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Large Asian Lakes in a Changing World

Natural State and Human Impact

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Chapter 3
Past and Current Changes in the Largest Lake of the World: The Caspian Sea

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Abstract The Caspian Sea (CS), located between Europe and Asia, is the largest lake in the world; however, its physical environment and its floor have oceanic characteristics. The CS is composed of a very shallow north sub-basin with a very low salinity mostly below 5 psu. The middle and southern sub-basins are deep and have a salinity of c. 13 psu. To the east, the Kara-Bogaz-Gol, a hypersaline lagoon, is connected to the middle sub-basin. The CS is endorheic and therefore very sensitive to changes in hydrography and climate. Because of its long history of isolation following the disconnection of the Caspian Sea from the Paratethys c. 6 million years ago, this ancient lake has many endemic species. The harsh environment of its brackish waters and the repeated salinity changes over the millennia, however, do not allow for a high biodiversity. The benthos is more varied than the plankton. The history of water-level changes remains poorly known even for the last centuries. Nevertheless, the amplitude was of >150 m in the Quaternary, several tens of meters in the Holocene and several meters in the last century. Many factors affect its natural state, such as petroleum pollution (an industry dating back to Antiquity), nutrient increase

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(alongside >14 million inhabitants along the coast), invasive species (e.g. the comb jelly *Mnemiopsis leidyi*), overfishing (including sturgeon) and modifications of its coastline (e.g. sand extraction). In comparison to other ancient lakes, the CS surface temperature has suffered from the fastest increase on record. Owing to the complex natural state of the CS, it is not easy to identify the Holocene-Anthropocene transition, although it may be suggested that is was approximately AD1950 when intense human activity started to modify the lake.

Keywords Hydrography · Brackish water · Water-level change · Endemism · Anthropogenic impact

3.1 Introduction

The Caspian Sea (CS) is currently the largest lake on Earth with an area slightly greater than Germany. It lies at the geographical border between Europe and Asia (Fig. 3.1). Originally it was created tectonically when the Paratethys Sea started splitting in smaller water bodies some 5.6 million years ago (Hinds et al. 2004). It may therefore be counted as an ancient lake. It can be considered to have been an endorheic water body for the last c. 2.6 million years, with only occasional outflow to the Black Sea and inflow from the Aral Sea. This situation has led to the development of endemism in many groups of animals and plants, living in the water or depending on it (e.g. the seals; Dumont 1998). The close nature of its water body also favours wide changes in water levels in reaction to changes in climate and in the main feeding rivers, such as the Volga (from the North) and the Amu-Darya (from the South-East, with decreasing frequency until perhaps the fifteenth century). The CS water level (CSL) has often changed dramatically: during its geological lifetime by more than 150 m, possibly several hundreds of metres (Kroonenberg et al. 1997; Mayev 2010; Forte and Cowgill 2013), during the Holocene by several tens of meters (Kakroodi et al. 2012), during the last millennium by >10 m (Naderi Beni et al. 2013) and during the last century by >3 m (Arpe and Leroy 2007; Chen et al. 2017; Fig. 3.2). However, CSL changes remain poorly identified, and their reasons not completely understood, even for the last decades.

Humans have lived along the shores of the CS since the Late Pleistocene at least, e.g. no less than four sites of Neanderthal occupation with Mousterian tools are known (Dolukhanov et al. 2010). Recently increasing human pressure is felt around the CS, as economic development is taking place. Nowadays the impact on the coastal environment and economical activities around and in the CS cause significant socio-economic problems. For many years, the main activity in the area was related to the fishery industry, as the CS holds the most appreciated sturgeon species in the world, with the export of caviar. In the last decades, the petroleum (oil and gas) industry has boomed, especially with large offshore infrastructures, e.g. offshore Baku (Azerbaijan's capital) and in the Kashagan offshore oil field (N CS).

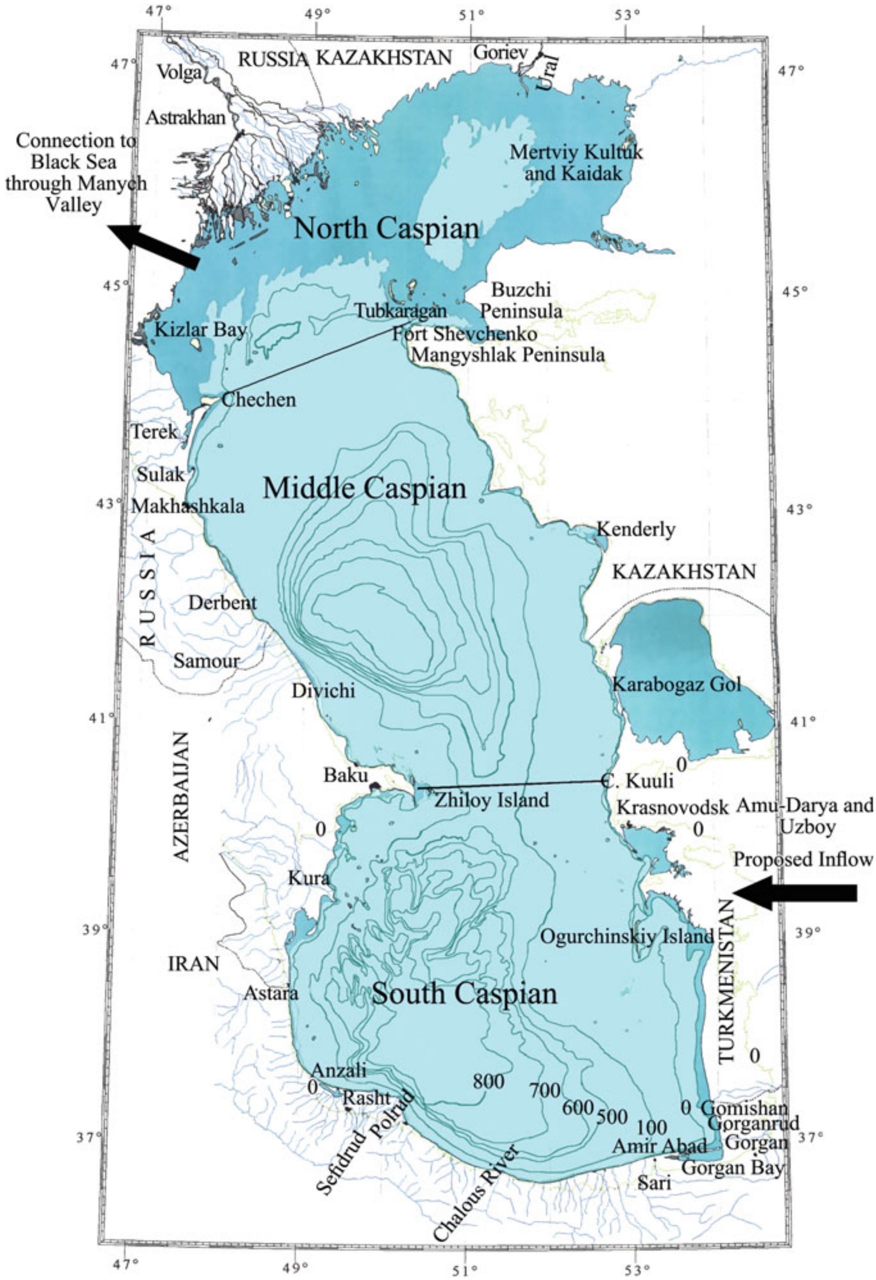

Fig. 3.1 Location map with bathymetry. The black lines through the Caspian Sea show the limit between its three sub-basins. The green contour is the zero in the Baltic datum

3.2 Modern Setting

3.2.1 Physical Geography

The CS is the largest endorheic water body of the world. It has an area of ~386,400 km^2, excluding the Kara-Bogaz-Gol (Fig. 3.1; Table 3.1). It is made of three sub-basins, deepening from very shallow in the north (5–10 m deep) to the deepest sub-basin in the south (maximal water depth 1025 m). The middle sub-basin has a maximum depth of 788 m (Kostianoy and Kosarev 2005) and is separated from the north by the Mangyshlak Threshold and from the south sub-basin by the

Table 3.1 The Caspian Sea in numbers

Caspian Sea	Information	Additional explanation	Source
Size	386,400 km^2 in 2017	Slightly larger than Germany	Arpe et al. (2018)
Level	At present 28 m bsl	Over last 21 ka, from c. +50 to c. −113 m	Several sources, see text
Depth	Maximum in South: 1025 m	North: max. 25 m Middle: max 788 m	Kostianoy and Kosarev (2005)
Volume	78,200 km^3		Dumont (1998)
Catchment	~3,500,000 km^2 (with E. drainage)	Catchment/surface area ratio: from ~7:1 to 10:1	Kostianoy and Kosarev (2005), Chen et al. (2017)
Length of coastline	7500 km	At water level of 27 m bsl	Kostianoy and Kosarev (2005)
N-S length and W-E width	Length 1200 km	Width 200–450 km, average 350 km	Kostianoy and Kosarev (2005)
Surface water temperature	Summer 28 °C in the S and 23 °C in the N	Winter 0 °C in the N with ice cover and 10 °C in the S	Kostianoy and Kosarev (2005)
Salinity	Summer 3 in the N and 13 in the S	Winter 5 in the N and 13 in the S	Kostianoy and Kosarev (2005)
Surface pH and dissolved oxygen	Summer pH 8, DO 6 ml/l	Winter pH 8, DO 10 ml/l in N to 7 ml/l in S	Kostianoy and Kosarev (2005)
pH and dissolved oxygen at 100 m	Summer pH 8, DO 6 ml/l in N, 4 ml/l in S	Winter, pH 8, DO 7 ml/l in N, 4 ml/l in S	Kostianoy and Kosarev (2005)
River inflow	290 km^3/year	84% Volga	Lahijani et al. (2008; this paper)
Number of inhabitants in the catchment	>80 millions	In five countries	Lahijani et al. (2008)

Apsheron Sill (150 m; Kuprin 2002). An ecogeographical classification of the CS based on its physical parameters shows the justification of the division into three sub-basins, as well as the role of the distance to the shore (Fendereski et al. 2014). The volume of the CS is 78,200 km^3 and this makes it three times larger than Lake Baikal (Messager et al. 2016). The north sub-basin is very shallow, and any small vertical change is translated in vast inundation or emersion along the north coast (the Caspian Depression) reaching a horizontal amplitude of c. 1000 km during the last glacial-interglacial cycle.

The CS is located in a depression bordered by the Caucasian mountains in the West, the central Asian plateaus and desert in the East, the Russian and Kazakh plains in the north, and by the Alborz Mountains in the south (Figs. 3.1 and 3.3). The CS watershed is approximately 3.5 million km^2 and it covers nine countries: Armenia, Azerbaijan, Georgia, Iran, Kazakhstan, Russia, Turkey, Turkmenistan and Uzbekistan.

The CSL was at 28 m below world sea level (bsl), geodetical station Kronstadt, Baltic, Russia, in 2018.[1] Recent CSL changes are not only rapid, e.g. a hundred times faster than global ocean level rise in the twentieth century, but also large (Kroonenberg et al. 1997). The instrumental record, starting in 1837, shows a 3-m amplitude with a minimum in 1977 and maxima in 1929 and 1995 (Voropayev 1997; Leroy et al. 2006), thus ranging between 26 and 29 m below sea level (Fig. 3.2a). Changes of the CSL can, moreover, be very abrupt as observed after 1930 when the level dropped by 2 m in approximately ten years and also when the water level increased by 2 m between 1979 and 1996. Since then, the CSL has dropped again by 1 m (June 2018). Between 1996 and 2016, the water level fell by 7–10 cm per year (Arpe et al. 2014; Chen et al. 2017). Since 2016, the CSL seems to have stabilized to equilibrium at ~−28 m (Fig. 3.2b). As it is an endorheic lake, the CSL variations are mostly controlled by water discharge from the rivers, the direct precipitation and evaporation over the CS and the discharge to the Kara-Bogaz-Gol (Kosarev et al. 2009).

Around 130 rivers flow into the CS from the north, west and southern coasts. They supply annually 250 km^3 of water and 70 million tons of sediments. The Volga discharge into the CS is highly variable and in total, it represents between 80 and 90% of the surface water inflow (Fig. 3.2c).

Because of its great meridional extension, the CS straddles several climatic zones (Fig. 3.3). The northern part of the drainage basin lies in a zone of temperate continental climate with the Volga catchment well into the humid mid-latitudes. The emerged Volga delta (the Caspian Depression) forms a low-lying area and is the most arid region of European part of the Russian Federation (UNEP 2004). The western coast features a moderately warm and dry climate, while the southwestern and the southern regions fall into a subtropical humid climatic zone. The eastern coast is desert.

[1]Since 1961, the water level reference is the Kronstadt gauge in the Baltic Sea. It is a historical reference for all former Soviet Union regions.

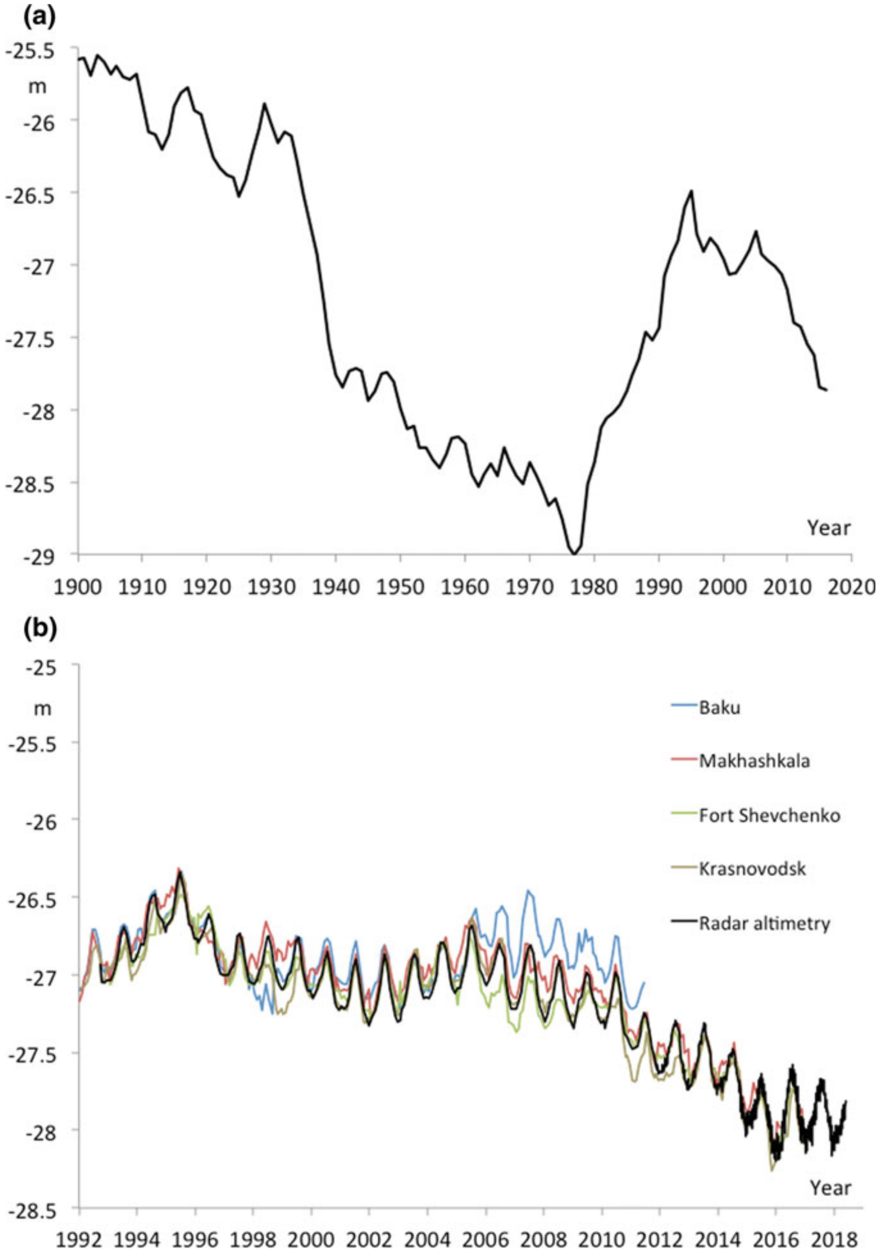

Fig. 3.2 **a** Instrumental data of Caspian Sea levels since AD1900 from in-situ average gauge data. **b** Monthly Caspian Sea level variations from 1992 to 2016 from in-situ gauge data collected in Baku, Makhashkala, Port Shevchenko and Krasnovodsk, and from radar altimetry using a constellation of Topex/Poseidon, Jason-1, Jason-2, Jason-3 and Sentinel-3A satellites. **c** Volga River discharge in percent of the total surface inflow. **d** Discharge in km^3 for each river excluding the Volga

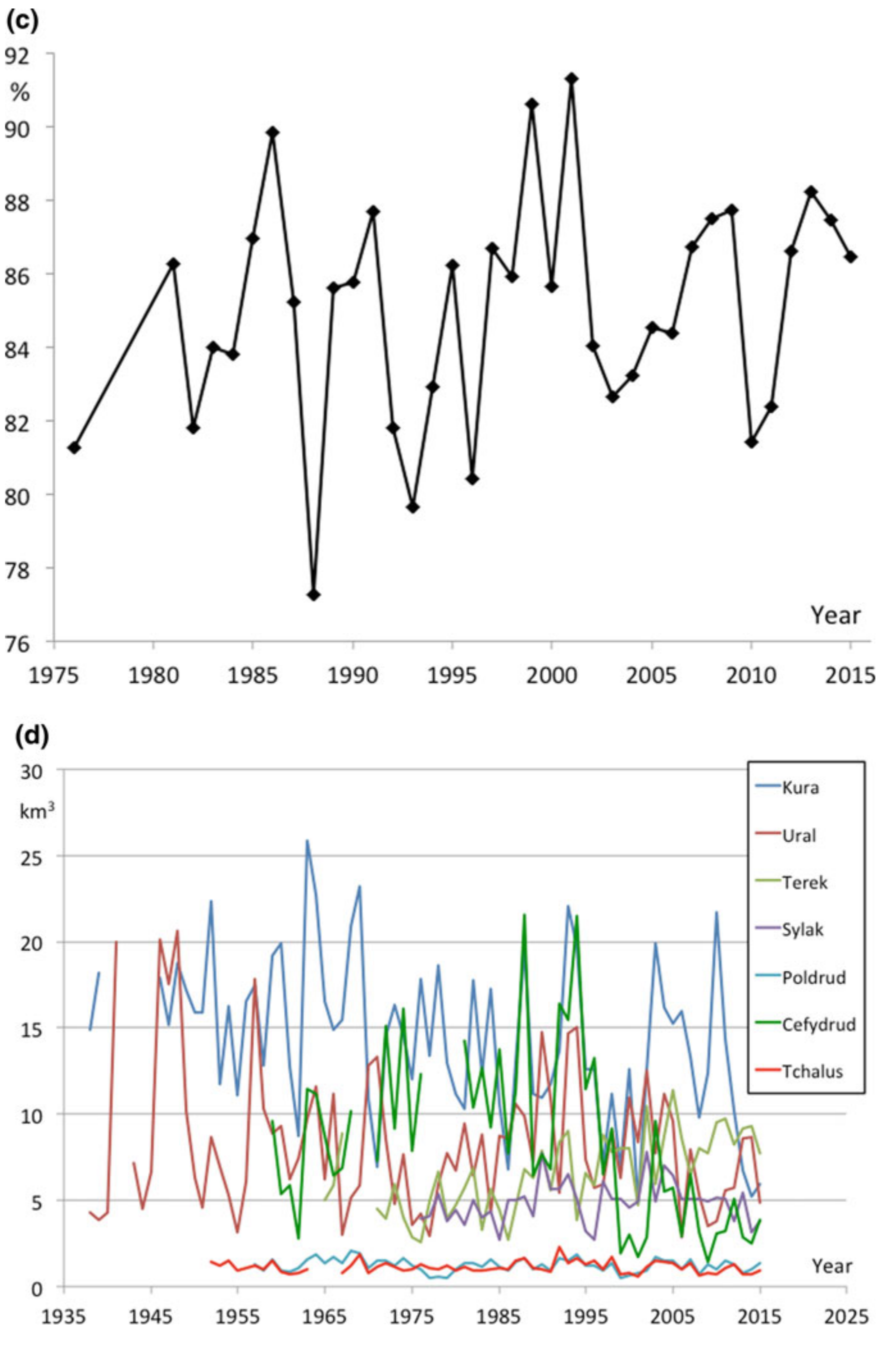

Fig. 3.2 (continued)

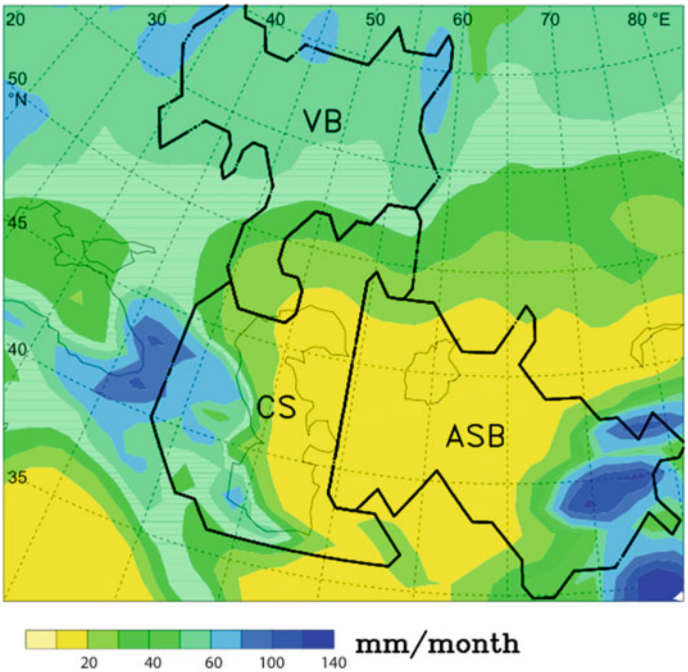

Fig. 3.3 Precipitation in mm per month (colour scale) and drainage basins (bold black line) over the Volga (VB) and the Amu-Darya and Syr-Darya (ASB) basins (provided graciously by K. Arpe)

At present, precipitation received over the drainage basin of the Volga River drives changes in the CSL, especially summer precipitation (Arpe and Leroy 2007; Arpe et al. 2012; Fig. 3.3). Nowadays, it is possible to forecast to some extent the CSL based mainly on the precipitation across the catchment area, considering that it takes a few months for the water to come down the Volga and feed the CS (Arpe et al. 2014).

Explanation of long-term CSL change has puzzled the scientists of many countries: Shiklomanov et al. (1995), Arpe and Leroy (2007), Arpe et al. (2000, 2012, 2018), Lebedev and Kostianoy (2008), Ozyavas and Khan (2008), Ozyavas et al. (2010) and Chen et al. (2017). Their objective was often to forecast future evolution of the CSL. The link between CSL and climate can be seen in two ways. Firstly the analysis of the causes of the observed CSL is made in terms of the inter-annual variability of the water-balance components (Ozyavas et al. 2010; Chen et al. 2017). Secondly the relationship between global large-scale phenomena like El-Niño southern Oscillation (ENSO) and atmospheric circulation in general (Arpe et al. 2000; Arpe and Leroy 2007), or extreme phenomena like drought events (Arpe et al. 2012), including feedback mechanisms from the CSL (Arpe et al. 2018), is analysed. It has, for example, been demonstrated in Arpe et al. (2000) that CSL long-term changes have been attributed partly to ENSO enhancing the teleconnection between regional water-level variability with a global index such as the Southern Oscillation Index calculated from sea surface temperature (SST) over the Pacific Ocean.

3.2.2 Physical Limnology

The modern salinity of the surface waters shows a gradient from freshwater in the large Volga delta to 13 psu in the middle and southern sub-basins (Kostianoy and Kosarev 2005). The Kara-Bogaz-Gol, a small basin connected to the east of the CS, serves as an overflow and is hypersaline, up to 20 times that of the CS (Giralt et al. 2003; Leroy et al. 2006). The shallow gulfs of Mertviy Kultuk and Kaidak in the east of the northern sub-basin also have a high salinity in the range of 30 psu (Fig. 3.1).

The chemical composition of the CS water is largely similar to that of oceanic water although with some differences (Kosarev and Yablonskaya 1994). The CS water is poorer in sodium and chlorine ions and is richer in calcium and sulphate ions. This difference in the ratio of salts has arisen due to the isolation of the CS from the world ocean and transformation under the influence of river runoff.

The surface water temperature gradients are from 23 to 30 °C in summer and from 0 to 10 °C in winter, with c. three months of ice cover in the north sub-basin (Kostianoy and Kosarev 2005). Beyond the complex surface and bottom currents, the overall water transfer is from the north to the south, as a result of the inflow of the Volga in the north and evaporation in the south. Satellite altimetry has indeed observed an amplitude of annual change of the CS water topography which varies by approximately 10 cm from north to south, and a CSL rise which is higher in the north than in the south by 3 cm/year (Cazenave et al. 1997; Lebedev and Kostianoy 2008; Kouraev et al. 2011).

The CS, as a large lake, has the biodiversity and bioproductivity of a lake. However, the physical water environment behaves as that of an open water due to its size and depth. The CS currents and water-mass circulations are strong and wave patterns are complex. The rate of the CS deep-water circulation has changed significantly during water-level fluctuations (Kostianoy and Kosarev 2005; Sapozhnikov et al. 2010). The physiography of the CS, riverine input, geographical distribution of salinity and temperature determine the formation of water masses and circulation processes (Terziev et al. 1992). The differences in water masses, mainly created by climate, lead to relatively distinctive physical and chemical specifications. To a lesser extent, geological forces may cause a mixing of water masses, e.g. caused by the dispense of materials and energy through the water column. Four water masses encompass the CS water column: (1) north CS water mass, (2) surface-water mass of the middle and south Caspian sub-basins, (3) deep-water mass of the middle Caspian sub-basin and (4) deep-water mass of south Caspian sub-basin (Fig. 3.4b; Lahijani et al. 2018a). The shallow water of north Caspian sub-basin and the huge freshwater influx of the Volga River form a relatively small water mass that is nevertheless crucial for circulation. This water mass has considerable annual variability in terms of salinity and temperature (Terziev et al. 1992). The upper layer of the middle and south Caspian

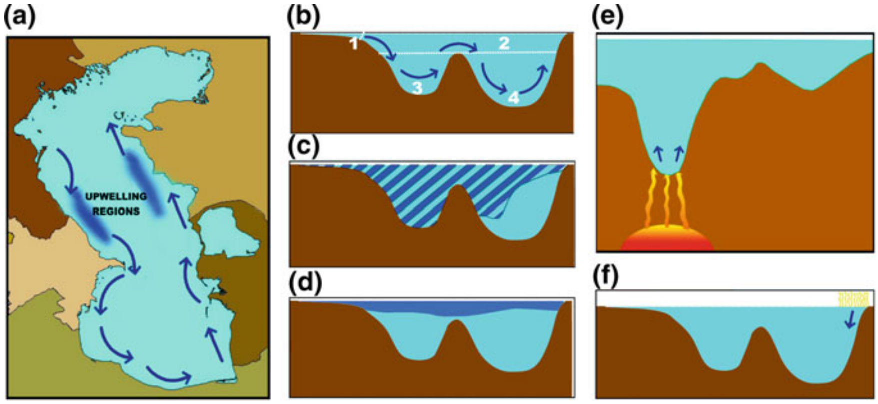

Fig. 3.4 Caspian circulation. **a** General circulation and main upwelling areas. **b** Circulation of water masses due to winter freezing of the N Caspian Sea; numbers denote to: 1 – North Caspian water mass, 2 – surface-water mass of the middle and south Caspian sub-basins, 3 – deep-water mass of middle Caspian sub-basin, and 4 – deep-water mass of south Caspian sub-basin. **c** Depth penetration of winter convection of 1969. **d** Depth penetration of winter convection of 1975. **e** Negligible geothermal impact of oceanic crust in the south Caspian sub-basin. **f** Local extensive evaporation and dense saline water formation in the southeastern part of the south Caspian sub-basin

sub-basins creates a separate water mass that is governed by the overall climate. Wind, wave, current and temperature cause mixing in a layer of around 100–150 m thickness in the middle CS and of around 50–100 m thickness in the south CS (Terziev et al. 1992). The Apsheron Sill separates the two deep-water masses of middle and south sub-basins and prevents free mixing between them. The middle and south Caspian deep-water masses differ in terms of their physical and chemical characteristics. The middle Caspian deep-water mass has lower temperature and salinity and higher dissolved oxygen content compared to the southern one. Various mechanisms trigger water exchange between these two deep-water masses. The first mechanism starts from the north Caspian sub-basin, as freshwater of the Volga and Ural rivers enter into the CS. The highest river discharge happens during spring and early summer when snowmelt increases runoff and moves southward via the bottom of the western coasts mainly due to Coriolis forcing and other river influxes (Ibrayev et al. 2010). It moves like a long counter-clockwise wave that can be detected by tide gauges as elevated water-level up to 45 cm in July (Terziev et al. 1992). Its salinity increases in the arid climate of the east coast and reaches the north CS waters. The mentioned mechanism and direct contact of the north Caspian water mass and middle and south Caspian surface-water mass cause water exchange between them. Vertical exchange in the middle CS is partially caused by wind forcing that forms a cyclonic gyre in the centre and upwelling along the east and west coasts of the middle Caspian sub-basin leading to contrasting temperatures (Fig. 3.4a). Moreover, the intense evaporation at the eastern coast may cause local warm but saline and dense water to penetrate into deeper waters (Fig. 3.4f). The higher geothermal impact of the ocean crust beneath the south Caspian sub-basin could increase water temperature causing upwelling, although this is negligible in comparison to other mixing mechanisms (Kosarev 1975; Fig. 3.4e).

Extensive water exchange among the water masses occurs during the cold season through two mechanisms: winter convection and north Caspian freezing. The winter convection mixes the water column vertically, the extent of which depends on the severity, distribution, frequency and duration of the driving cold air masses. During mild winters, the winter convection penetrates down to around 200 m in the middle and 100 m in the south Caspian sub-basins, which is not strong enough to mix all water masses (Fig. 3.4d). During severe winters, it reaches down to the middle Caspian bottom waters and to the depth of around 400 m in the south Caspian sub-basin, which enables vertical mixing of oxygen and other biochemical elements (Terziev et al. 1992; Ghaffari et al. 2010; Fig. 3.4c). The vertical mixing is forced by wind, evaporation and winter convection; this however, is not affected by the current water-level fluctuations. The Arctic-type mixing occurs annually in the CS and it affects the whole Caspian water mass (Kostianoy and Kosarev 2005). The strength of this type of mixing is closely related to the severity of winter and the Caspian water-level status (Fig. 3.4b).

During water-level lowstand, mixing would be stronger and deeper; however, in the highstand, it could hardly reach deep-water masses. The Caspian water-levels during highstands and lowstands are correlated to the increase and decrease of Volga River inflow, respectively. The salinity of north Caspian water mass increases during water-level fall (decrease of Volga discharge) and decreases during water-level rise (increase of Volga discharge).

In winter, when the surface water of the north CS is frozen, salt is released to the deeper water mass and a saline water plume flows southwards to mix with the middle Caspian water mass (Kosarev 1990). Cold (c. 0 °C) and saline water becomes denser close to $\sigma_T = 11$ to $\sigma_T = 11.5$ and sinks downward into the middle Caspian water mass. The plume pushes the middle Caspian deep-water mass into the south Caspian deep-water mass where water flowing from the south, via the eastern coast, further increases salinity. The depth penetration is strongly controlled by water level. In the course of water-level rise, dense water formation is weaker inhibiting downwelling. During water-level fall, the north Caspian water mass is saltier. It can release more salt during freezing which makes the adjacent water denser, which thus penetrates deeper. High nutrient and oxygen-bearing north Caspian water mass triggers a circulation pattern that engages the whole CS water (Kosarev and Tuzhilkin 1995). This mechanism enhances the biochemical condition for marine productivity and favours off-shore fishery after a few years of stabilized lowstand.

3.3 The Past of the CS and CS Level Changes

3.3.1 Geological Background

The geological structure of the CS basement is heterogeneous, including the south Russian platform and the Scythian-Turanian Plate to the north and the Alpine folded zone to the south. Three-layer structure of the crust under the CS was disconnected by rifting since the Late Triassic when thick sedimentary sequences overlaid the basaltic rocks (Ulmishek 2001; Brunet et al. 2007). The crust of the south Caspian sub-basin shows more oceanic characteristics. Rifting and extensive subsidence provided accommodation space for sediments with an estimated thickness of c. 25 km (Brunet et al. 2003). The geological setting of the CS and the past water-level changes are reflected in the morphology of CS floor and coastal areas. The CS was a part of the Paratethys Sea until the Pliocene and experienced a common history with the Black, Azov, Mediterranean and Aral seas. The Alpine Orogeny during the Cenozoic led to uprising of the Caucasian territory and consequently separated the CS and Black Sea at the Manych Valley (between north Caucasian Mountains and southern Don River, Fig. 3.1) around five million years ago. The CS began its independent geological, hydrological, and biological history as an enclosed basin during the Pliocene (Forte and Cowgill 2013). The CSL has changed drastically since the isolation from the world ocean. Old river valleys and deltas are preserved on the CS bottom morphology, which represents extreme lowstand conditions. Throughout the Quaternary, the CSL changed widely, possibly in relation with Milankovich cycles, but with a clear overprint of large changes in river palaeogeography. During the Akchagylian transgression (very late Pliocene and very Early Pleistocene), a brief connection to the Arctic has been highlighted (Agalarova et al. 1940; Richards et al. 2018; Hoyle et al. 2020).

Mud volcanoes of the CS are mainly concentrated in the southern part and are very active due to a high sedimentation rate associated with compressional forces and seismicity. Their eruptions bring old sediments, gas and water into the CS and form dome-shaped features up to 400 m in height on the CS lake bed and in the coastal area (Huseynov and Guliyev 2004). Annually around 2 million tons of sediments associated with 0.001–0.01 km^3 of fossil water and 0.36 km^3 of gas is brought to the lake floor by mud volcanoes and gas is released to the atmosphere (Glazovsky et al. 1976). If the onshore-mud volcanoes are included, the total annual gas emission by the mud volcanoes reaches 1 km^3 (Huseynov and Guliyev 2004). Offshore mud-volcano eruptions have environmental consequences including high amounts of hydrocarbons and heavy metal concentration around the cone and mass death of biotas (Glazovsky et al. 1976; Ranjbaran and Sotohian 2015).

Bottom sediments of the CS have different origins including terrigenous, biological and chemical. The terrigenous sediments are supplied mainly through riverine discharge as well as by aeolian transport, coastal erosion and mud volcanoes. Biological components comprise calcareous and siliceous shells and organic materials. Chemical sediments are mainly formed by precipitation of calcium carbonate and sulphur minerals (in deep anoxic environments during early diagenesis). Rates of sedimentation are closely related to the proximity of the sink and source areas of sediments and the hydrodynamics of the environment. The highest sedimentation rate is measured around the river mouths of the Kura (23 mm per year) and Sefidrud (14 mm per year) in the south Caspian sub-basin (Lahijani et al. 2008). In contrast, the deep middle and south Caspian sub-basins have the lowest sedimentation rate (0.1 mm per year). The areas with strong wave and current actions experience continuous erosion that exposes bedrocks. The sedimentation rate in the geological past was strongly dependent on the synsedimentary tectonics such as subsidence, rifting and closure from and connection to the adjacent basins. The past geological history of the CS is a key issue to determine the rich hydrocarbon resources that are distributed in the three sub-basins. The north CS hydrocarbon resources originated from the Palaeozoic, while the south CS resources are attributed to the Late Cenozoic (Ulmishek 2001).

3.3.2 Changes Since the Last Glacial Maximum

Transgressions are usually accompanied by freshening of water masses and cold climate; while regressions primarily correspond to increased salinities and warm climate (Chalié et al. 1997), although many exceptions exist. For example, during glacial periods, this simple relationship is complicated by a large influx of meltwater (including via rivers that are now dry) originating from the North and East of the CS catchment area (Grosswald 1993) and climatic feedbacks (Arpe et al. 2018).

No agreed terminology and stratigraphy exist for the CSL, but common points can be summarised broadly as follows. The Khvalynian is a highstand in the Late Pleistocene (Fig. 3.5). A large part of the Holocene equates roughly to the intermediate levels of the Neocaspian (or Novocaspian). However, no consensus exists about the exact date for the transition between the Khvalynian and the Neocaspian. In addition, the Khvalynian and the Neocaspian (separated by a deep lowstand) were both interrupted by several lowstands, some very deep (>100 m), with an inconsistent terminology.

3.3.2.1 The Last Glacial Maximum

Available CSL change reconstructions from the Last Glacial Maximum (LGM) to the present have been compiled and compared (Fig. 3.5). Most of the dates are with uncalibrated radiocarbon ^{14}C dates, as many dates are from before the calibration era (Table 3.2). The CSL in the LGM is poorly known and reconstructions differ amongst investigations.

A lowstand, named the Atelian (or Enotayevian), which reached 50 to 113 m bsl, is reconstructed by several authors around the LGM; and this is when the Early Khvalynian is now mostly recognised to have started rather than much earlier (Varushchenko et al. 1987; Chepalyga 2007; Svitoch 2009; Yanina et al. 2018). In addition, a level lower than the modern CSL has been reconstructed by climate modelling for the LGM (Arpe et al. 2011, 2018). However, higher than present-day water levels are proposed by other authors: 15 m above sea level (asl) by Klige (1990) and 25 m asl by Toropov and Morozova (2010). If we accept very low levels for the Atelian lowstand, the transition to the highstand of the Early Khvalynian had to have been extremely rapid with a rise of 2.5 cm per year (Svitoch 2009), resulting in dramatic

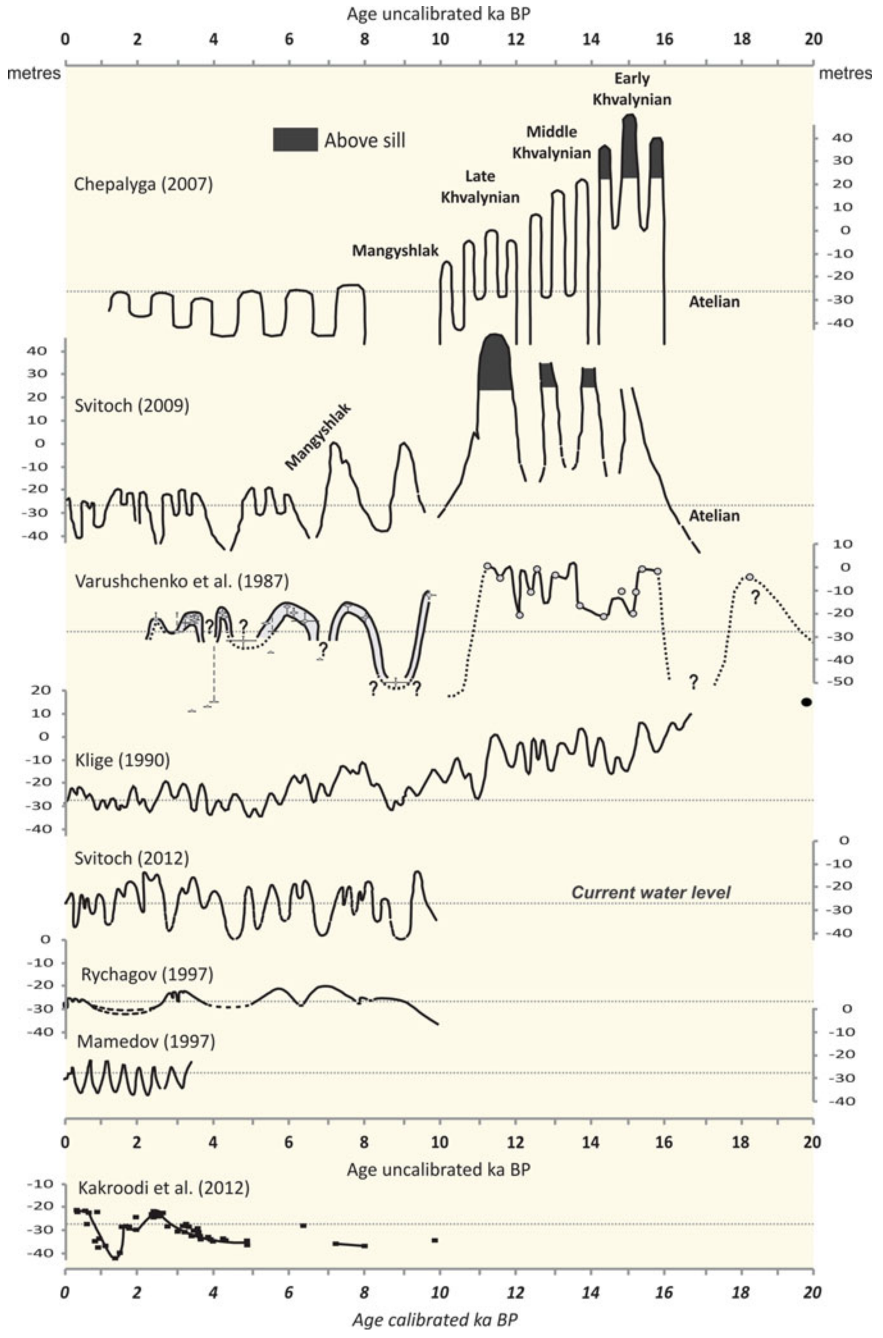

Fig. 3.5 Different Caspian Sea level reconstructions since the Last Glacial Maximum. In black, water levels above the sill causing flow to the Black Sea (upper two panels)

Table 3.2 Published Caspian Sea level curves (shown in Fig. 3.5), the reconstruction methods and the availability of metadata

Authors	Proxy for water level
Chepalyga (2007)	Geomorphology and dating of mollusc shells, scheme largely theoretical for the pre-Holocene part
Svitoch (2009, 2012)	Geomorphology and dating of mollusc shells, mostly collected in the 1960s, but some recently. Onshore and offshore areas
Varushchenko et al. (1987)	Compilation and integration of geology, geomorphology and archaeology. >35 points dated using shells with metadata (in their Tables 6 and 7)
Klige (1990)	Not documented
Rychagov (1997)	Original data. Levelling of terraces for highstands and base of alluvium in river mouths for lowstands. Dating of mollusc shells
Mamedov (1997)	Critical review of dating methods. Archaeological evidence and radiometric dating for the last four millennia. Theoretical scheme based on 450–500 year long cycles
Kroonenberg et al. (2005), Hoogendoorn et al. (2005, 2010), Kakroodi et al. (2012), Richards et al. (2014)	Geomorphology of coastal outcrops, seismic profiles and offshore cores. With metadata

flooding in the north of the north sub-basin with an horizontal advance of as much as 5–10 km per year (Chepalyga 2007).

3.3.2.2 The Deglaciation

After the LGM, the deglaciation brought a large amount of Eurasian ice-sheet meltwater to the CS through the Volga drainage basin (Tudryn et al. 2016), although part of the meltwater may also have flown through the Aral Sea and then to the CS (Chepalyga 2007). Large ice-dammed freshwater lakes formed along the southern edge of the Eurasian ice sheet (Mangerud et al. 2004). The timing of this palaeolake development is poorly known. Their drainage into the CS caused the Late Pleistocene Khvalynian highstand, especially high in the Early Khvalynian (Chepalyga 2007; Kroonenberg et al. 1997; Rychagov 1997) when the CS filled up to c. 50 m asl and the Precaspian plain was flooded (Fig. 3.5).

This means that the CSL was above the Manych sill (between the CS and the Black Sea; Fig. 3.1), which is at c. 26 m asl nowadays, but this sill is considered to have been higher in the Late Pleistocene (Mamedov 1997; Svitoch 2008, 2009). Water that spilled over the sill flowed into the Black Sea, where the inflow from the

CS is marked by red clay layers (16.3–15 calibrated kiloyears before present (cal. ka BP)), although a debate still exists regarding their origin (Bahr et al. 2008; Tudryn et al. 2016). By 13.8 cal. ka BP the Eurasian ice-sheet had become so reduced that its meltwater failed to reach the Volga drainage basin (Tudryn et al. 2016). This is when the meltwater channels were finally abandoned and the meltwater moved north-west, i.e. through the English Channel as a river (Tudryn et al. 2016).

3.3.2.3 The Mangyshlak Lowstand

After the Younger Dryas climatic deterioration, an important regression, usually called the Mangyshlak lowstand, has been reconstructed in many records. This lowstand was perhaps as far down as 113 m bsl, although its water level reconstruction varies significantly among authors. It caused the Volga River to carve deeply incised valleys into the emerged shelf, and formed a lowstand delta in the middle CS. The Mangyshlak lowstand may have lasted between c. 3000 years (on the shelf of the shallow north sub-basin at c. 12.5–9.5 cal. ka BP; Bezrodnykh and Sorokhin 2016) and c. 1000 years (recorded in deep-water cores at 11.5-10.5 cal. ka BP; Leroy et al. 2013c, 2014).

The causes of the rapid regression and following rapid transgression are unknown, but factors other than climate alone must have been involved, such as changes in hydrography (Leroy et al. 2013c). Mayev (2010) suggests a rise of 20 cm/year at the end of this period, i.e. twice the rate of the end of the twentieth century. It is during this lowstand that the Amu-Darya would have switched its flow from the south CS sub-basin to the Aral Sea (Boomer et al. 2000).

3.3.2.4 The Neocaspian Phase

Around 10.5 cal. ka BP, the CS filled up again to the present intermediate level or even higher (Leroy et al. 2013c, 2014). Some authors consider that the Neocaspian period started at this time (Varushchenko et al. 1987); others consider that the high levels can only be part of a later final phase of the Khvalynian highstand lasting until c. 7 ^{14}C ka BP and the subsequent lowstand is a “late” Mangyshlak dating of c. 6.5 ^{14}C ka BP (Svitoch 2009). Svitoch (2009, 2012), after reviewing radiocarbon dates of coastal deposits, suggests that the Neocaspian phase (characterized by the mollusc *Cerastoderma glaucum*) starts after 3.9 ^{14}C ka BP, with an earlier high level, the Gousan at 6.4–5.4 ^{14}C ka BP. Thus, the preceding high phase (8.6–7.3 ^{14}C ka BP) is still attributed to the Late Khvalynian on the basis of its mollusc assemblages. Dinoflagellate-cyst analyses tend to confirm this. The latter have highlighted a major assemblage change at 4 ka (Leroy et al. 2007, 2013a, c, 2014). Most authors agree that the Neocaspian period began no later than 6.5 ^{14}C ka BP. During this period, the water levels are generally moderately high with some fluctuations, although their number and their dates are equivocal (Varushchenko et al. 1987; Mamedov 1997; Rychagov 1997).

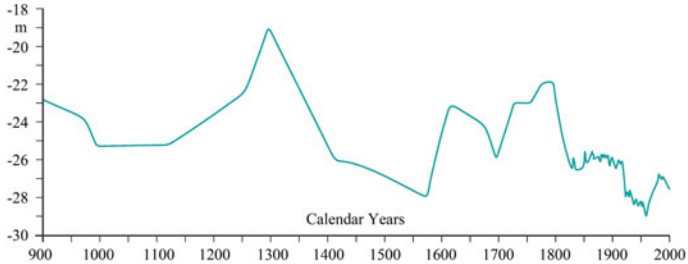

Fig. 3.6 Caspian Sea level curve based on historical data and instrumental measurements modified from Naderi Beni et al. (2013)

A more consensual reconstruction exists around the highstand of 2.6–2.3 cal. ka BP (Kroonenberg et al. 2007; Kakroodi et al. 2012). The last important regression is the Derbent regression that was relatively pronounced, down to 34 m bsl at least which corresponds roughly to the Late Antiquity-early Middle Ages (Sauer et al. 2013; Fig. 3.6). During the Little Ice Age, the levels were generally, but not continuously, high (Naderi Beni et al. 2013; Fig. 3.6). Since a maximum in the early nineteenth century at −22 m, the CSL decreased with a minimum at −29 m in 1977.

The last major connexion with the Aral Sea, via the Uzboy (now dry) and the Amu-Darya, took place c. 5 ka ago when *C. glaucum* invaded the Aral Sea (Boomer et al. 2000). Much more recently, the flow of the Amu-Darya has been briefly diverted to the CS due to human activities: in the thirteenth century by Gengiskan troups destroying the dam built in the tenth century, again in the fourteenth and finally in the fifteenth century by others (Herzfeld 1947; Naderi Beni et al. 2013; Krivonogov et al. 2014).

3.3.2.5 Limitations to Reconstruct CS Level

It is important to be aware of the following: (1) that most of the published CSL curves do not match with each other (Fig. 3.5), (2) that usually no metadata on levels and dates are available to check the validity of the points on the curves with the noticeable exceptions of Varushchenko et al. (1987) and Kakroodi et al. (2012; Table 3.2), (3) that many schemes are based on theoretical assumptions rather than based on real data (existence of a cyclicity, e.g. Mamedov 1997; Chepalyga 2007), and (4) that most of the records have been obtained from the coast, hence it is impossible to estimate the depth and duration of the lowstands precisely and from the south sub-basin with the confounding influence of basin subsidence and mountain uplift.

Only a transect of long cores from the coast to depths below the lowest stand would provide clear information, but this is far from reach at the moment. In brief, a reliable record of water-level changes in the CS since the LGM is not yet available. This situation is changing now with a modest increase in the number of offshore cores providing continuous records (Ferronsky et al. 1999; Kuprin et al. 2003; Leroy et al.

2013c, 2014; Bezrodnykh and Sorokhin 2016). Moreover, no stratotypes[2] are defined for the main highstands and lowstands. So, confusion is easily introduced with names having different meanings, as no rules govern the use of terms such as the Mangyshlak lowstand. Moreover, chronozones and biozones are often mixed up. This is partially due to the continued difficulty of using and calibrating radiocarbon dates in the CS. The correct identification of the reservoir effect with a range currently between 290 and 747 years is plagued with problems due to, for example, the changing sources of water in space and time, and the hard-to-constrain influences from methane seepage in this zone of petroleum production (Leroy et al. 2018).

3.4 The Biota of the Caspian Sea

3.4.1 Biodiversity and Endemism

The CS has a high diversity of biotopes, biotic and abiotic conditions (Zenkevich 1963); the main cause is the range of salinity that varies from fresh in deltas to hypersaline in the Kara-Bogaz-Gol. Due to this large salinity range, freshwater, brackish, euryhaline and hyperhaline hydrobionts can inhabit the water. Owing to the similarity of chemical compositions between marine and Caspian waters, many marine organisms thrive. As a result of the complexity of its geological origin and connexion with other water bodies, the modern fauna and flora of the CS consists of five main components: (1) Caspian origin (species that survived the closure of the Paratethys Sea), (2) freshwater reservoirs of the pre-glacial and the glacial periods, (3) Mediterranean origin, (4) Arctic origin (overlap between the edge of the Eurasian ice-sheet and the drainage basin of the Volga; Tudryn et al. 2016), and (5) a few recent Atlantic and freshwater invaders (Fig. 3.7a; Zenkevich 1963; Kosarev and Yablonskaya 1994). The total biodiversity of the CS is nevertheless lower than that of the Black Sea and of the Barents Sea (Zenkevich 1963).

The main reason for the relatively low biodiversity is probably the salinity change over time: for freshwater species the salinity is often too high, for marine species it is often too low. Only brackish-water species from both marine and continental water bodies are favoured (Mordukhai-Boltovskoy 1979). Most aquatic biota have a great plasticity to salinity: marine species that can tolerate low salinities (down to 13 psu) and freshwater and very low salinity species that can tolerate high salinities (up to 13 psu). In comparison to freshwater lakes, the diverse salinity conditions in the CS serve to increase biodiversity rather than reduce it (Aladin and Plotnikov 2004; Plotnikov et al. 2006). The fauna and flora belong to the Pontocaspian biota: i.e. found in parts of the current Caspian, Black and Aral seas, satellite lakes and river mouths. They are mostly remnants of the larger Paratethys Sea and are characterised by unusual and fluctuating salinities. Fish and Crustacea (especially benthos) have

[2]The type section of a layered stratigraphic unit that serves as the standard of reference for the definition and characterization of the unit (www.stratigraphy.org).

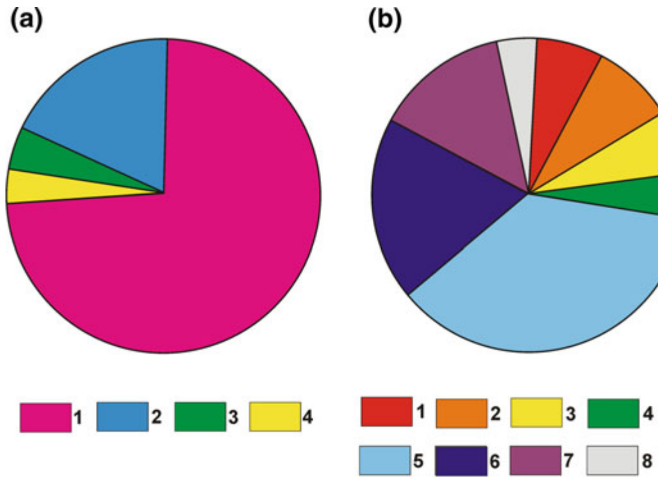

Fig. 3.7 Faunal composition of free-living Metazoa of the Caspian Sea in percentages (redrawn from Kosarev and Yablonskaya 1994). **a** by origin: 1—Autochthonous, 2—Freshwater, 3—Mediterranean, 4—Arctic. **b** by systematic groups: 1—Turbellaria, 2—Nematodes, 3—Rotatoria, 4—Annelida, 5—Crustacea, 6—Mollusca, 7—Pisces and Cyclostomata, 8—others

the largest species numbers with 63% of all modern species (Fig. 3.7b). This is because of their osmoregulation capacities that allow them to live in a wide range of salinities, from fresh to hypersaline waters (Zenkevich 1963). Owing to its isolation since the beginning of the Quaternary, the CS shows a high endemism level (Dumont 1998; Grigorovich et al. 2003; Marret et al. 2004). This is due to a complicated and long history of formation of the Caspian fauna and flora with successive episodes of isolation and connections. Nowadays, descendants of many ancient organisms, whose ancestors had penetrated into the region some millions of years ago, inhabit the CS.

The phytoplankton of the northern CS includes more than 400 species (Chrysophycea – 1, Euglenophycea – 7, Dinoflagellata – 58, Cyanobacteria – 90, Chlorophyta – 138, Bacillariophycea – 149; Aladin et al. 2001). However, only a few species predominate. Diatoms are widespread all over the CS. They take a leading place by number of species. Marine diatom *Pseudosolenia calcaravis* represents the basic part of the phytoplankton. In the CS, this alga is an invader that appeared before 1935 (Karpevich 1975; Karpinsky 2010). Thirteen Caspian endemics were previously recognised in the phytoplankton (Proshkina-Lavrenko and Makarova 1968), but in recent years only *Thalassiosira inserta*, *Th. caspica* and *Chaetoceros subtilis* were found. More recent investigations on dinoflagellates have highlighted a range of forms, species and even genera, typical of the CS (Marret et al. 2004; Leroy et al. 2018; Mudie et al. 2017). The species composition of periphyton amounts to some 200 species of algae (Phaeophycea – 8, Rhodophyta – 11, Chlorophyta – 12, Cyanobacteria – 33, Bacillariophycea – 126). Of the 87 species of algal macrophytes recorded (Zaberzhinskaya 1968), green algae (Cladophoraceae – 11, Ulvaceae – 10, including *Enteromorpha* – 9) and charophytes (Characeae – 10) dominate.

According to Derzhavin (1951) and Zenkevich (1963), 476 species of free-living Metazoa inhabit the CS (Fig. 3.7b). The fauna of Arctic origin is represented by one species of Polychaeta, one of Copepoda, four of Mysidacea, one of Isopoda, four of Amphipoda, two of fish and one species of mammal. The fauna of Atlantic–Mediterranean origin is represented by one species of Turbellaria, one of Coelenterata, two of Polychaeta, one of Copepoda, two of Cirripedia, three of Decapoda, three of Mollusca, two of Bryozoa and six species of fish. The endemic fauna is the most diverse. It comprises four species of Porifera, two of Coelenterata, 29 of Turbellaria, three of Nematoda, two of Rotifera, two of Oligochaeta, four of Polychaeta, 19 of Cladocera, three of Ostracoda, 23 of Copepoda, 20 of Mysidacea, one of Isopoda, 68 of Amphipoda, 19 of Cumacea, one of Decapoda, two of Hydracarina, 53 of Mollusca, 54 of fish and one mammal species. Many species are of freshwater origin, particularly from the Rotifera, Cladocera, Copepoda and Insecta (Derzhavin 1951; Mordukhai-Boltovskoy 1960; Zenkevich 1963). According to the more recent data of Chesunov (1978), the number of species of free-living Metazoa in the CS is larger, up to 542.

In the zooplankton, 315 species and subspecies are registered, 135 species of them are ciliates (Agamaliev 1983; Kasimov 1987, 1994). The main part of the zooplankton population comprises species of Caspian origin. Crustaceans *Eurytemora grimmi*, *E. minor*, *Limnocalanus grimaldii, Acartia clausi, Heterocope caspia, Calanipeda aquaedulcis, Evadne anonyx, Podonevadne camptonyx, P. angusta, P. trigona, Polyphemus exiguus, Apagis* spp., *Cercopagis* spp., and *Pleopis (Podon) polyphemoides* are common in the zooplankton. Freshwater complex – rotifers *Brachionus* and cladocerans *Moina*, *Diaphanosoma*, and *Bosmina* occupy low salinity areas. Larvae of benthic organisms – of barnacles *Balanus* spp. and molluscs – are abundant especially in spring and summer plankton of coastal zone (Bagirov 1989). According to Derzhavin (1951) and Zenkevich (1963), the Crustacea include 114 autochthonous species. The Mysidae include one species of *Diamysis*, one of *Limnomysis*, four of *Mysis*, one of *Hemimysis*, one of *Katamysis*, one of *Caspiomysis*, one of *Schistomysis*, and 12 of *Paramysis* (Stepanjants et al. 2015). Of them, 13 species are endemics of the CS. In the Pseudocumatidae are 19 species. Isopods have three species, including *Mesidothea entomon* of Arctic origin. In the amphipods, the Gammaridae have 60 species and the Corophiidae have eight species. The Decapoda have five species (Vinogradov 1968; Karpevich 1975; Aladin et al. 2002), including ancient native crayfishes *Astacus leptodactylus* and *A. pachypus*, prawns *Palaemon elegans* and *P. adspersus* introduced incidentally by humans in the 1930s during acclimatization of mullets, and one species of small crab *Rhithropanopeus harrisii* that was inadvertantly introduced by vessels in the 1950s.

The diversity of Mollusca species is also large: according to Bogutskaya et al. (2013), the unusual number of 124 species and subspecies, including 101 endemics, are recorded from the CS. Four families of gastropods are present: Neritidae with two species of *Theodoxus*, Hydrobiidae with 85 species, including species of genera *Andrusovia, Pseudamnicola, Caspia, Caspiohydrobia*, *Turricaspia* with 17 endemics, and 38 endemic species of *Pyrgula,* Bythiniidae with one endemic species and Planorbidae with three endemics from genus *Anisus*. The bivalves include several species and subspecies from two families. The Dreissenidae have five species: *Dreissena polymorpha* (subspecies *D. p. polymorpha* and endemic *D. p. andrusovi*), endemics *D. rostriformis* (subspecies *D. r. compressa*, *D. r. distincta*, *D. r. grimmi*, *D. r. pontocaspica*), *D. caspia* and *D. elata* (the last two have become extinct in the last century) and the invader *D. bugensis* that was introduced relatively recently with ballast waters. The Cardiidae have up to 21 species: *Adacna* with nine species (invader *A. colorata*, endemics *A. acuticosta, A. albida, A. caspia, A. laeviuscula, A. minima, A. polymorpha, A. semipellucida, A. vitrea), Monodacna* with one species (endemic *M. caspia*), *Didacna* with eight species (endemics *D. baeri, D. barbot-demarnii, D. longipes, D. parallela, D. profundicola, D. protracta, D. pyramidata, D. trigonoides*), *Hypanis* with one species (*H. plicata*) and *Cerastoderma* with two species (*C. glaucum*, *C. rhomboides*; Bogutskaya et al. 2013; Leroy et al. 2018).

Four species of Porifera are recorded: two species of *Metschnikovia*, *Protoschmidtia flava* and *Amorphina caspia*. The coelenterate *Moerisia pallasi* is an endemic species. Three species of Polychaeta belonging to the Ampharetidae are recorded.

Derzhavin (1951) and Zenkevich (1963) stated that the ichthyofauna consisted of 78 species in the middle of the twentieth century. The family Petromyzonidae had one species, Acipenseridae five, Clupeidae nine, Salmonidae two, Esocidae one, Cyprinidae 15, Cobitidae two, Siluridae one, Gadida one, Gasterosteidae one, Syngnathidae one, Atherinidae one, Percidae four, Gobiidae 30, Mugilidae two, Pleuronectidae one, and Poeciliidae one species. According to more recent data of Kazancheev (1981), the total ichthyofauna amounts to 76 species and 47 subspecies, referring to 17 families and 53 genera. In comparison with other southern seas (Azov, Black, Mediterranean), the ichthyofauna of the CS is extremely poor and consists of representatives of autochthonous (63 species and subspecies), Mediterranean (5), Arctic (2) and freshwater (56) faunistic complexes. Some species have populated the Caspian because of human activities. The distinctive feature of the Caspian ichthyofauna is its high endemism, observed from the category of genus down to the subspecies level. Early separation of the CS from the world ocean has ensured a high level of endemism of its ichthyofauna. According to Kazancheev (1981), the number of endemics at the genus level account for 8.2%, at species level for 43.6%, and at subspecies level for 100%. The greatest number of endemic forms belongs to Clupeidae and Gobiidae. In general, the CS is inhabited by four endemic genera, 31 endemic species and 45 endemic subspecies.

Sturgeons – *Acipenser gueldenstaedtii*, *A. nudiventris, A. persicus, A. stellatus* and *Huso huso* – are the most valuable commercial fish species in the CS. In the 1950s, the main dams blocking migratory routes of anadromous fish species were built on many rivers of the Caspian basin. Main estuaries and deltas are also now heavily polluted. The total area of the spawning grounds of all sturgeons shrank by around 90%. In order to compensate for losses of natural spawning and to protect sturgeon stocks, special sturgeon-rearing stations were built. From the early 1960s, sturgeon catches steadily increased for almost 20 years. After 1980, a sharp decline in catches took place. This was caused both by the increased catch of previous years and by a decrease in the number of mature fish as a result of a decrease in natural reproduction due to loss of spawning grounds. By the early 1990s, the catches were almost halved and they continue to decline. Poaching significantly increased (Bogutskaya et al. 2013).

The Caspian seal, *Pusa caspica,* is the only aquatic mammal. It is a small species (Goodman and Dmitrieva 2016) that is almost exclusively fish-eating. In winter, seals concentrate in the northern CS along the margins of the ice cover. Almost all of whelping, mating and molting take place on ice. In summer, seals migrate to feed in the middle and southern CS, with some part of the population remaining in the northern CS (Aladin et al. 2001). Phylogenetic studies indicate that the seals originated from the Arctic during past connections 3–2 million years ago (Palo and Väïnolä 2006). At the end of the nineteenth century, the seal population exceeded one million. During the twentieth century, hunting pressure increased and the population declined, being halved by the 1950s. Since that time, sealing quotas have been reduced, but population decline has continued due to many factors. At the end of the twentieth century, about 25% of Caspian seal population had died out due to various diseases. By 2005, the population was estimated at 34,000 (Goodman and Dmitrieva 2016).

Thus the CS has a high level of endemism, but is not especially biodiverse. The main characteristic of many species is their great plasticity to salinity.

3.4.2 Recent Changes in the Caspian Sea Biota

Although there is evidence for the anthropogenic introduction of species during the Middle Holocene, greater change took place in the twentieth century. For example, widespread invasion from the Black Sea to the CS by the mollusc *Cerastoderma*, occurred in the Middle Holocene (Grigorovich et al. 2003), although earlier dates were suggested (8–6 ^{14}C ka BP; Tarasov and Kazantseva 1994). Some researchers (Starobogatov 1994) deny the natural colonization of the CS by this species, since a strong current in the Manych Gulf was only directed away from the CS. Thus, they assume that the penetration was associated with the activities of ancient humans.

In the twentieth century, many invertebrate and fish species were introduced to the CS due to anthropogenic activity (Aladin et al. 2002). In the 1920s, algae *Pseudosolenia calcar-avis* and bivalve *Mytilaster lineatus* were accidentally introduced. This mollusc was introduced (Bogutskaya et al. 2013) by unusual manner – with biofouling of military vessels transported to the CS by railway. Bivalve *Mytilaster lineatus* is unwanted in the CS. It forces out native bivalves and is not much consumed by fish. Later, people deliberately introduced several species into the CS including mullets *Mugil auratus, M. saliens* and polychaete worm *Hediste diversicolor* (in the 1930s), flounder *Pleuronectes flesus luscus* and bivalve *Abra segmentum* (in the 1940s). *Hediste diversicolor* and *Abra segmentum* were introduced deliberately for consumption by fish because for them these invertebrates are valuable food. Together with mullets, two species of shrimps – *Palaemon elegans* and *P. adspersus* were introduced accidentally. All these species have adapted to the conditions of the CS.

In the middle of the twentieth century, after the Volga-Don channel had been built, a new group of species was introduced into the CS. Some of them were transported in ballast water of vessels; others were attached to their bottom. Barnacles *Balanus impovisus, B. eburneus* and bryozoan *Membranipora crustulenta*, were introduced with biofouling. Planktonic crustacean *Pleopis polyphemoides*, jelly fish *Blackfordia virginica*, algae – *Ceramium diaphanum*, *C. tenuissimum*, *Ectocarpus confervoides* f. *fluviatilis*, *Polysiphonia variegata* and crab *Rhithropanopeus harrisi* were introduced with ballast waters. The introduction of invasive species into the CS through the Volga-Don channel continues. At the end of the twentieth century planktonic copepods *Calanipeda aquaedulcis, Acartia clausi*, *A. tonsa* and ctenophore *Mnemiopsis leidyi* were introduced with ballast waters. As for the ctenophore, this species is a clear example of a negative impact on the biodiversity of the CS (Ivanov et al. 2000; Nasrollahzadeh et al. 2014). It consumes zooplankton and hence outcompetes zooplankton-feeding fish. The decrease of zooplankton thus encourages the bloom of phytoplankton. This is probably the most dangerous alien species for the CS ecosystem.

An increase in the dinocyst *Lingulodinium machaerophorum* has been observed since the late 1960s and it has been attributed to the increase in the temperature of surface waters (Leroy et al. 2013b). Since 2005, harmful algal blooms, including potentially toxic dinoflagellates, have been observed owing to a combination of higher temperatures and increased nutrient availability.

3.5 The Changing Physical World

The Caspian deep-water environment has benefited from the water-level fall until 2016 and the consequent accelerated circulation that causes deep-water ventilation and nutrient exchange. However, most changes are felt at the surface.

3.5.1 Recent Changes to the Lake Surface

3.5.1.1 CSL Changes from in-situ to Satellite-Altimetry Observations

The first measurement of water level was made in Baku in 1837, followed by many other sites around the margins of the CS during the nineteenth–twentieth century. Annual water-level variations of four base stations, Baku, Makhashkala, Port Shevchenko and Krasnovodsk, were then averaged to provide the “official” CSL (Figs. 3.1 and 3.2a, b; Terziev et al. 1992).

Figure 3.2a shows the CSL from 1900 to 2016. It was obtained using level gauges installed around the CS. Initially the measurements were made in different datum systems (Black Sea, Baltic Sea, local relative system). However, due to improved accuracy in levelling, particularly in the 1970s, allowing vertical crustal movements (~2.5 mm/year) to be determined, new zero marks have been defined, with different height systems for the east and west coasts (Pobedonostsev et al. 2005). This led to some differences in recorded water-level changes between gauges that caused ambiguities in the water-level-time series between one gauge and another. Even the recent data over the four historical gauges are not coherent all the time (Fig. 3.2b). For this reason, satellite altimetry offers an interesting complementary source of information.[3]

Over the first period between 1900 and 1929, the CSL slightly decreased with an average level around −26 m (Fig. 3.2a). In the 1930s, several large reservoirs along the Volga were filled. It led to a sharp decrease of 1.8 m by 1941, then more slowly until 1977 when the CS reached its lowest level over the last hundred years at −29 m. However, not all of this decline can be assigned to the building of dams. A good deal of the CSL variation can be simulated from the mean precipitation over the CS catchment area (Arpe and Leroy 2007a). Between 1977 and 1995 the CSL rose rapidly by 2.5 m, after which it again fell; so that by 2016 it had stabilized at a level of approximately −28 m. In such a large inland sea, the water-level changes observed over the last decades represent a very large amount of water-storage change. The two and half meter of increase between 1977 and 1995 is equivalent to additional water storage of ~900 to 1000 km^3. Such variability needs to be analyzed and understood since it has serious consequences. Understanding the mechanism behind these changes would allow forecasting the rise or fall of the level in the future, which is a topic of serious public concern for riparian countries (Arpe et al. 2014).

3.5.1.2 Water Balance of CS

[3]Since the middle of the 1990s, a noticeable progress occurred in the use of radar and laser altimetry for continental hydrology. It is important to note that this technique was initially designed for oceanography; but it very quickly became clear that satellite altimetry is an attractive technique for monitoring the water levels of lakes (Crétaux et al. 2016). Essentially, this technique has benefited from a continuous service since the launch of the satellite Topex/Poseidon in 1992, and this will continue in the years to come with various new missions.

The combined global altimetry data set has more than 2-year-long history and is intended to be continuously updated in the coming decade. A given lake can be flown over by several satellites, with potentially several passes, depending on its surface area. Thus, combining altimetry data from several in-orbit altimetry missions increases the temporal resolution and the accuracy of the water-level estimation which depends on several factors: range, orbit and correction errors (Crétaux et al. 2009). Comparisons of average water level from satellite altimetry and in-situ data for a set of 24 lakes of various locations and sizes have been established by Crétaux et al. (2016). Accuracy has been estimated by the calculation of the Root Mean Square (RMS) of the differences between both types of data: it ranges from 3 cm for large lakes to few tens of cm for small lakes, currently achievable using nadir altimeters.

Analysing the CSL changes is generally interpreted as balance between water budget components of the CS and the Kara-Bogaz-Gol resulting from dynamical response to the variations in inflow (precipitation P, river and underground discharge R and G) and output (evaporation E and discharge to the Kara-Bogaz-Gol, K). It can be expressed by the following equation (Eq. 1):

$$\frac{dV}{dt} = R + (P - E) + (G - K) \tag{1}$$

Many past studies were performed to analyse the water balance of the CS. It is generally based on in-situ data for some components (P, R, K) and/or model based on global climatological data (P, E, R, G) and/or remote sensing data (P, dV/dt). G is not measured or modelled in the most recent studies and is assumed to be a constant of 4 km^3/year (Shiklomanov et al. 1995). Ozyavas et al. (2010) however demonstrated that groundwater inflow could cause significant errors in the water balance and is presumably not constant year over year.

Discharge of the rivers is principally driven by the P-E ratio over the CS watershed. It can also be obtained from direct measurement. The calculation of evaporation over the CS can be inferred from a model based on the generalized Penman equation (Van Bavel 1966); but needs a large number of additional variables not always easy to measure (air and water temperature, air humidity, wind speed, wave height, net radiation, latent heat of vaporization). Ozyavas et al. (2010) used this model and found an average value of approximately 1100 mm/year of direct evaporation, while in Kouraev et al. (2011), average evaporation over the twentieth century is estimated to 970 mm/year. For many studies, the size of the CS, used to calculate the evaporation, is kept constant. However, as shown by Arpe et al. (2018) due to the high level variation of the CS and the high variability of its extent, in particular in the shallow northern part, the total evaporation over time can also significantly vary. Moreover, feedback of the change of CS size in the local precipitation should also be taken into account as shown by Arpe et al. (2018). Indeed, E-P is controlled by the presence of the CS itself since precipitation over the CS region is partially generated by water evaporated from the CS. In the context of CSL drop (as observed since 1995), a positive feedback (reduction of humid air in the CS watershed due to lower total evaporation) is combining with a negative feedback (lower size implies lower direct evaporation) and could reach an equilibrium state where gains are equal to losses (Mason et al. 1994). The volume change of the CS can be measured using water level changes from satellite altimetry and average lake extent.

In the paper of Chen et al. (2017), similar to Arpe et al. (2014), a model of water balance was setup using the climate model Climate Forecast System based on the National Centers for Environmental Prediction datasets. Considering only $R + (E - P)$ components of the right member of Eq. 1, using the Climate Forecast System model and in-situ discharge data of the Volga River, Chen et al. (2017) reconstructed the volume change of the CS. Then they compared it to the volume variations inferred from in-situ data and satellite altimetry. Their conclusion was that over the 37 years of analysis, the increased evaporation rate is the main cause of

CSL changes; while precipitation changes and river discharge play a secondary role, although not negligible. In that study however, the inter-annual variability of small river discharge, of Kara-Bogaz-Gol outflow and of underground water inflow have not been considered. This conclusion in Chen et al. (2017) seems to contradict the study made by Arpe and Leroy (2007a), which showed that CSL changes are at first order driven by the discharge over the Volga River basin, which is directly linked and correlated to total rainfall over the watershed of this river. However, it is also shown by Arpe and Leroy (2007a) that the post-1995 drop in CSL cannot be attributed to a drop in the Volga River discharge. Arpe and Leroy (2007a), Chen et al. (2017) and Arpe et al. (2018) consider the relationship between evaporation and CSL to be significant.

The link between CSL change and Kara-Bogaz-Gol is an important contribution to the water balance and is not always considered in literature as a specific water body with its own variability. For example, Chen et al. (2017) did not take the *K* term into account. Ozyavas et al. (2010) calculated the water balance of the CS from 1998 to 2005. They considered that the quasi-constant value of *K*, corresponding to a water balance of ~5 cm/year, is insignificant. This was partly due to the resolution of the model-generated data, being too low to resolve the Kara-Bogaz-Gol. In Arpe and Leroy (2007a), discharge to the Kara-Bogaz-Gol is considered as a constant outflow ~5% of the total surface runoff to the CS.

In most studies, the Volga River discharge to the CS is considered to be 80% of the total from all rivers. A recent dataset (www.caspcom.com) gives a discharge-time series of the eight main rivers inflowing in the CS (Volga, Ural, Terek, Kura, Sulak, Sefidrud, Polrud and Chalous; Fig. 3.1). It is obvious that discharge is not stable (Fig. 3.2d). Indeed, surface inflow from the Volga over the last 40 years has varied between 80 and 90%, and the total inflow from other rivers is very irregular from year to year (Fig. 3.2c, d). From wet to dry years, inter-annual variability of rivers excluding the Volga ranges from ~10 to ~20 cm of equivalent CSL. So, it is clear that the accurate calculation and understanding of the water balance of the CS can only be done with exhaustive data on small rivers (Arpe et al. 2014).

The Kara-Bogaz-Gol depression is shallow and at the beginning of the twentieth century when the CSL was high, the difference in water level between the CS and the Kara-Bogaz-Gol was low (c. <1 m). The long-term fall of the CS between 1930 and 1977 resulted in a decline of the discharge to the Kara-Bogaz-Gol. From 1930 to 1980, it decreased from ~30 km^3/year to 0. It therefore accounted for ~7 cm of decrease of the CS in 1930 to zero in 1980. In March 1980, in order to stop the filling of the Kara-Bogaz-Gol from the CS, the narrow strait between them was blocked by a solid and sandy dam. It immediately resulted in a full evaporation of the bay in only four years. At the end of 1984, the dam was broken and the water came back very rapidly to its full extent. From 1993 to 1995, the annual water flow reached 37–52 km^3/year (Kosarev et al. 2009) and the level rose by 5 m in three years to reach its maximum value around −27 m. Then the Kara-Bogaz-Gol level variations slightly decreased down to −28.5 m in 2017 with small annual oscillations linked to seasonal climate change.

By some assumption on the E-P term over the Kara-Bogaz-Gol (~800 mm/year, Kosarev et al. 2009), and using size and volume change of Kara-Bogaz-Gol extracted from satellite altimetry and imagery available in Hydroweb (n. d.), the inflow from the CS to the Kara-Bogaz-Gol can be recalculated. Therefore, one may calculate the corresponding water-equivalent changes of the CS, which is the opposite of the term K in Eq. 1. From 1993 to 1996, the total discharge K is 9 cm/year, and after 1996 it is only 4 cm/year. If we calculate the total loss of water from the CS to the Kara-Bogaz-Gol, it represents the significant number of >1 m from 1993 to 2017.

3.5.1.3 Caspian Sea Ice and Surface-Water Temperature

Ice formation[4] over large areas on the northern CS occurs every winter and ice stays for several months. Ice over the middle CS can also form to a smaller extent. The presence of ice has several impacts on navigation, fisheries and oil industries especially in the Russian and Kazakh coastal areas. Using active and passive microwave remote sensing data has allowed measuring time series of ice formation, break-up and duration of ice period, in the eastern and western parts of the northern CS, as well as estimating the mean and maximum ice extent over this area. Kouraev et al. (2011) reported results with remote sensing data, which exhibited a warming trend since the mid-1980s followed by a short cooling period in 1993–1994, and then again a warming trend characterised by diminution of ice duration and of maximum ice coverage for the western and eastern parts of the northern CS.

The same trend was observed in the CS SST (Ginzburg et al. 2005; Leroy et al. 2013b). Seasonal and inter-annual variability of SST were measured over four distinct regions (North, Middle, South and Kara-Bogaz-Gol) in that study. Trends for the period 1982–2000 were calculated for each hydrological season (February, April, August, and October) and compared to historical period from 1940 to 1980. Their results exhibited a significant global-warming signal with much higher rate of change in the recent period of time. In the middle and southern CS, warming trends of 0.05

[4]The study of ice cover in this region started in the nineteenth century using observations from coastal stations. It then became a monitoring system of the Soviet Union and measurements were collected on a regular basis using aerial surveys. After 1970s, ice-cover observations from airplane have drastically decreased for financial reason. It has then been compensated by using satellite imageries in the visible and infrared parts of the spectrum (Buharizin et al. 1992). However, these surveys from satellite imagery in the visible spectrum are strongly affected by cloud formation and cover, particularly in winter, and these types of information were consequently not dense enough to perform a full survey of ice presence over the CS. Since the mid-1980s, microwave-satellite observations, providing reliable, regular data on ice without masking from cloud, have been used. Since 1992, another source of data was from a synergy between active (radar altimetry) and passive (radiometer used to correct altimetry measurements) instruments. A discrimination method, developed and tested over the CS and the Aral Sea in Kouraev et al. (2003, 2004), was applied on the data of Topex/Poseidon, Jason-2, Jason-3 and Envisat missions. Combining results from this technique after 1992 (when the Topex/Poseidon satellite was launched) with microwave observation on SMMR and SSM/I missions allowed better spatial and temporal resolution than using satellite altimetry alone. This method has been successfully validated using independent in-situ measurements (Kouraev et al. 2003).

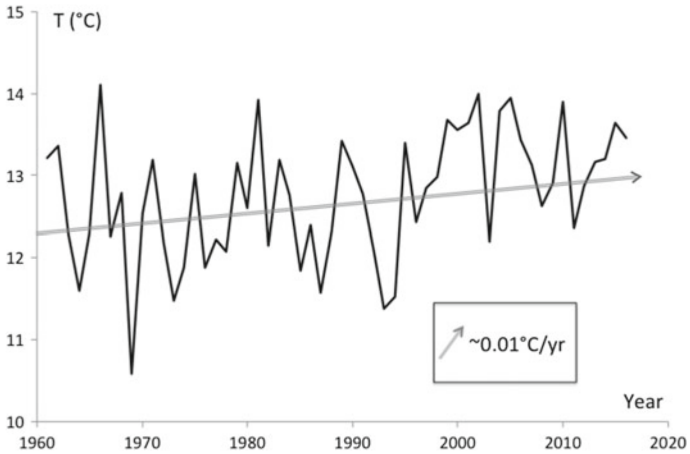

Fig. 3.8 Sea surface temperature at the station of Makhashkala in Russia on the western coast of the CS. Data from in-situ gauge over the period from 1960 to 2016. The arrow shows the 0.01 °C increase per year. *Source* http://www.caspcom.com

and 0.1 °C/year were observed respectively. SST was also compared with the ENSO and NAO phases. A strong correlation between SST in the central Pacific and the CSL has been observed, which is the sign of a linkage between ENSO and the CSL. No influence from NAO has been found (Arpe et al. 2000).

In a more recent paper (Khoshakhlagh et al. 2016), using 30 years of Advanced Very High Resolution Radiometre measurements, the SST over the four regions of the CS was analysed and trends investigated using a Mann-Kendall test. Based on this study, it can be unambiguously stated that increasing SST trend has been seen in all the four regions, mostly during March to November months. In the middle and the southern CS however, it has also been shown that no trends at all are observed in wintertime. Nazemosadat and Ghasemi (2005) have moreover shown that SST fluctuations have direct impact on winter and spring rainfalls, and that warm SST causes increasing rainfall in spring and, in contrast, cold SST causes low rainfall in spring, especially in the western areas of the CS. As an example, increasing rate of temperature in the middle part of the CS from data at the station of Makhashkala from 1961 to 2018 exhibits a trend of ~+0.012° C/year (Fig. 3.8).

3.5.2 Pollution of the Caspian Sea

The CS and its bottom sediments are the final destination for a wide variety of contaminants originating from the coast and the water itself through natural processes and anthropogenic activities. Sediments from the catchment basin mainly by riverine influx (particularly the Volga), water-bottom-mud volcanoes, submarine groundwater discharge, wind-blown sediments, and biological and biochemical activities are the main natural sources. However, offshore-and onshore-oil industries, agricultural activities and coastal urban areas are the main anthropogenic sources of the contaminants. Many contaminants could have both a natural and an anthropogenic source, while others, i.e. persistent organic compounds, only originate from human activities. Their concentration and distribution in the water column and bottom sediment are related to the proximity to source area and hydroclimatic conditions of the CS.

3.5.2.1 Heavy Metals

Heavy metal investigations demonstrate that fine-grained sediments are enriched compared to coarse sediments (de Mora et al. 2004a; Kholodov and Lisitsina 1989; Lahijani et al. 2018b). Their relationship to the sediment grain-size could be grouped as follows: the first group (Cr, Zr) displays association with silty sediments. They are mainly accompanied with Piconite and Zircon. The second group (Cu, Co, Ni, Ga, Mo, Mn, Fe) and, in some regions, Pb demonstrate a relationship with clay sediments. The third group (Ti, V, Ge) have mutual dependence, either with fine-grained or coarser-grained sediments. They are present in a wide variety of minerals that originate from the catchment basin (Klenova et al. 1962; Lahijani et al. 2018b).

Elevated amounts of some heavy metals are attributed to the natural source of mineral-rich bottom sediments (Kholodov and Lisitsina 1989). Higher concentration of Ba in the middle Caspian sub-basin is likely due to oil industry. Higher amount of Ag, Cd and Pb in west, south and north Caspian coastal sediment might be the signature of mining in the catchment basin. Baku Bay has the highest pollution level of Hg in bottom sediments (de Mora et al. 2004a).

3.5.2.2 Oil Pollution

Oil pollution is a major concern in the modern CS. Although exploitation dates back to Antiquity, natural leakage of oil and gas into the CS were higher than those due to exploitation until mid-nineteenth century. Deep wells started to be dug only in the nineteenth century, with a boom around AD1872 following a change in the law and improved technology. Since that time, both extensive oil exploitation and transportation through Volga River caused drastic change in the CS pollution (Tarasov 1996). During the Soviet period, the oil and gas industries were mainly limited in the west and north Caspian coasts, while after the dissolution of the Soviet Union, all riparian countries engaged in this industry.

Contaminants from petroleum industry are preserved in the bottom sediments as polycyclic aromatic hydrocarbons that have similar characters as those from biological activities. They can be classified in three groups based on their origins: pyrolytic (from combustion), fossil (as raw petroleum) and natural (diagenesis from biological activities). However, the limits between the three groups are not sharp. Pyrolytic compounds have elevated amounts in the Baku Bay and the north-west CS, whereas fossil compounds are very high in Baku Bay and diagenetic compounds in the southern Caspian lake bed (Tolosa et al. 2004).

3.5.2.3 Nuclear Pollution

Some pollution from nuclear experiments on the Mangyshlak Plateau (Kazakhstan) in 1969 and 1970 is felt in the CS (Nordyke 2000). For example, radiocarbon dating of surface sediment shows a distinct modification in ^{14}C activity (Leroy et al. 2018).

3.5.2.4 Organic Compounds

The production of many organic compounds including plastics, surfactants, drugs, fertilizers and organochlorinated compounds such as PCB, HCB, HCH and DDT, started at an industrial scale during the twentieth century. The PCB and DDT are among the persistent organic compounds that have severe and adverse impacts on the environment. Some components of DDT and HCH have elevated amounts in the north, west and south Caspian coastal sediments; the total amounts of PCB and HCB, however, are much lower than the world standards (de Mora et al. 2004b). The CS is the final receptacle for the agricultural, industrial, rural and urban wastewater that causes elevated nutrient levels in the CS water (Ivanov 1986).

Events of blue-green cyanobateria blooms in the last 20 years have been observed in the CS and can be attributed to the extra nutrient flux by rivers (Karpinsky et al. 2005; Leroy et al. 2013b; Naghdi et al. 2018). The status of the CS is oligotrophic, but in some coastal and shallow areas, owing to the input of nutrients, it has become meso-eutrophic (Nasrollahzadeh et al. 2014).

3.5.2.5 Extreme Impact on Environment and Humans

Finally, environmental degradation has created dead zones such as in the Baku Bay (Zonn 2005; Zonn et al. 2010). Contaminants transfer to the biota through dietary and non-dietary mechanisms. Accumulation of contaminants higher in the food chain of the Caspian biota directly impacts upon human health. Indeed, contaminants have been detected in the CS fish, some of which are used for human consumption, e.g. kutum (Nejatkhah-Manavi and Mazumder 2018).

3.5.3 Changes to the Coast Line

Rapid CSL changes impose various impacts on coastal and offshore environments. Shoreline migration, river mouth avulsion, disappearance of old wetlands and emergence of new ones (Leontiev et al. 1977; Kaplin and Selivanov 1995; Kroonenberg et al. 2000; Haghani et al. 2016; Haghani and Leroy 2016, 2020), and modification in the rate of deep-water exchange are some examples of impacts (Lahijani et al. 2018a). The setting and the origin of lagoons determine their final fate. Accordingly, the lagoons that formed under highstand conditions (such as the maximum in 1995) desiccated due to the current sea-level fall (post-1995). They are shallow-water lagoons that form behind beach ridges along sandy beaches with gentle to moderate slopes, where a low-lying area is fed by freshwater, groundwater and/or seawater inlets. They are strongly governed by water level. The shallow depth (1–2 m) is sensitive to water-level changes. Shortage of freshwater from agricultural fields and higher evaporation due to increasing temperature are superimposed on the water-level falling trend that cause drying up of almost all shore-parallel lagoons after the last rise. A good example is the Gomishan Lagoon, a wetland mentioned in the Ramsar convention,[5] situated in a low-lying area on the southeastern flank of the CS, which is almost dry since 2015 (Fig. 3.1).

The bar and spit-lagoon complexes that have weak water connection to the CS, or a connection in only one direction, are intensely influenced by freshwater inputs. The inlets provide limited exchange of offshore water or are incapable of transferring offshore water into lagoons. Extensive freshwater exploitation for agricultural uses along with dam construction on rivers lead to changes in hydrological regime around these lagoons and consequently accelerate lagoon shrinking and desiccation. Rapid sea-level fall facilitated freshwater outflow by not supporting surface-water level and groundwater table stabilization. They are undergoing major shrinkage, which requires water-resources management.

Other anthropogenic changes to the coastline include sand mining in spits, coastal dunes and islands, modifications of the coast for touristic purposes such as the canals in the AZAWA resort in Turkmenistan, the large-scale infrastructures recently erected or planned on Baku's waterfront and the damming of the Kara-Bogaz-Gol inlet in 1980–1983 (Leroy et al. 2006).

Thus, the impacts of natural water-level changes may be mitigated or exacerbated by human intervention and current global warming.

3.6 Discussion

In light of these considerable environmental and water-level changes, a deep investigation of their causes and impacts on coastal zones and water masses is still needed.

[5] International treaty for the protection and sustainable use of wetlands.

Only limited observational, instrumental and geological data are available, however, which reduces the capacity of forecasting models.

3.6.1 Critical Appraisal

3.6.1.1 Long-Term Data

Most CSL research has been made onshore, not only because of the easier access, but also because offshore sediment often enters the domain of petroleum exploration, which is under a certain degree of confidentiality. In addition, offshore coring requires the collaboration of large research teams, large budgets and planning in countries too often affected by political volatility. Academic research and its need for open-access information to the scientific community are incompatible with this situation common along large parts of the CS coast.

As an example, seismic profiles are rarely made available (Hoogendoorn et al. 2010; Putans et al. 2010), although at times they were obtained before coring, e.g. the European INCO-Copernicus project "Understanding the Caspian Sea erratic fluctuations" of the 1990s, but could not be published (Leroy et al. 2014). Also more research should be undertaken into dating of sediment, not only on the reservoir effect on radiocarbon dates, but also in tephrochronology that offers an excellent regional potential (Leroy et al. 2018).

3.6.1.2 Observational Data

The network of operating stations along the coast has sharply declined after a peak in the mid-1950s (Osmakov 2009). Furthermore in the last decades, the situation is not improving. No stations are maintained to international standards and no transnational uniform geodetic levelling network exists along the coasts, with the consequence that the measurements of water level at different sites are not comparable (Fig. 3.2b).

The satellite-altimetry technique demonstrates a great potential in this type of application to the CS, since the water-level variability can be measured over the whole basin beyond political barriers (Kostianoy et al. 2019). Moreover, satellite altimetry provides continuous measurements over open-water regions that have never been covered by direct water-level observations.

3.6.1.3 Models and Forecasts

In 1977 and the following years, the increase in CSL is linked to an increase in the number of ENSO events. Also, recently the recognition of the role of the small rivers and especially of rivers from the South, such as Kura and Sefidrud, is taking place, but not implemented yet in the models. In brief, one can say that the fluvial influx to the CS, hydrometeorological conditions over the water and catchment and to a lesser extent bottom-morphology changes are the main factors that control the water characteristics (Arpe et al. 2014).

With this in mind, the short-term water-level forecast seems relatively successful (Arpe et al. 2014), although, the longer-term forecast remains difficult (Arpe and Leroy 2007a). This is a real societal challenge for the riparian countries.

3.6.2 Threats to the Caspian Sea

Threats to the CS are numerous and some changes occur very rapidly, making it difficult to adapt. The following five are the most important.

Firstly, the regulation of rivers has an anthropogenic impact on the biodiversity by the construction of reservoirs, damming for hydroelectricity generation and irrigation. Every year ~3% of the annual flow of the Volga is lost due to evaporation from the surface of reservoirs (Zonn 2001). Used for irrigation, water from the rivers is also a loss to the CS if precipitation is not falling over its catchment. Shallower deltas and obstacles such as dams hinder fish migration, a particular problem in spring when spawning begins. Thus, many anadromous and semi-anadromous fish species lose their natural spawning habitats. This affects sturgeons and salmonids most severely. Populations of salmonids have disappeared almost completely. Fish farms maintain populations of sturgeons and salmons in Iran and Russia (http://sturgeon.areeo.ac.ir; Vassilieva 2004). Natural spawning grounds are available only in the Ural River and the Iranian rivers where dams are absent (Aladin et al. 2001).

Secondly, overfishing *and illegal fishing* in the CS strongly affect the populations of most commercial fish species. Sturgeons are endangered most of all. After the USSR collapse, fish such as Caspian lamprey, Volga shad, Caspian trout and whitefish were included in the Red Books; whereas in the 1920–1940s, they were still important commercial species. For species with a short life cycle, e.g. sprats, overfishing is less dangerous because their reduced abundance can recover within a few years (Aladin et al. 2001). Anthropogenic water pollution negatively influences sturgeon fish causing toxicoses (Aladin et al. 2001).

Artificial canals have connected the CS via the Volga and then, via other rivers, with the Sea of Azov, Baltic and White seas. They are a route for the third main threat: *uncontrolled penetration of many alien species* by shipping, either in ballast water or by biofouling. The influence of alien species on the CS biota and ecosystems is often negative. For example, the invasive bivalve mollusc *Mytilaster lineatus* is a competitor for the autochthonous *Dreissena* and cannot be used as food for fish because of its thick shell. The most dangerous alien species in the CS is clearly ctenophore *Mnemiopsis leidyi*.

Fourthly, the *CSL changes* are often rapid, e.g. water-level changes of 10 cm/year in the last century. For comparison, the rate was perhaps up to 20 cm/year in the Holocene. They have a clear influence on biodiversity (Dumont 1995). Following the high levels of the late Little Ice Age, the CSL decrease of 1920s–1970s (Fig. 3.6) had a negative impact on aquatic life. Shallow waters of the north CS and deltas of rivers suffered the most. Shallow bays, such as Kaidak and Mertviy Kultuk, dried and the populations died. The increase of 1978–1996 had a negative impact both on the biodiversity and coastal facilities such as those for industry and agriculture. Many pollutants were discharged into the CS. First of all, flooding of oil production and transportation facilities had a damaging effect on the biodiversity. Nevertheless, the positive impacts of long-term CSL rise are the improvement of spawning-ground conditions, increased spawning-ground areas, reinforced water exchange between different sections of the CS, extension of freshwater buffer zone and increase of potential productivity in the north CS.

Lastly the impact of *climate changes* on the biological diversity of the CS is not well studied. Studies of past climatic-change impacts have been only based on biotic proxies. Climatic changes impacted on the biodiversity of the ancient CS significantly, although indirectly, through impact on water level and salinity (Rodionov 1994). These changes nevertheless significantly altered the biodiversity. During Quaternary transgressions, freshwater species dominated, while the abundance of marine species reduced. Marine species survived only in the most saline parts of the CS. During regressions, the situation was the opposite. Marine species dominated, while freshwater species survived only in deltas and areas adjacent to rivers. However in some periods of the Quaternary history, changes of climate caused such extreme or fast changes of the CSL, salinity and temperature that many ancient species were lost. At present, climate change also has an indirect impact on the CS biodiversity. This impact is very weak and less obvious compared to those of earlier geological periods (Aladin et al. 2001), although the human factor may considerably accelerate natural changes.

3.6.3 An Ideal Baseline?

If one wishes to restore the CS to its pristine state before human influence, it is important to choose a realistic baseline. The start in the rise of the water temperature would be a good place to put this baseline. Indeed, the rate of 0.1 °C/year places the CS amongst the lakes with the strongest warming (Hampton et al. 2018). However, we do not know when it started as the oldest instrumental information we have is only from 1982. An increase in the number of phytoplankton cysts of the potentially toxic dinoflagellate *Lingulodinium machaerophorum* in the late 1960s has been suggested to be due to warming (Leroy et al. 2013b).

A point in water level during the twentieth century cannot be chosen as an ideal situation to return to, as fluctuations have been wider just before the start of instrumental measurement, i.e. during the natural state of the lake (Fig. 3.6). Thus, the CSL seems to be in permanent flux, never in a stable state. Other factors, developed hereafter, have significantly altered the CS and should be considered to define the start of the Anthropocene in the CS (Zalasiewicz et al. 2017).

The Caspian catchment has experienced human occupation since Late Pleistocene. However the signature of human impact on the CS is negligible until nineteenth century. A milestone is the start of the pollution by hydrocarbons in c. 1872 in Azerbaijan when improved technology led to higher well production and when legislation changed. Intensive petroleum exploitation and transport through the Volga-Baltic as well as forest removal for shipping fuel are key points in the Caspian environment. They caused hydrocarbon pollution, changed sediment discharge and in 1920s, introductions of alien species. Human activity intensified with industrialization and water regulation in Russia-Soviet Union mainly in the first half of the twentieth century. Despite the century-long human impact on the CS, the environment damage is recoverable, and its biological resources are well preserved.

The main turning point in the CS started after World War II when the catchment basin and its north, south and west coasts were subject of water regulation, agricultural development and urbanization. They led to water shortage in river mouths that prevented fish reproduction and released more nutrients and pollutants into the sea. Discharge of nitrogen and phosphorus by catchment population became significant (Hampton et al. 2018). Physical changes in the rivers, e.g. dams, barriers beneath bridges, sand excavation and overfishing, affected natural fish reproduction. Intensive occupation of the coastal environment for agriculture and urbanization drastically restricted the environment for the Caspian endemic species and wildlife refuges. It thus seems that the physical changes in the Caspian catchment and coast since the mid-twentieth century are the main concern about the Caspian environment.

Finally, as it is difficult to influence CS water levels and water temperature; it is more realistic to aim at environmental remediation by controlling pollution, biological invasions and the impact of dam construction. If a base level has to be suggested, the middle of the twentieth century would be the best candidate. It moreover fits with the definition of the Anthropocene by Zalasiewicz et al. (2017).

3.7 Conclusions

Many changes have been experienced by the CS in the past. However, the current environmental changes are faster and more profound as a result of the multiple aspects of human intervention. The environment receives anthropogenic stresses that are superimposed to natural ones.

The CS is a fascinating topic of study owing to its complexity and the many surprises it reveals. It is however foremost the source of living for more than 14 million people (Rekacewicz 2007) and its catchment has 43 urban centres larger than 300,000 inhabitants (Hampton et al. 2018). It is important to preserve its state for a sustainable future. The CS Anthropocene could be suggested to have started in the middle of the twentieth century as in the rest of the world.

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