Responses of Lakes to Climate Variability

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Abstract: Lakes have repeatedly changed in size and volume over long-term periods due to climatic influences. The extreme dry conditions found presently in the Sahara region have caused many former lakes and rivers to completely evaporate. The prevailing regional climates from the past can be determined from deposits beneath lakes. They provide evidence of earlier climatic changes including alterations in the vegetation and erosion. In addition, they give historical indications of early human activities, such as the first evidence of the use of coal and oil, introductions of new cultivated plant species, and emissions of pesticides and heavy metals. In this paper, changes in several important lakes and inland seas, such as the Caspian Sea, Aral Sea, Dead Sea, Lake Titicaca, and the Great Salt Lake, will be outlined. The example of the Great Salt Lake shows that tectonic factors strongly influence the characteristics of inland bodies of water. The water levels in the Aral and Dead Seas have decreased due to the use of water for agricultural projects bringing catastrophic ecological consequences. Tectonic movements in land masses and anthropogenic impacts can greatly outweigh climatic influences.

Over long-term periods lakes have changed repeatedly in their volume and extent because of climatic variability. Lakes as well as running waters (rivers, streams) are important links in the hydrological cycle of the Earth. They are important water reservoirs and often economically significant. On the one hand lakes are dependent on precipitation and draining and on the other on evaporation. During the last ice age low temperature reduced evaporation and in many regions the ratio of precipitation to evaporation was shifted in favour of precipitation. In mid latitudes lakes and others inland waters were not or only slightly affected by freezing. For example the Caspian Sea expanded over its present boundaries to the north-west and north and was twice its present size. In low latitude regions like North Africa and Australia lakes and rivers existed which have completely dried out today probably due to a displacement of the climate zones.

The reconstruction of the regional climate is possible through analysis of lake sediments. Lakes as the lowest part in a landscape collect materials from erosion processes in the adjacent areas. They are therefore reliable archives of animal and plant remains and precipitated minerals that reflect environmental changes caused by climate or provoked by human activity in the recent past. The small lakes react thereby more quickly and above all more sensitively than the large lakes which are buffered through their enormous water volume. In some small and relatively deep lakes there are deposits of annually laminated sediments as in the Greenland ice core. They contain exact yearly information dating back many thousands of years stemming from global and regional climate changes, ash from volcanic eruptions as well as traces of human activities from the Stone Age to the Industrialisation. The later are characterised by soot particles from the combustion of coal and oil and by pesticides and heavy metals. Other important indicators in the lake sediments are remains of cultivated plants, change in the vegetation e.g. through forest fire or erosion, eutrophication of the lake with the consequences of algae blooms etc. (CLARK et al.1989). In the following, several important lakes – itemised by continents – are briefly described in reference to their climatic changes.

Africa

The Sahara is the largest desert of the world today. However, several investigations (SONNTAG et al. 1979, PACHUR 1987) have shown that the climate of the Sahara has changed repeatedly in the past 25,000 years: from semi-arid to arid, then more humid and ultimately arid climate. There were lakes and rivers with an extensive drainage system in the Sahara during the moist climate period. Their locations and courses can be reconstructed today through air and satellite images as well as with the help of sediment analysis (see Chapter 1.10). The eastern Sahara was always dryer than the western part. Because of the fact that the rain front came particularly from the Atlantic and the amount of rain decreased from west to east, the east side had a disadvantage. Also the vegetation in the east was not as dense as in the west and the dry periods lasted longer and began earlier. There is even a hyper-arid climate today. The investigations from PACHUR (1987), PACHUR and WÜNNEMANN (1996) describe in detail the beginning and development in the eastern Sahara from the moist climate period and to its subsequent dryness (see. *Fig. 1.14-1*). Fresh and brackish water lakes existed over several thousand years. Rivers were up to 800 km long; they started in the north and the east part of the Tibesti mountains and formed thereby small lakes or flowed directly toward the Mediterranean region. Other rivers originated in the south of the Tibesti mountains. They fed Lake Chad or flowed south-westerly and emptied into the Atlantic. Several lakes whose draining system formed other lakes and several wadis (brooks subject to flooding during seasonal rains) were found in Meidob (volcanic mountains in the eastern Sahara). Some of these wadis were tributaries of the Nile.

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Also in the Libyan and Nubian desert there were lakes with local drainage systems. BAUMHAUER (1991) dealt with the development of lakes and rivers in north-eastern Niger. He ascertained that the character of adjacent lakes can be very different. Lake Zoo Baba had fresh water and Lake Dibella only about 70 km away contained brackish water with a strong salinity variation. BAUMHAUER supposes, that Lake Zoo Baba received more fresh water through a larger groundwater system than Lake Dibella.

PACHUR and WÜNNEMANN (1996) analysed the sediments of former lakes in the Nubian desert and in the Meidob-mountains, which are dry now. They reconstructed the local climate through analysis of sediment cores and on the basis of radiocarbon-dating (^{14}C). The results obtained from a lake which was approx. 1,100 m above sea level showed that the sedimentation started about 10,000 years BC. In contrast to this the sedimentation in lakes of lower elevation began later at approx. 7,300 years BC. The authors suppose that the moist climate first started in the mountain region. The time difference probably corresponded to the time necessary for the accumulation of groundwater and the formation of a drainage system. The same was observed in the region of the Tibesti-mountains.

Fig. 1.14-1 shows the results of a sediment core from a former lake in the Meidob Mountains about 1,100 m above sea level. The figure indicates the age of the analysed material as well as some chemical substances contained

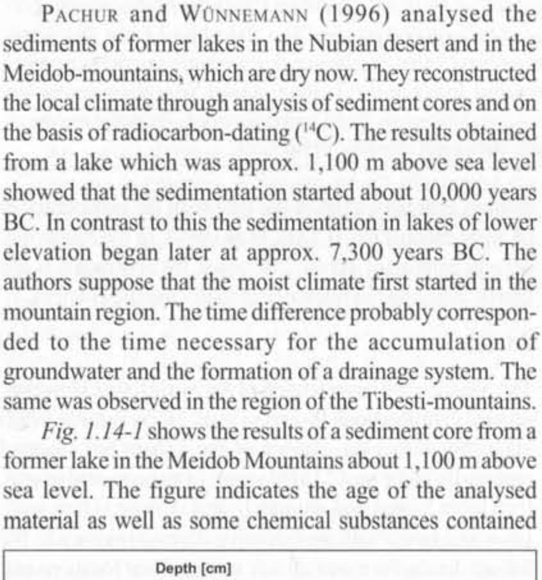


Fig. 1.14-1: Radiocarbon dating and geochemical analysis of a sediment core (220 cm) from a lake in the Meidob mountains (eastern Sahara) (Based on PACHUR and WÜNNEMANN 1996).

therein. A tephra-input could not be observed in the 0–130 cm stratum. There is also no evidence of eruptions in the vicinity after 12,095 years BP. The 100–170 cm stratum showed a high carbonate content. This section is characterised predominantly by ostracods and diatoms with high carbonate content. Geochemical facts indicated that it was a freshwater lake with stabile hydrological conditions over several thousands of years without large water level fluctuations.

The quaternary *Lake Chad* which lay at the southern border of the Sahara has a surface area between 10,000 and 20,000 km^2 today depending on the season. During the moist climate approx. 4,000 years BP Lake Chad had a surface area of about 400,000 km^2 and it was 30–40 m deeper than today (SERVANT and SERVANT 1980). It had approx. the same size as the Caspian Sea today. Its earlier size can be determined from recognisable shorelines and the location of fossil fish.

Today there are salt lakes – especially in the Sahel and northern Sudan – which are in danger of drying up. These inland waters are very important for many water bird species. If the water conditions in this region change due to global warming, these species could be seriously affected. Especially the migratory birds within Africa and from outside Africa which depend on reeds are threatened.

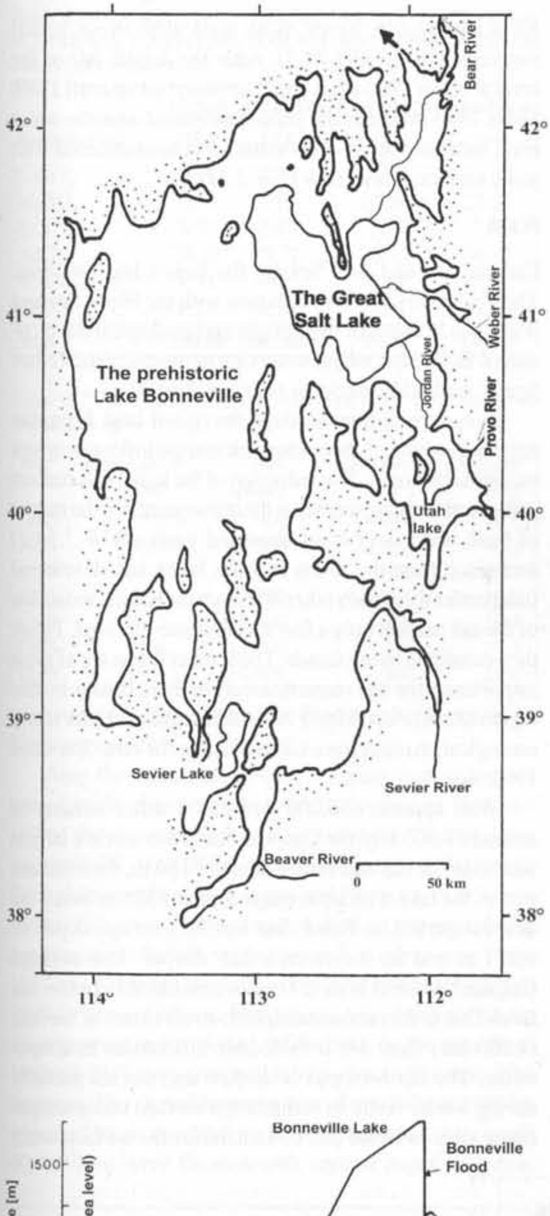
For species like purple heron (*Ardea purpurea)*, white stork (*Ciconia ciconia)*, sand martin (*Riparia riparia)* and sedge warbler (*Acrocephalus schoenobaenus)* there is evidence already that a connection exists between the strength of a year-class and the ecological situation in the Sahel and northern Sudan (see also Chapter 3.24).

America

The *Great Salt Lake* in northern Utah (USA) and the small Sevier Lake and Utah Lake are remnants of the prehistoric Bonneville Lake (*Fig. 1.14-2,* above). Analysis of sediments indicates that the Bonneville Lake already existed 25,000 years ago. Approx. 15,000 years ago it had a maximum depth of over 300 m and covered about 50,000 km^2. It was the largest freshwater lake in North America and harboured an abundant flora and fauna. The Bonneville Lake was 1,550 m above sea level and had a connection to the Pacific through the Snake and Columbia rivers (VAUGHN 1994).

Table 1.14-1: Current ion composition in per cent for the Great Salt Lake (GSL), the Dead Sea and ocean (Based on VAUGHN 1994).

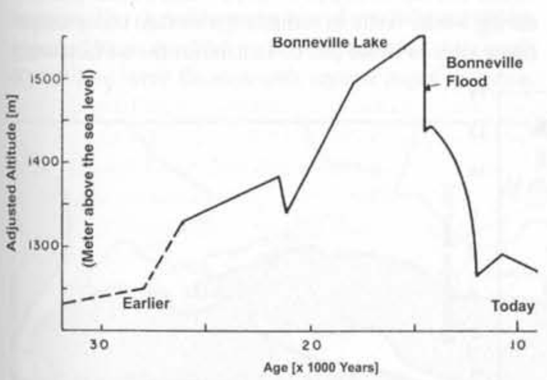
	Sodium	*Chloride*	*Sulphate*	*Magnesium*	*Calcium*	*Sum*
GSL	14.1	7.6	2.0	1.1	0.02	24.8
Dead Sea	17.5	3.3	0.7	3.4	1.4	26.3
Ocean	1.94	1.08	0.27	0.13	0.04	3.5



The Great Salt Lake is situated today at a height of 1,275 m (see *Fig. 1.14-2,* lower right). The historic change of the prehistoric lake was reconstructed through the analysis of sediment cores at different places in the lake basin. Different ashes from well-known volcanic eruptions completed the radiocarbon-dating and the information from oxygen isotope measures (*Fig. 1.14-2,* lower left). Approx. 14,500 years ago the water level sank by 100 m within a short time because of geomorphological changes at the northern border of the lake (OVIATT 1997, OVIATT et al. 1994). At the end of the last ice age the climate of this region changed involving a decline in precipitation and an increase in evaporation. This led to the rapid reduction of lake surface area and to the formation of the Great Salt Lake. The name is derived from its size and high salt content (*Table1.14-1*). The brine compositions of the Great Salt Lake, the Dead Sea and ocean are quite different.

The salt content of the Great Salt Lake is considerably higher than in the ocean and a little lower than in the Dead Sea. Sodium and chloride make up approx. 90% of its salts. Because of the extremely high salt content only organisms with a high salt tolerance like the brine shrimp, *Artemia salina*, and the blue algae, *Dunaliella salina* and *Dunaliella viris*, can flourish in the Great Salt Lake water. Furthermore bacteria of the species *Halobacterium* and *Halococcus* can be found there which are salt loving (halophyles) organisms and require at least 12% sodium chloride for their growth.

The Great Salt Lake has no outflow. Despite inflow through the Weber, Bear and Jordan rivers its water level sank about 3 m from 1900 to 1982 because of intensive evaporation and high water consumption (*Fig. 1.14-2c*). A highway as well as a railroad were built through the middle of the lake and small industries were set up during this period. In the fall of 1982 the precipitation increased by around 45% and the evaporation decreased simultaneously



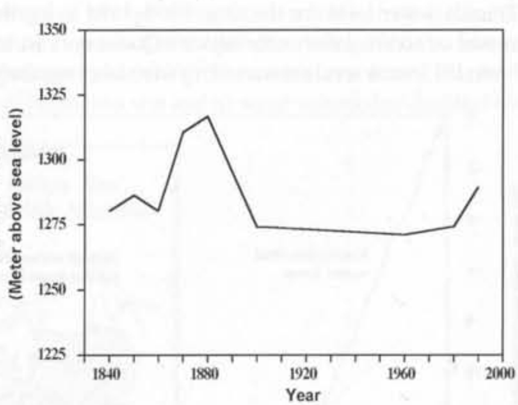


Fig. 1.14-2: Above: the prehistoric Lake Bonneville showing the position of the remnants lakes: Great Salt Lake, Sevier Lake and Utah Lake. *Lower left:* Radiocarbon chronology of Lake Bonneville showing the changes of its altitude (From OVIATH et al.1994). *Lower right:* Variation of the water level of the Great Salt Lake since 1840 (Based on VAUGHN 1994).

due to high cloud cover. In the following winters snow fall was high. Thus the water level rose by almost 7 m and its surface area expanded from 4,248 to 6,345 km² with many negative consequences in 1986. The state of Utah built dams and a pumping station for US $ 71 million. Due to climatic variation the lake level sank again later (VAUGHN 1994).

Lake Titicaca in the area of the Altiplano (region of Peru and Bolivia) has a surface area of 8,448 km² with an average depth of about 100 m. Consequently, it is the largest lake of South America. With its altitude of 3,810 m above sea level (a.s.l.) it is the highest navigable lake of the world. The annual water inflow from the 25 tributaries totals 8.25 km³. The inflow from the precipitation is 7.9 km³. Approx. 90% of this water is lost through evaporation (CARMOUZE 1981). Less than 5% of its water input flows out through the Desaguadero. Thus, Lake Titicaca can almost be called a closed lake.

Due to the altitude of the lake solar radiation is relatively intense. Its size and the low water temperatures (11–14°C) allow a large heat storage during the warm months (October–November).The heat is lost during the winter months (June-July) and it causes mild winters in the region (CARMOUZE 1983) and favours the growing of grains e.g. barley and wheat.

The period after 1500 AD was very wet which could be seen as a manifestation of the »Little Ice Age« in the Altiplano. This led to a marked increase of the water inflow and the lake level was approx. 35 m higher than today. It is therefore probable that the lake extended to the vicinity of the town Tiahuanaco at the beginning of colonialism through Spain.

According to THOMPSON et al. (cit. in KESSLER 1994) a dry period began around 1720 and continued to 1860. KESSLER (1994) has undertaken a reconstruction of the Titicaca water level for the time 1800–1984 using the annual ice accumulation in the adjacent Quelccaya Glacier. From 1915 water level measurements were taken regularly. KESSLER's results agree quite well with these actual measurements (*Fig. 1.14-3*). After the drastic fall of the level at about 1860 a rise could be observed up until 1880. From 1920 onwards the inflow increased and the water level increased again. This water level has remained with some variations until now (*Fig. 1.14-3*)

Asia

Caspian Sea and Aral Sea are the largest lakes of Asia. They have very much in common with the Black Sea and Azov Sea because of their origin and geological developments. Both these inland waters are remnants of the Tethys Sea of the Middle Miocene (see *Fig. 1.14-4*).

They were formed through the rise of land. From the ion composition of their water the marine influence is still recognisable today. The reduction of the initial salt content in the Aral and Caspian Sea is the consequence of the inflow of fresh water over many thousand years (*Table 1.14-2*) and since then the fauna in both lakes has developed independently of each other. Through the natural reduction of the salt content only a few species have survived. Today they constitute living fossils. These relict forms are of great importance for the reconstruction of the climate in this region (ZENKEVITCH 1963). As will be explained later many ecological changes have taken place in the Aral Sea since 1960.

With approx. 436,000 km² and a water volume of around 77,000 km³ the *Caspian Sea* is the world's largest lake today. It has an average depth of 180 m, the southern part of the lake with an average depth of 325 m being the deepest part. The Black Sea has an average depth of 1,271 m and is, therefore, much deeper. The average Caspian Sea level with -27 m lies considerably below sea level. Due to the pronounced north-south extent of the lake (1,200 km) there are considerable differences in temperature. The northern part is shallow and freezes partially during winter while in summer the surface water temperature rises to about 24 °C. In contrast the surface water

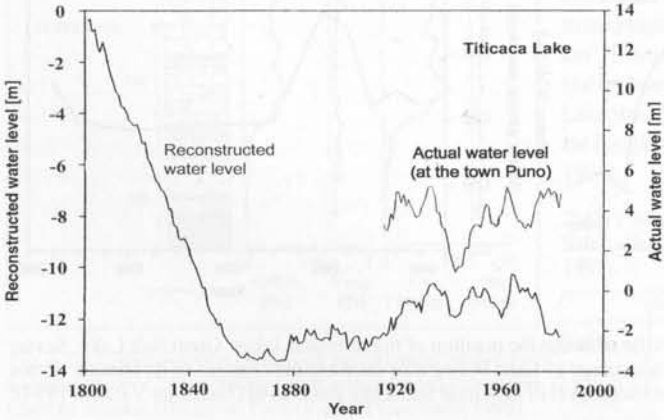


Fig. 1.14-3: Variation of the water level in Lake Titicaca. Reconstructed water level from 1800 based on KESSLER (1994). Actual annual water level at the Peruvian town Puno since 1915.

Table 1.14-2: Comparison of the ion composition of the water in Black Sea, Caspian Sea, Aral Sea (up to 1960) and in the ocean (aus ZENKEVITCH 1963).

	Ocean	***Black Sea***	***Caspian Sea***	***Aral Sea***
Salinity (‰)	***35.0***	***18.6***	***12.8***	***10.6***
$CaSO_4$	3.94	2.58	6.92	14.98
$MgSO_4$	6.40	7.11	23.56	25.87
KCl	1.69	2.99	1.21	2.05
NaCl	78.32	79.72	62.15	56.07
MgCl, $MgBr_2$	9.44	9.07	4.54	0.82
$CaCO_3$, CO_3	0.21	1.59	1.24	0.21
Sum	***100.00***	***103.06***	***99.62***	***100.00***

Table 1.14-3: Changes in the Aral Sea from 1960 till 1990 (After GOLUBEV 1996).

Year	*Water level [m]*	*Area [km²]*	*Volume [km³]*	*Salinity [‰]*
1960	53.3	67 900	1 090	10.6
1965	52.5	63 900	1 030	10.5
1970	51.6	60 400	970	11.1
1975	49.4	57 200	840	13.7
1980	46.2	52 500	670	16.5
1985	42.0	44 400	470	23.5
1990	39.0	38 000	300	29.0

temperature in the southern part fluctuates between 9 °C in February and 27 °C in August.

Also the water level of the Caspian Sea undergoes considerable changes over time. According to GOLUBEV (1996) the water level fluctuated between -20 and -34 m since 600 BC. 90% of it is caused by changes in the inflow through the tributaries (GOLYTSIN and PANIN, cit. in GOLUBEV 1996). GOLYTSIN (1995) indicated, that geological and geodynamical factors might play only a minor role. From 1917 to 1925 it fell by about 70 cm and rose from 1925 to 1929 by around 60 cm. The greatest fall of about 180 cm was observed in the period 1929–1941. In the time from 1942 till 1977 the water level fell by about 130 cm to -29.0 m again. The rise of the water level from 1978 to 1996 by approx. 250 cm (to -26.5 m) was considerable. As a result 40,000 km² were flooded with serious negative conse-

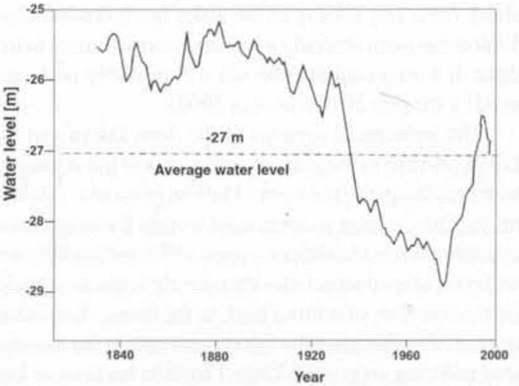


Fig. 1.14-5: Variation of the water level in the Caspian Sea (Based on GOLUBEV 1996 completed).

quences. After the decline of the water levels to -27 m from 1996 to 1999 the situation improved again (SHIVAREVA et al. 2000) (*Fig. 1.14-5*). The average annual water inflow from 1900 to 1985 was approx. 300 km³, of which the Volga delivered approx. 75%. 40–50 km³ are consumed annually before the water reaches the lake. Without this removal the water level of the lake would rise by about 150 cm (KUKSA, cit. in GOLUBEV 1996). The impact of the water level rise on settlements and infrastructures is especially strong during storms at the flat coastal area of the Republic of Kazakhstan. This inland water is of great economic importance for the region. For example the fishing industry achieves a total annual catch of approx. 400,000 t.

The *Aral Sea* – the fourth largest lake in the world – is situated in the Central Asia desert (see *Fig. 1.14-4*). The two most important tributaries are Amu Darya and Syr Darya. The lake has no outflow and its water balance is therefore determined essentially through evaporation and water inflow. In 1960 its surface area was approx. 67,900 km² with a water volume of about 1,090 km³ and a salt content of around 10.6 g/liter (see *Table 1.14-3*). Due to the enormous water consumption since 1960 the lake is dramatically shrinking. The surface area is now less than half its original size and its water volume has declined by

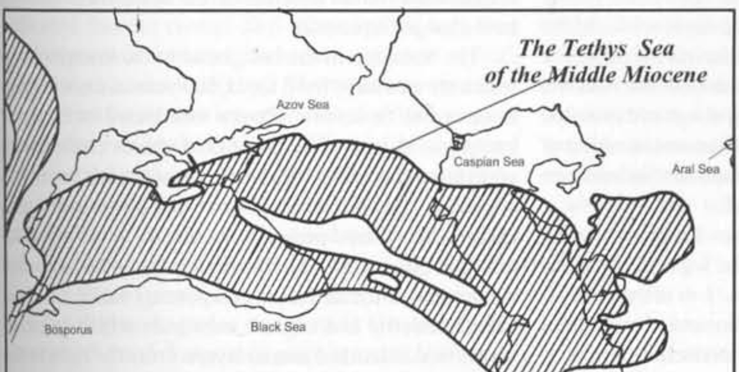


Fig. 1.14-4: The Tethys Sea with marine connection during the middle Miocene (Based on ZHIZHCHENKO (cit. in ZENKEVITCH 1963).

about 75%. The salinity of the water has increased since 1960 to the point that only a few organisms are able to live there. It is expected that the sea will probably no longer exist by the year 2010 (HANNAN 2000).

The upstream diversions of the Amu Darya and Syr Darya resulted in a significant reduction of the amount of water reaching the lake from 55 billion m³/yr to 1–5 billion m³/yr. The diverted water is used mainly for irrigation of extensive cotton plantations – approx. 7.4 million hectares. Water is pumped sometimes excessively to the areas under cultivation. Part of it flows back to the rivers. As a consequence of evaporation the salt content rose in the drainage area reducing crop yield. Over 1 million hectares of land have became saline already and are now useless. The often strong winds in the region carry the saline dust (an estimated in 75–100 million t) over long distances into Uzbekistan and Turkmenistan causing many of the health problems in the region.

Only 55–65% of the pumped water are used; lakes of several 1,000 km² have emerged in the desert. A part of this highly saline water returns to the river which, in addition, is heavily contaminated through pesticides and other agricultural chemicals. The peculiar fauna of the Aral Sea is threatened dramatically. Many endemic species have already lost their habitat. Fish species like the Aral Sturgeon (*Acipenser nudiventris*), the Asiatic Shovel Sturgeon (*Pseudoscaphirhynchus* spp) and the Aral trout (*Salmo trutta aralensis*) have practically disappeared (KLIGE 1996).

Even if climatic changes and land use alterations have played a role in this development the main cause for the shrinking of the Aral Sea is the immense water consumption for agricultural purposes. The chances to find a solution have worsened in consequence of the political changes since 1991 (PAVLOVSKAYA 1995). Many million of people depend on this agricultural project. First, land degradation and over-watering must stop. To achieve this a well founded, long-term strategy for an economically and environmentally sustainable system is required.

Lake Baikal – like the large eastern African lakes – lies in a tectonic graben between two continental plates. With a depth of over 1,700 m it is the deepest lake of the Earth. This several million year old lake has not experienced changes of area as spectacular as those of the Aral and Caspian Seas. Because of its geological age and over 400 endemic species, it has very recently become an object of international research from which important information about the Siberian climate is expected.

The *Dead Sea* is situated between Israel and Jordan and its surface area is 1,049 km². The water depth in the north reaches 399 m and only approx. 3 m in the south. It lies about 396 m below the Mediterranean and constitutes the deepest point of the terrestrial landscape. Jericho – probably the oldest city on Earth – was founded at the Dead Sea 9,000 BC. At that time the salt of this lake was already being exploited (see *Table 1.14-3*). Due to the long historic development in this region there is plenty of written records about this inland water. KLEIN and FLOHN (1987) using this documentation reconstructed the water level of the Dead Sea for the period 1100–1800 AD (*Fig. 1.14-6*). There are reliable data from 1800 over the annual water level. From their work we know that the water level has varied in height by more than 20 m. The phase of the »Little Ice Age« after 1500 is characterised by a rise of the water level because the precipitation and inflow were greater in volume than evaporation.

Since 1964 both neighbouring countries (Israel and Jordan) have taken large amounts of water for irrigation projects from the Jordan River, the only tributary of importance. The consequences have been negative. The water level has declined till now continuously. KLEIN and FLOHN (1987) estimated the decline of the water level from 1964 to 1984 at 24.3 cm/yr. From ca. -400 m in 1980 and -406 m in 1992 the level fell to -413 MSL in 2000. Consequently, the water column stability has been reduced. The lake, which for centuries was stratified without full circulation (meromictic), experienced a full circulation for the first time in the 1980s. Since then many full circulations have been observed (NIEMI et al. 1997) (http://ocean.org.il).

Europe

Most natural European lakes have emerged in indirect or direct connection with the last ice age. They are thus younger than 20,000 years and owe their existence to climate change. Only a few older lakes have a volcanic origin (crater lakes) or have emerged through geomorphological changes. Because of the small size of Europe compared with Asia, Africa and America almost all European lakes are located in a moderate humid climate zone. Their water levels and shorelines are relatively constant as opposed to the North African, Australian and the large Asiatic lakes because the hydrological changes were weaker since the last ice age. Nevertheless, the composition and the structure of the lacustrine sediments have changed repeatedly.

The transition of the last glacial to the interglacial in which we now have lived for 11,500 years did not happen at once but in several phases that lasted over many centuries. At least three arctic cold phases (with tundra vegetation) alternating with warm climate phases have been observed. The duration and course of a phase with warm climate, the Allerød period, is shown in *Fig. 1.14-7* as an example (MERKT 1994a). The figure shows the measured sublamina of the different components sand, silt/clay, calcite, siderite and organic substance which together constituted individual annual layers. From the right to the left the thin layers of sand, silt/clay and calcite indicate a

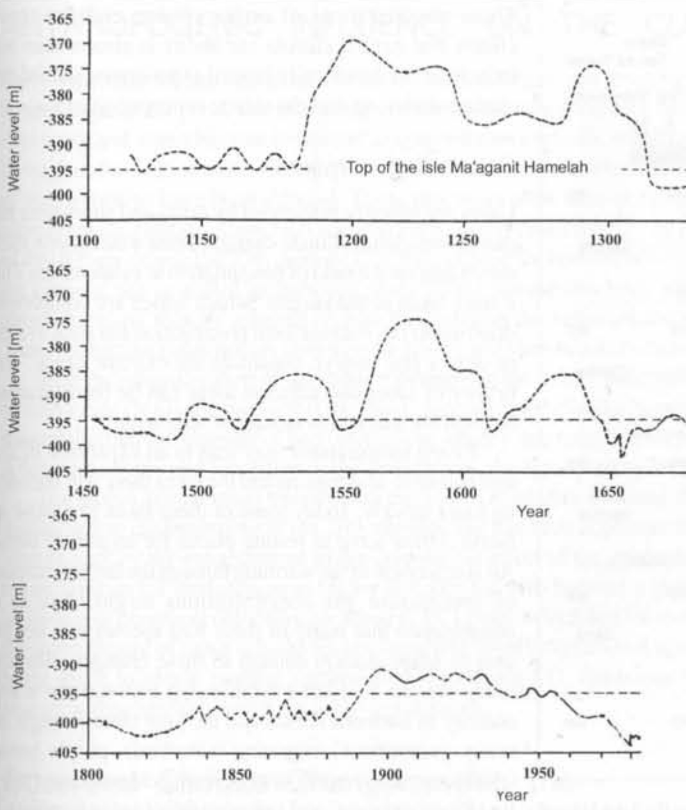


Fig. 1.14-6: Variation of the water level in the Dead Sea. *Above:* Reconstruction of the water level from 1100 to 1800 (Based on: KLEIN and FLOHN 1987). *Down:* Actual water level from 1800 till now. The heights should be corrected by +2.571 m. For example, -395 m is equivalent to -392.429 m MSL (Mediterranean Sea Level).

tundra period whose sparse vegetation only slightly slowed down the erosion. During the transition to the warm Allerød the allochtonous input of sand stopped completely and the sporadic supply of clay/silt indicates that the vegetation became denser: A birch-pine forest expanded (changes in the vegetation can be recognised through pollen analysis). The appearance of organic substances and especially iron (ferric) mineral siderite as well as undisturbed lamination indicated warm summers and cold winters with long ice cover but without storms and high precipitation.

The wave form of the thickness of the siderite layers indicated that the climate also showed slight long-time oscillations over centuries. The increase of calcite crystals indicated an unstable climate. They were unexpectedly eroded from the shallow water for more than 100 years and transported into depth of the lake. The erosion of clay and silt first and then those of sand again reflects the end of the taiga forest and the return of the tundra vegetation. Afterwards the production of organic substances and the precipitation of siderite crystals disappears (*Fig. 1.14-7*).

The Allerød period lasted 625 years; the transition to the following tundra period started about 130 years earlier. However, the real change took place in less than 50 years. The end of this tundra period after 1,140 years was even more drastic; it lasted a maximum of only 20 years. The temperature probably increased much more abruptly by 5–7 °C. Then it fell again after only 120 years. One hundred years later the temperature increased again gradually to the present warm period.

The ash of the eruptions of the volcano whose crater now forms Lake Laacher can be recognised in *Fig. 1.14-7*. It occurred 12,900 years ago, 200 years before the end of the Allerød period (MERKT 1994b). The position of its ash is an important time mark in the lakes between Turin (Italy) and Gotland (Baltic Sea). Clay/silt and even sand and calcite were deposited at an increasing rate during the following 8–10 years. Climate deterioration is observed for a short time similar to the beginning of a tundra period. This short-term change of climate through volcanic aerosols was found in several German and Swiss lakes.

Also in the humid climate zone of Central Europe with a positive water balance throughout the year at present, there have been considerable hydrological fluctuations in the past. Many European lakes had low water levels repeatedly for short- and long-term periods. Since a series of these lakes has neither inflow nor outflow, the low water levels must have been the result of reduced precipitation. According to KLEINMANN et al. 1997 short-term extreme

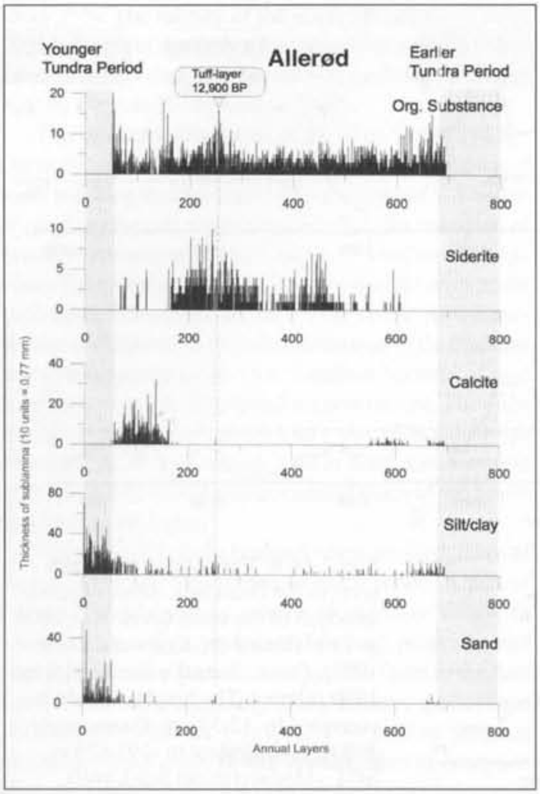


Fig. 1.14-7: Analysis of a sediment core from the lake Hämel (Hannover, Germany) showing the warm period Allerød between two Tundra periods: Younger Dryas (11560–12700 BP) and Older Dryas (13325–13375 BP) at the end of the last ice age. The ash of the eruptions of the Laacher-Volcano (eastern Eifel, West Germany) which occurred 12,900 years BP is an important time mark. The ash reached a height of 20–30 km. Its impact on climate was probably higher than that of El Chichón (Mexico) and Pinatubo (Philippines).

lows were the cause, interrupted by periods with normal water levels. There were no dry periods lasting for a century. At times there were frequent dry periods so that we get the impression today of a persistent precipitation deficit.

Low water levels cause only irrelevant changes at lakes with steep shores. However, for very shallow lakes (e.g. Lake Müritz, Lake Dümmer and Lake Feder) or lakes with low shores (e.g. Lake Constance and Lake Starnberg) even slightly lower water levels have led to dryness of large surface areas which were soon settled by man during the Neolithic and Bronze periods. These settlements were flooded and destroyed in the following period by the higher water levels, covered through sediments and preserved.

These manifestations of earlier climate changes show clearly that natural climate variability is greater than we infer from our historically limited experiences. Indeed the climate shows, against the classic concepts, »jumps«.

Concluding remarks

Lakes are strongly influenced by long- and short-term regional and global climate change. Their water levels vary depending on the ratio of precipitation to evaporation. The former lakes in the eastern Sahara which are completely dried out today, because local precipitation has sunk to zero or only a few mm/yr, constitute the extreme cases. The history of lakes and adjacent areas can be reconstructed through the analysis of lacustrine sediments.

Rising temperatures may lead to an expansion of the arid and semi-arid regions and the lakes there will then dry up more quickly. Today some of these lakes like those in North Africa serve as resting places for migratory birds. An acceleration of the warming through the farther increase of greenhouse gas concentrations might have as a consequence that many of these bird species will not be able to adapt quickly enough to these changes. Already today we can find out a relationship between the water scarcity in northern Africa and the year class strength of many international migrating waterbirds: purple heron (*Ardea purpurea*), white stork (*Ciconia ciconia*), sand martin (*Riparia riparia*) and sedge warbler (*sedge warbler*).

The different changes of the lakes described in this chapter show that climate changes have not been similar in all regions of the Earth. Depending on geographical situation, prevailing wind direction, distance to the sea and altitude the individual lakes react differently to climate change. Tectonic changes of the Earth's crust are long-term influencing factors which – added to climate change – complicate a reconstruction of past climate in some regions.

Already one-fifth of the world's population suffer from scarcity of drinking water. As water scarcity in many dry regions will increase in the future it is very important that all drinking water reservoirs (lakes, river, groundwater, etc.) be protected against contamination and oversalting. New techniques must be applied to reduce the amount of water consumed, e.g. in agriculture. The excessive extraction and wrong use of water from the tributaries of the Aral Sea since 1960 have caused the water level of this lake to sink and the salinity to increase with incalculable ecological risks for the water availability of the region and for the survival of the endemic fauna of the Aral Sea¨