values (in cm) for 2005 of western and eastern Aral basins as measured by Secchi disk depth. Values are mean and standard deviation (S.D.) of n observations; min./max. = minimal/maximal value, respectively, observed; hyphen (-) = no observation.

Month	Western basin					Eastern basin				
	Mean	S.D.	n	Min.	Max.	Mean	S.D.	n	Min.	Max.
March	161.1	56.4	9	70.0	200.0	21.5	4.7	10	15.0	30.0
April	223.9	69.9	9	115.0	320.0	21.0	2.1	10	20.0	110.0
May	-	-	-	-	-	-	-	-	-	-
June	272.5	118.2	20	110.0	420.0	66.2	4.2	20	60.0	70.0
July	548.2	140.8	14	240.0	780.0	-	-	-	-	-
August	273.0	96.1	20	90.0	440.0	105.8	51.1	20	60.0	185.0
September	279.4	131.2	9	90.0	470.0	114.0	67.5	10	30.0	190.0
October	140.0	51.5	5	100.0	210.0	41.0	6.52	5	35.0	50.0

time of sampling may have been suboptimal and therefore may have diminished the per capita reproductive potential of resident *Artemia*.

The *Artemia* population size and ontogenetic structure in both basins showed monthly variations quite typical for *Artemia* populations found in temperate regions such as those found in the Great Salt Lake (GSL), Utah, USA (Marden, 2008; Wurtsbaugh and Gliwicz, 2001) or in salt lakes of Siberia (Litvinenko and Boyko, 2008; Litvinenko et al., 2007; Van Stappen et al., 2009). The results of detailed field and laboratory studies on *Artemia* population dynamics indicate that sampling needs to take place frequently (e.g. weekly), otherwise significant population fluctuations will be undocumented, thereby masking the true stage-specific population fluctuations (Conte and Conte, 1988; Lenz, 1984; Lenz and Browne, 1991; MacDonald and Browne, 1990; Marden, 2008; Wurtsbaugh and Gliwicz, 2001). Though our sampling frequency may not have afforded a precise recording of the full extent of

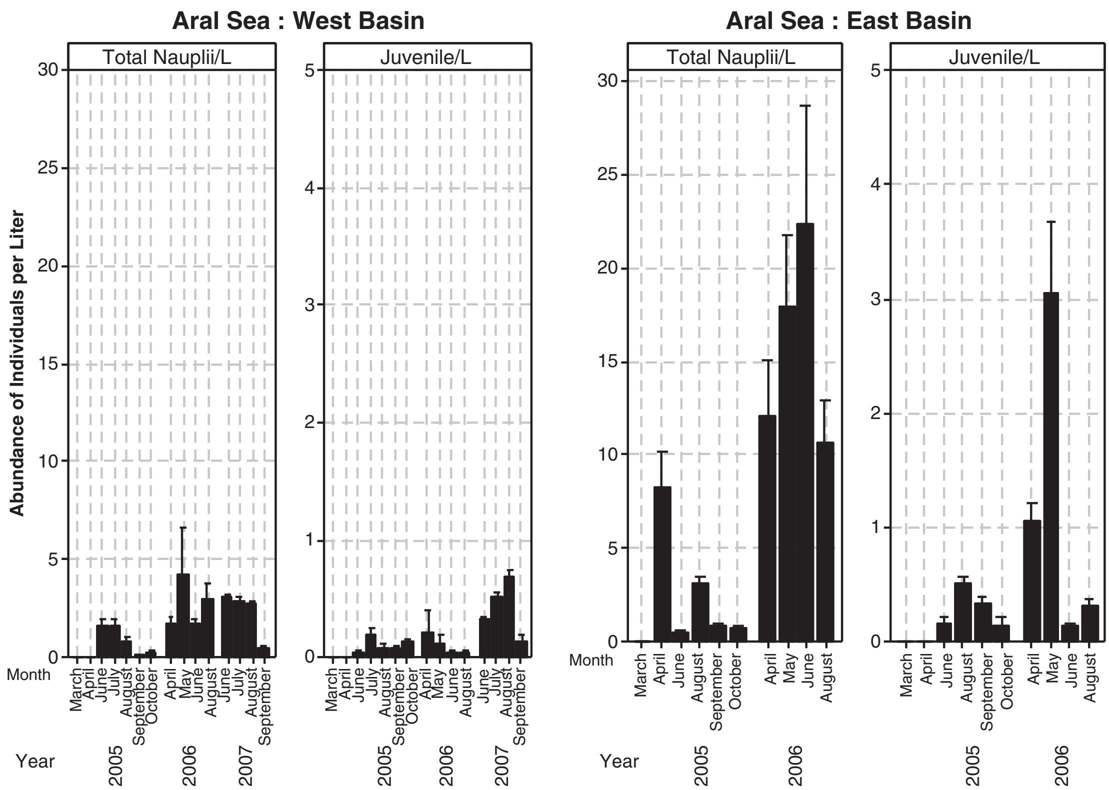

Fig. 5. Abundance (in individuals per liter) of nauplii and juvenile stages of *Artemia* from eastern and western Aral basins. Bars represent averages (with error bar for one standard error) of all monthly observations (see Tables 1 and 2).

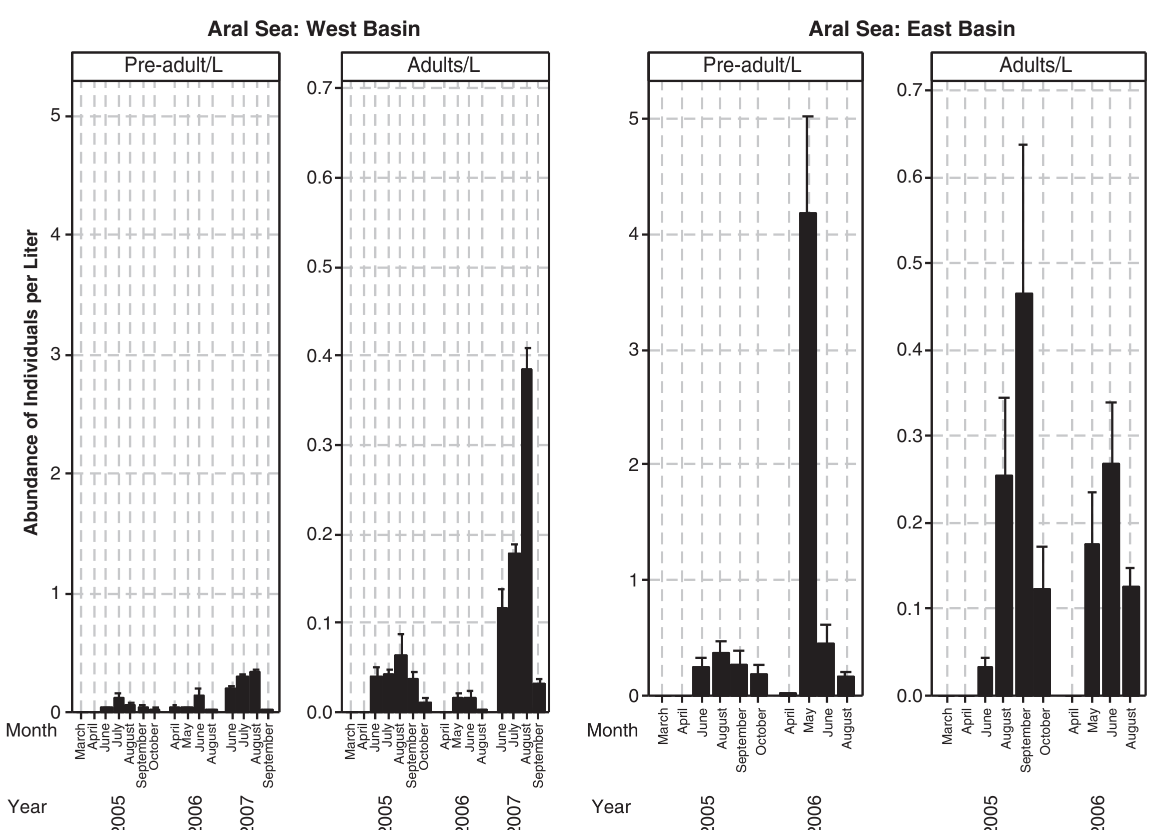

Fig. 6. Abundance (in individuals per liter) of adult and pre-adult stages of *Artemia* from eastern and western Aral basins. Bars represent averages (with error bar for one standard error) of all monthly observations (see Tables 1 and 2).

Table 5
Yearly average abundance values for four ontogenetic stages of *Artemia* from western and eastern Aral basins; mean and standard deviation (S.D.) of n observations; min./max. = minimal/maximal value, respectively, observed; hyphen (-) = no observation.

	Year	Western basin					Eastern basin				
		Mean	S.D.	n	Min.	Max.	Mean	S.D.	n	Min.	Max.
Nauplii l^{-1}	2005	0.91	1.24	93	0.00	6.15	2.22	3.49	75	0.00	24.62
	2006	2.71	3.43	40	0.00	15.33	14.90	13.65	52	0.84	62.32
	2007	2.15	1.19	50	0.11	3.99	-	-	-	-	-
Juveniles l^{-1}	2005	0.09	0.16	93	0.00	1.35	0.23	0.29	75	0.00	1.07
	2006	0.07	0.14	40	0.00	7.67	1.05	1.55	52	0.00	6.36
	2007	0.42	0.28	50	0.01	1.01	-	-	-	-	-
Pre-adults l^{-1}	2005	0.05	0.10	93	0.00	0.64	0.21	0.37	75	0.00	1.70
	2006	0.05	0.10	40	0.00	0.65	1.12	2.19	52	0.00	9.69
	2007	0.21	0.15	50	0.00	0.55	-	-	-	-	-
Adults l^{-1}	2005	0.04	0.06	93	0.00	0.38	0.15	0.32	75	0.00	1.75
	2006	0.01	0.02	40	0.00	0.08	0.14	0.17	52	0.00	0.68
	2007	0.19	0.15	50	0.01	0.62	-	-	-	-	-

population fluctuations throughout the reproductive season, the data do depict characteristic population fluctuations. Recruitment, as shown by naupliar abundance, was lower in the western than in the eastern basin (Fig. 5); younger ontogenetic stages are limited in their swimming and foraging capabilities (Davenport and Healey, 2006) and may thus not be able to exploit benthic microalgae in times of phytoplankton depletion as readily as nauplii and juveniles in the shallow eastern basin. The average monthly abundance of *Artemia* adults was not higher than about 0.5 adults l^{-1} (eastern basin in 2005), but more often less (Fig. 6), which is thus quite below the values recorded in the GSL (0.5–2.0 adults l^{-1}) or adult abundance in *Artemia* lakes in southwest Siberia which are generally slightly lower than the GSL values (Van Stappen et al., 2009). Arashkevich et al. (2009), working primarily in the northern, Kazakh region of both basins calculated abundances of 0.14 adults l^{-1} (2005) and 0.28 adults l^{-1} (2006) for the western basin, which is higher than our average counts and more comparable to our peak counts for August and September. Our data indicate that there may be some gradual gains in the population size in the western basin over the period 2005–2007 and that conditions during 2006 were less favorable for *Artemia* population growth than in 2007. The improvement in the *Artemia* population in the western basin may be a function of increasing salinity coupled with the documented increase in microalgae density in 2007, as demonstrated in a separate study (Marden et al., unpublished results).

There were no significant differences in brood size between the *Artemia* populations of both basins, though average annual values for cysts brood^{-1} were higher for the eastern basin and in any case in the range 10–25 cysts brood^{-1} (Table 6). The increasing trend of oviparous brood size in the western basin towards 2007 may indicate that local conditions were increasingly favoring reproductive success. Brood size of *Artemia* females is influenced by genetic predisposition, food availability, and abiotic factors (e.g. temperature and salinity) (Browne et al., 1984). Research on *A. franciscana* from the GSL from 2006 to 2008 (Marden, 2008) has recorded average brood sizes of 64 nauplii brood^{-1} and 81 cysts brood^{-1}, whereas Wurtsbaugh and Gliwicz (2001) reported lower reproductive output of 15 to 30 cysts brood^{-1} for GSL *A. franciscana* over a 12 month period in 1994 and 1995. Among parthenogenetic *Artemia* investigators have observed fecundity levels of 12 to 100 offspring brood^{-1} for a population in southern France (MacDonald and Browne, 1990), and 10 to 35 offspring brood^{-1} for a variety of populations from southwest Siberia (Van Stappen et al., 2009). Aral Sea *Artemia* brood sizes were thus on the lower side as compared to values reported for *A. franciscana* and parthenogenetic *Artemia* from other saline lakes of the world.

Cyst abundance, as reported in this study for both Aral basins (Fig. 8), was well below values reported for GSL (19–180 cysts l^{-1}; Marden, 2008). Cyst abundance in the water column provides the critical measure of *Artemia* population production with regard to the potential for commercial exploitation of the resource, and is more reliable than surface accumulations ('streaks'), which are very patchy due to wind and water currents. In both basins there was a yearly trend of increasing cyst abundance with peak concentrations observed in late summer and fall months, as is the case in other saline lakes in temperate areas. This pattern of increasing cyst numbers in the water column generally coincides with the shift to oviparity during times of environmental stress (Lenz and Browne, 1991) coupled with the production of buoyant cysts. Among *Artemia* populations, such as *A. franciscana* in the GSL, that produce buoyant cysts there is a definable relationship between fecundity, the transition to oviparity and the abundance of cysts in the water column (Marden, 2008; Stephens, 2000). These studies also indicate that the buoyancy of *Artemia* cysts increases from approximately 20 to 80% buoyant cysts as salinity increases from 125 to 175 g l^{-1}, with the greatest increase in floating cysts occurring as salinity increased from 140 to 160 g l^{-1}. Considerable fractions of cysts being suspended in the water column and/or sedimented on the lake bottom is a phenomenon also evidenced for Siberian lakes (Van Stappen et al., 2009) and demonstrated in the laboratory for *A. urmiana* from Lake Urmia, Iran (Abatzopoulos et al., 2006). Comparing the values for the non-streak density of surface cysts to the cyst congregations in bottom sediments, as given by Arashkevich et al. (2009) gives a percentage floating value in the range

Table 6
Brood sizes for gravid *Artemia* adults from of western and eastern Aral basins. Values are mean and standard deviation (S.D.) of n observations; min./max. = minimal/maximal value, respectively, observed; hyphen (-) = no observation.

	Year	Western basin					Eastern basin				
		Mean	S.D.	n	Min.	Max.	Mean	S.D.	n	Min.	Max.
Nauplii brood^{-1}	2005	26.8	16.5	190	1.0	62.0	20.0	16.7	30	5.0	38.0
	2006	10.0	11.3	20	2.0	18.0	27.0	14.7	50	2.0	41.0
	2007	19.4	7.7	70	12.0	34.0	-	-	-	-	-
Cysts brood^{-1}	2005	16.6	10.2	310	1.0	36.0	22.9	14.5	90	9.0	55.0
	2006	10.1	9.4	130	2.0	32.0	11.1	7.7	240	2.0	30.0
	2007	24.9	17.5	400	1.0	61.0	-	-	-	-	-

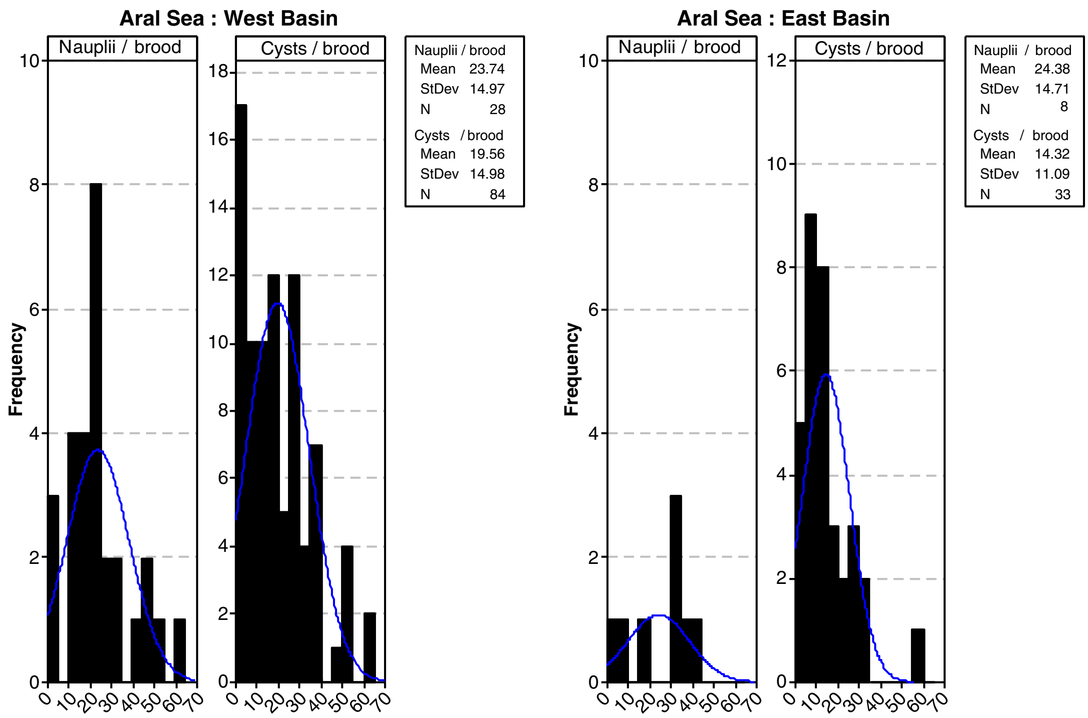

Fig. 7. Frequency distribution (with Gauss curve) of brood size in eastern and western Aral basins (based on all observations throughout 2005–2007, see Tables 1 and 2).

11–17%, suggesting that the Aral Sea cysts do exhibit similar buoyancy characteristics as found for GSL *A. franciscana* cysts. An increase in the salinity of the Aral Sea, coupled with increased nutrient loads, could lead to greater production of cysts. However, the comparison of water column cyst density is complicated by the fact that salinity fluctuated through the study and between basins. Cyst density is also affected by other factors: it is likely that cysts are more often suspended due to wind-driven mechanical mixing in the shallow eastern basin compared to the deep western basin. Moreover, the buoyancy of *Artemia* cysts is a function of the complex interaction between the internal biochemical characteristics of the cysts and the surrounding saline conditions (Campbell and Dower, 2003), and therefore it cannot be simply assumed that a salinity increase, independent of increased per capita production of offspring, will directly improve cyst buoyancy. In contrast, a dramatic decrease in the salinity of either basin of the Aral Sea could have adverse consequences on the population (Mathew et al., 2011).

4.3. Potential cyst production and future perspectives

Using the average cyst abundance values from our study, and a total volume estimate of 81 km^3 (Micklin, 2007) for both basins in the period of sampling, the standing crop of cysts totaled for both basins could potentially have been 678.9 tons of cysts (dry weight). This is within a same order of magnitude as the annual harvest of *Artemia* cysts from

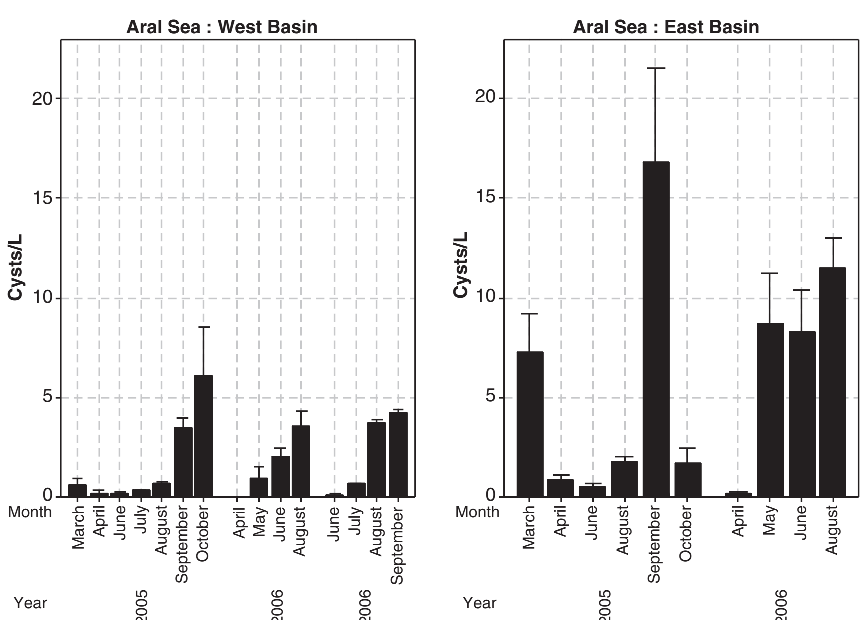

Fig. 8. Average monthly *Artemia* cyst abundance for eastern and western Aral basins, based on all observations throughout 2005–2007 (see Tables 1 and 2). Error bars are one standard error from the mean.

the GSL. However, the 240 to 2350 tons of dry cysts harvested annually over the past 15 years in GSL all come from the lake's south arm (8.0–11.4 km^3 or an elevation range of 1278–1280 m above sea level) which is only about 10% of the Aral Sea (Baskin and Allen, 2005). Based on these comparisons it is evident that cyst abundance needs to increase by three to fourfold in order for the Aral Sea *Artemia* resource to become more financially compelling for large-scale international commercial investment. However, in 2009 and 2010 the resource did reach the threshold to justify a commercial operation in the northern region (Kazakhstan) of the Aral Sea, with annual harvests amounting up to 50–70 tons wet weight (Marden, unpublished results). In the southern, Uzbekistan, region of the Aral Sea commercial efforts have been underway but have only had limited success. Both the Kazakhstan and Uzbekistan governments have issued quotas for the commercial harvesting of *Artemia* cysts from the Aral Sea. The considerable obstacles inherent to the logistics of harvesting and product transport remain a significant obstacle to commercial success. Since our study, the eastern basin has alternately been inundated with water, or has been almost entirely depleted of open water, except for a few small residual water pockets. The water volume of the western basin is still considerable, given its depth, and its shoreline is relatively easily accessible, as compared to the eastern basin. In the western basin colonization of *Artemia* progressed throughout our study, as shown by gradual increases in abundance of the respective age classes. Transparency data, confirmed by data from a separate phytoplankton study (results further not shown here), suggest that the rather low present productivity of the parthenogenetic Aral Sea *Artemia* population is not due to innate genetic factors, but is to a large extent the result of suboptimal primary production and hence food limitation (both in terms of phytoplankton density and species composition). Changes in the hydrochemistry and ecology of the Aral Sea, such as continued increases in salinity and fluctuations in nutrient levels are linked with the irrigation policy and water management in general of the countries in the Amu Darya basin (Kubo et al., 2009; Micklin, 2010), which are determined by factors such as economic development, urbanization and population growth. Changes in salinity and nutrients are coupled with changes in the microalgae population size and structure, and thus affect reproductive success and survival of *Artemia*.

The long-term survival of the remaining basins of the Aral Sea on Uzbek and Kazakh territory, and the possible restoration of depleted water bodies, highly depends on the respective water policies of the Central Asian countries. It is difficult to predict how the western and the (presently largely desiccated) eastern basin will exactly evolve, but an evolution towards a gradual further salinization of the western basin is likely. Our data justify that the *Artemia* population of the western basin should continue to be monitored in order to detect critical reproductive and population level changes and to develop stage-structured population models (Manly, 1990). Particular emphasis for future field research should include quantifying cyst accumulations along accessible shoreline regions, expanding nutrient assessments of the lake and conducting surveys of optimal harvesting areas and transportation routes.

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