Sarykamysh Lake: Collector of Drainage Water – The Past, the Present, and the Future

Leah Orlovsky, Offir Matsrafi, Nikolai Orlovsky, and Michael Kouznetsov

Abstract Sarykamysh is one of about 2,500 artificial lakes-collectors of drainage water in Central Asia. The Lake is located in a natural depression in the northwestern part of Turkmenistan, it receives irrigation surpluses and soil washing drainage water from Dashoguz and Khoresm oases. The area of the Lake has grown from 12 km^2 in 1962 to 3,955 km^2 in 2006. In terms of volume the change is from 0.6 km^3 to 68.56 km^3, respectively. Currently, the national plan is to create a new lake-accumulator in the Karashor depression – the Golden Age Lake. Nowadays, less water is being discharged into the Lake, and in the future its area/level will decrease significantly. With average annual evaporation rates of 1.2–1.4 m/year, the drying process is expected to be rapid. The study attempts to model the possible scenarios in the development of the Lake following a change of inflow. This research deals with the retrospective study of the parameters of the lake in the past 40 years using GIS and remote sensing methods in order to suggest a forecast of these parameters. The forecasted parameters will enable the mitigation of the negative regional impacts of the Lake's changes. A three-dimensional model of the Sarykamysh depression was built using the 1940s topographic maps. Topex/Poseidon altimeter data, early Corona satellite images, and time-series of the Landsat satellite images were applied on Digital Elevation Model (DEM) together with ground measurements of the parameters of the Lake and meteorological data. The model was calibrated and validated, and the water balance of the Lake was calculated, enabling us to suggest with higher accuracy, an optimal future inflow.

Keywords Aral, Central Asia, Forecast, Model, Remote sensing, Turkmenistan, Water balance

L. Orlovsky (✉), O. Matsrafi, N. Orlovsky and M. Kouznetsov
The Jacob Blaustein Institutes for Desert Research, Ben-Gurion Universiry of the Negev, Sede Boqer Campus, 84990 Midreshet Ben-Gurion, Israel
e-mail: orlovsky@bgu.ac.il

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Contents

1 Introduction

The Aral Sea Basin is one of the most ancient areas of irrigated agriculture – favorable climate and natural soil fertility contribute to the development of farm production here. The total irrigated area in the Aral Sea Basin reaches up to 8 million ha [1]. Irrational use of the land and water resources during last 3–4 decades resulted in the intensive salinization of the irrigated lands. At present more than half of all irrigated lands in the region are salinized at a different rate. In order to keep the soil fertility and/or to improve its ameliorative state the construction of the collector and drainage network started in early 1960s. Since that time about 161.8 thousand km of collectors and drainage canals and more than 6,000 drainage wells have been built [2]. In the Aral Sea Basin this network produces drainage water flow within the volume of 32.71 km^3 annually. Part of it (20.29 km^3/year) returns to the rivers, and 12.42 km^3 drain out of the irrigated area and flow to the desert depressions [3]. As a result, in the periphery of irrigated area 2,341 water bodies of new type – collectors of drainage flow within the total area of 7,066 km^2 have been formed [4]. Sarykamysh Lake is the largest one among them occupying more than 50% of the total area of such water bodies. Its volume takes even bigger portion of the total volume of newly forming lakes of Central Asia. Water of Sarykamysh Lake is highly salinized and contains biogenic matters, admixtures of pesticides, defoliants, and fertilizers.

Formation of such a vast water body in the arid region has had an important and practical significance. Nevertheless, the problem of formation and development of the water bodies – accumulators of drainage water is not adequately explored. The researchers regarded the Sarykamysh Lake as a natural object [5–7] with quickly developing fishery [8, 9]. It should be noted that before early 1960s such approach was justified, since the first discharge of the drainage water into Sarykamysh depression took place in 1961.

Hydrological and hydrochemical regime and water quality in the Lake are studied rather poorly, in spite of several publications dealing with above-mentioned problems [10–12], as well as the problem of interaction of the Sarykamysh Lake and surrounding environment [13, 14]. The future of Sarykamysh Lake depends on the plans of Turkmen government to create the “Lake of the Golden Age” in Karashor depression within the distance of approximately 80 km from Sarykamysh in order to collect the drainage water from the Turkmen irrigated areas and Khoresm oasis of Uzbekistan. According to this plan the inflow into Sarykamysh Lake will be reduced significantly – to 0.7–1.1 km^3 [15].

This paper presents an attempt to reconstruct dynamics of water and salt regime of the Sarykamysh Lake from the beginning of its infill by drainage water and to give the forecast of its future after construction of the Turkmen Lake.

2 Study Area

2.1 Geographic Features

Sarykamysh is a natural depression located about 200 km southwest to the Aral Sea, south to the Ustyurt Plateau (Uzbekistan), and north to the Karakum Desert (Turkmenistan). The depression is located to the west of the Dashoguz agricultural massif – the most densely populated area in Turkmenistan. The depression stretches approximately 150 km from the north to the south, and by 90 km from the east to the west. The deepest point in the depression rests at altitude of −46 m ASL.

The Lake borders west Ustyurt cliffs where the altitude differences are 50–80 m. Northwest of the lake is another depression – Assake-Audan, which stretches north-westward and is surrounded by the Ustyurt plateau. North of the Sarykamysh there is another small depression, which (like the previous one) is connected to the Sarykamysh by steep slopes and not by cliffs. Further on the north and northeast, the borders are still part of the Ustyurt cliffs. In the east the Lake borders with the ancient delta of the Amu-Darya, with the area adjacent to the Lake being flat lowland, with an altitude of 58 m ASL, and a moderate slope to the northwest.

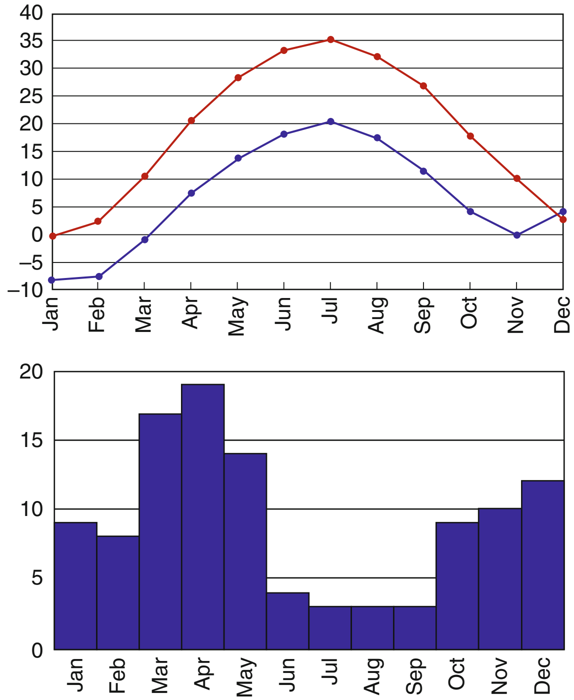

Fig. 1 Climatic parameters at Kunya-Urgench meteorological station. Average summer (*red line*) and winter (*blue line*) temperature distribution (*upper*) and precipitation (*lower*) (after www.allmetsat.com)

2.2 Regional Climate Characteristics

The climate is defined as extremely continental. The region is characterized by very hot and dry summers, combined with relatively cold winters with very little snow. Approximately 190–210 days a year are above 10°C. The air is very dry and creates enhanced evaporation conditions. The average annual precipitation in the area is 99.7–110 mm (measured at the Shakhsenem and Kunya-Urgench meteorological stations, respectively, for 1953–2006 years). The temperature in Kunya-Urgench (located 120 km northeastern to Sarykamysh and 70 km northern to Shakhsenem) can range between a maximum of 35°C (Fig. 1), while minimum temperatures can drop down to −9°C. The depression bed consists mainly of 30–50 m clay formations, making it almost impermeable. Average infiltration rates reported by Kes' [16] regarding the pre-flooding era, ranged between 0.3 and 0.6 m/day. The groundwater salinity stands on 40–60 g/L.

2.3 Geological History of the Sarykamysh

The formation of the depression is related to the Neogene (Upper Tertiary System). As a result of the alpine collision, the foundation of the Turanian plate collided into the sub-plates of the Ustyurt and the Trans-Ungus faulted and lifted. The parent material consists of marls, limestones, clays, and sands of Paleogene and Miocene, which lay in the shallow depths and are sometimes exposed. These formations are evidence to the presence of the Sarmatian Sea, which covered this area during the Tertiary period.

After the formation of the graben at the end of the Pliocene, the high sandy-pebble banks were formed, as well as dense sandstones and conglomerates containing the Apsheron fauna. These banks survived the forces of erosion in the Sarykamysh and in the Assake-Audan Lakes at the heights of −5, 0, 40, 50, 75, and 80 m ASL. This phenomenon is evidence of different periods of marine cover, whereby the sandy belts imply stable periods of marine cover, whilst the sedimentations in-between imply periods where the bodies of water experienced rapid drying.

In the late Pleistocene period, for approximately 1–2 million years, the Amu-Darya River flowed through the Central Karakum. Within this period the Sarykamysh was dry with typical desert landscapes. The sandy ridges that stretched in meridianal and sub-meridianal directions were formed as a result of the Aeolian processing of Sarmatian, Akchagyl, and Apsheron deposits. Ridges were represented by the whitish and yellow Oolite sands of local origin.

In the late Khvalynian age (about 16,000 years ago) the Sarykamysh's history connected with the dynamics of the Amu-Darya River's downstream [16, 17]. This process evolved in three main stages:

1. The Amu-Darya filled the deep Khoresm depression creating a vast lake.
2. Alluvial deltaic sediments filled the lake and turned it into a wide marsh area (water logging plain). Water made its ways westward and "found" the Sarykamysh depression.
3. Discharge into the Sarykamysh brought the water level up to 58 m ASL. The water levels covered the Sarykamysh, the Asake-Audan, and the northern depression. The surplus water flowed southward via the Neogene tectonic trough and formed the Uzboi course. The flow through Uzboi to the Caspian Sea existed from the X to the II millennia B.C.E. (Fig. 2).

According to several scientists the climax of the Holocene flood period was around the fifth or sixth millennia. As a result of the major climax the whole area of the Sarykamysh and the Aral Sea was covered. Currently this area is referred to as "The Great Aral Sea" [17, 46]. Figure 3 indicates suggested stages of the Paleo-hydrological system of Western-Central Asia. It is important to note that the existence of the great Aral Sea at this phase is not accepted by all the scientific community who deal with this issue.

Along with the shift of the Amu-Darya's course northward, the outlet to the Sarykamysh also migrated. Alluvial sediments forced the water to migrate northward from the Kanga-Darya to a new channel, the Daudan. The same process forced the water northward again toward the Daryalyk, which is the current inlet to the Sarykamysh. Since the water flows through the deepest channel, the Daryalyk is also the deepest of all three channels mentioned (to 60 m).

Fig. 2 Terraces in the southern shore of the Sarykamysh Lake. Photography: March, 2007

The Uzboi absorbed the surplus water (we do not know how far) up until the second or the third millennia B.C.E. In these times, accumulated sediments ceased the Uzboi flow and forced the Sarykamysh water to seek a way out northward, i.e. into the Aral Sea, forming the Akche-Darya channel. This last event significantly reduced the flow into the Sarykamysh. Together with the geomorphologic events described, the evolution of agricultural systems unfolded.

There is still evidence that suggests the Sarykamysh Lake was present in the first millennia B.C.E. Apparently the disconnection of the Amu-Darya from the Sarykamysh took place somewhere in the end of the second millennia. In this phase the Sarykamysh absorbed only significant floods water.

2.4 Human Presence Impact

The beginning of the artificial irrigation era downstream from the Amu-Darya is related to the end of the second millennia B.C.E, when the main part of the Amu-Darya flow went to the Sarykamysh. In the middle of the first millennia B.C.E. when the Amu-Darya's delta to the Aral Sea started to form, the man-made irrigation system began to evolve as well.

Part of the new irrigation canals led water from the Amu-Darya to the Sarykamysh. Deltaic and agricultural sediments went through processes of erosion and transportation on the western slope of the Sarykamysh (barkhan dunes, hillocks, and longitudinal ridges of sand).

Around 1,500 years ago, agricultural systems were destroyed, due to the invasion of nomad tribes into the area, which put an end to the slavery system. This process was followed by the destruction of the irrigation system, and with it all the

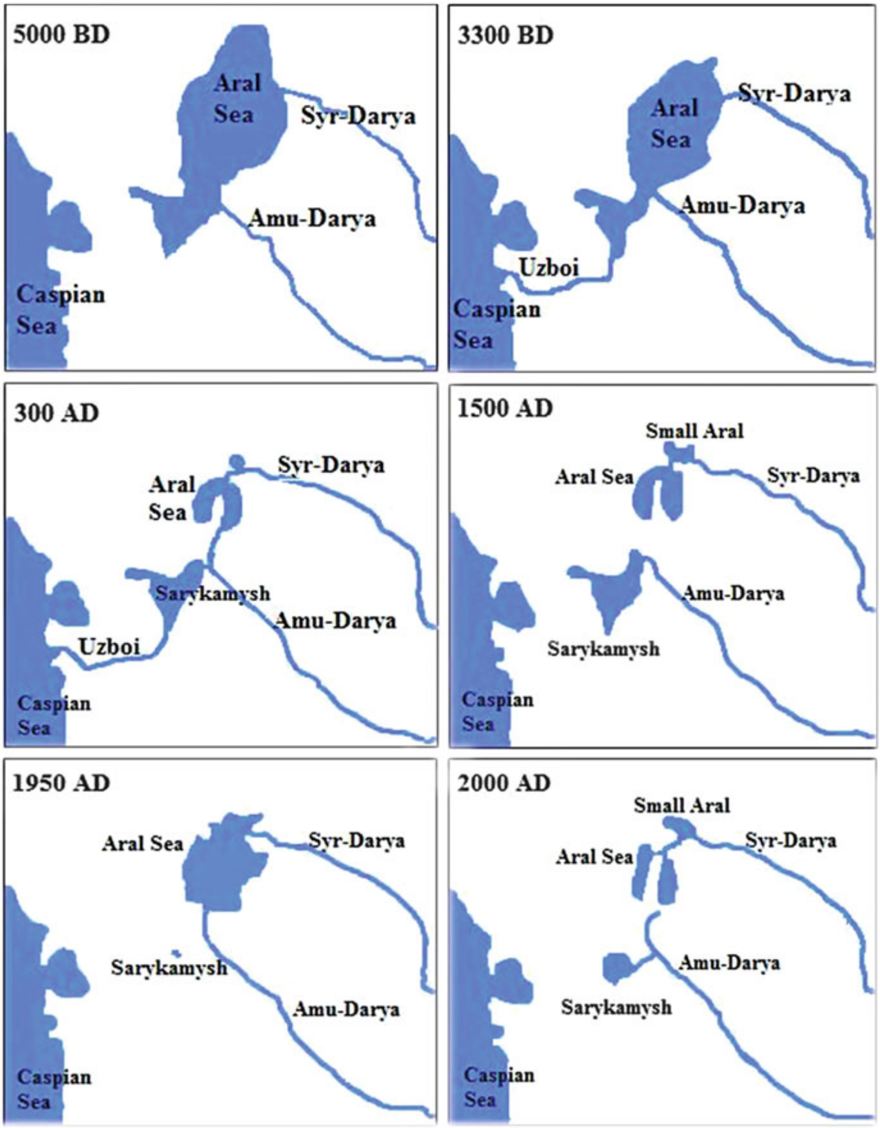

Fig. 3 Development of hydrographical systems of Central Asia (after IFAS–Aral Sea home page)

systems that diverted water toward the Aral Sea. The waters breached the basis of the Daudan and the Daryalyk. This resulted in the refilling of Sarykamysh up to the level of +52 m ASL.

The Sarykamysh is mentioned in Muslim and Persian scripts (seventh to eighth centuries), as an important and famous freshwater body in the area. Within these scripts the “Igdik-Kal’at” is referred to as an important fortress on the eastern bank of the Sarykamysh.

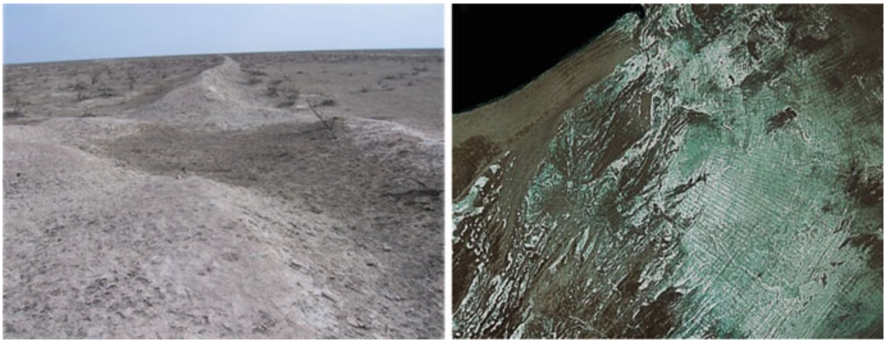

Fig. 4 Remnants of batteries in an ancient agricultural area south to the Sarykamysh Lake. The batteries apparently used to collect runoff for irrigation purposes. This set of batteries can be seen by satellite imagery (*right*). Photography (*left*): O. Matsrafi (March 2007). Source (*right*): www.Google.com

The development of the feudal agrarian system signaled the revival of the cultivation and reconstruction system. Again, the drainage was to the Aral Sea, i.e. the flow to the Sarykamysh has ceased once more.

Remnants of ancient agricultural settlements can be found around the Sarykamysh Lake. One area is so clear that it can be observed by satellite imagery about 5–10 km from the shore (Fig. 4). This settlement can be affiliated with population climax near and around the Sarykamysh during the fourth to sixth centuries or the fourteenth to sixteenth centuries [18]. Another option is that the ancient settlement was inhabited by Turkmens who lived in the neighborhood of Sarykamysh, namely the Adakly-Hyzyr tribe and created a complicated system of artificial irrigation [19].

The cultivation in the Amu-Darya's delta continued until the Mongolian invasion in the thirteenth century. The dams and irrigation canals were demolished, which created another flow to the Sarykamysh depression. Again, the water filled up the depression to the level of +50 m ASL. After a short period of rehabilitation, destruction took place at the end of the fourteenth century by Timur. In this phase the Sarykamysh was flooded, together with the Assake-Audan, which even caused surpluses to the Uzboi. A gradual reconstruction of the irrigation system led to a situation where the main part of the Amu-Darya's discharge flowed to the Aral Sea, and the Sarykamysh water level decreased down to +10–15 m ASL.

Aladin et al. [20] highlights the description by Jenkinson, who arrived in 1548 from Russia through the Ustyurt Plateau, and camped on the shore of the Sarykamysh, "the lake from which the Uzboi originates." The water he found was "fresh and sweet." Jenkinson's description teaches us that in the sixteenth century the lake's water level rose again and stabilized around +30 m ASL. At that time the western slopes of the depression were cultivated more intensively than previous times. Later the water level slowly dropped till around +10 m ASL.

The presence of the mollusk *Cardium edule* in the sediments of that period implies that the water's salinity increased and the lake became saline. The water level continued to drop until the seventeenth century, when the Sarykamysh almost completely dried up. In this phase a few heavily salinated ponds located at the deepest spots of the depression were found. For a short period, the few floods occurring in the eighteenth and nineteenth centuries disturbed the Aeolian and geochemical processes that took place during the dry period.

In 1881 an expedition mapped the area and defined two longitudinal saline lakes and between them, a natural canal. The total area of the lake was measured: 148 km^2 and the level measured was -37 ASL, and was no deeper than 5–6 m. The expedition reported salinity rates of 40–47 g/L.

Around 1914–1917 the lake was reported to be completely dry with a typical arid landscape (it is possible that the expedition did not reach the actual water body due to the size of the depression). At the end of the 1920s a lake was found in the depression. This was fed by saline groundwater (springs) from the western slopes of the depression (eastern slopes of the Ustyurt). The dehydration of the lake led to a sharp decrease of the groundwater table, resulting in all the springs going dry except for one: "Gurluk-Su" ("Saline-Water").

2.5 Landscapes and Geomorphology of Sarykamysh Depression

The landscape is well defined with the topographic variety: the water, the soil, alluvial deposits, and flora. Most of the formations are identical to the base of the Ustyurt and are sometimes exposed on the surface. In the southern, "Chirli" area ("the well"), the limestone formation "sinks" under the Quarterian deposits. Terraces found on the banks of the lake provide evidence for different levels. The terraces are built from clayey sand and in some cases with rounded pebbles that imply intensive costal-marine activity [21].

There are five large clusters of erosion and sedimentation from the Pleistocene and Holocene. In the upper part of the eastern coast five large channel entries are noticed: Kichkne-Darya, Kuruja-Uzak, Kanja-Darya, Daudan, and Daryalyk. The last two also transfer water from the CDW system. Irrigation canals can be found occasionally on the alluvial fans. These canals are evidence of an ancient agricultural activity.

The products of the Aeolian activity are connected with the dry periods. Parts of the Aeolian products result from local transport. Others are the results of Aeolian import processes from the surroundings into the depression. The imported matter tends to be white in color and finer in texture comparing to the internal transfer sands. The Aeolian Products are mainly sandy ridges from all sizes with inter ridges (honeycombs, barkhans, and sandy plates).

The position of the Ustyurt cliffs sets the trajectory of the winds and consequently the position of the dunes. In the south the dunes face the Karakum Desert. Most sandy ridges are 3–5 m high and form a mass of dunes, stretching from north–north–east to south and south–south–west of the depression toward the Uzboi corridor, where the high sandy ridges were covered by the ancient Sarykamysh Lake. The common type of dunes are 1–2 m high and are typical mainly to the bottom of the depression, while higher dunes and sandy ridges are more common in the outer circle of the sandy area. The honeycomb ridges are formed especially in the areas were the dominant winds create a whirlwind where the ridges meet uplands, especially in the center of the depression. These honeycombs are found mainly in the northern parts and in the southwestern parts of the depression toward Uzboi corridor. Barkhan dunes are found especially between the honeycomb structures. Strong winds in the hilly areas are accelerated due to the presence of these topographic features. In addition, the area receives very low amounts of precipitation, which do not contribute to vegetation development.

Solonchaks and saline lakes were an important part of the depression landscape. Conditions of extreme evaporation encourage an increase in capillar flows of water, up to the ground surface. Furthermore, the high evaporation pressure salts remain on the soil surface after the evaporation. Solonchaks are found in the lower spots of the depression because of the natural tendency of water to accumulate by gravity.

According to all the conditions described so far the Sarykamysh depression can be classified into five areas:

1. Central part – solonchaks and sands, which can be defined mainly by isolines of altitude 0 m ASL. Five deep depressions that were covered in the Pliocene. The soil is characterized by salty clay.
2. Caplarkyr – the high ridge that stretches into the depression from north–east to south–west. This ridge has a relative height of 40–50 m above the surroundings, and divides the central part into two parts northwestern and southeastern.
3. The slopes – with evidence of remains from previous floods (the sandy-pebbly terraces) all slope facing inward to the center of the depression. The slopes are divided according to different characteristics such as slope angle, morphology, and sediments composition:

   (a) The slopes of the Ustyurt in the north and in the west (from the piedmont of the Ustyurt toward the center of the depression) form a 5–6 km strip. The surface consists mainly from loamy-clay, a formation of 15–20 m thick, which thins toward the center of the depression down to several meters. Besides a few channels that cross the strip from the Ustyurt to the center of the depression, this section is pretty flat. The northeastern part of the strip is around 3 km wide and becomes wider toward the southwest area.

   (b) The northwestern area of the strip meets the Assake-Audan and the northern depression. Eastern slopes strip: generally flat area but highly scared by rills. As previously described, this is an area of deltaic sediments (ancient Amu-Darya) which are the main component covering the soil. The strip width is 15–30 km. The slope becomes steeper and deeper, from 0 m isoline upward, and rills can be found 3–10 m deep. In some places the rills are as deep as a 40–50 m. Here as well, the dominant wind trajectory is from northeast to southwest. Large sand bodies are found: Barkhans can be found between

Kichkane-Darya and the Daryalyk. In the southwestern part of the delta several local depressions are covered by saline water (4–13%), and there is higher salinity in the center of the depressions. The salt types are mainly chlorides and sulfates, where the chlorides concentration decreases and sulfates concentration increases with distance. Gypsum is also found on the edges 0–40 m. Humus concentrations are found, increasing in concentration with depth.

(c) The southern plain is stretched southward in a long fin into the Uzboi. Here the flattest slopes of the Sarykamysh depression are found. Within this area, the lithographic base is identical to the Ustyurt plateau. In the southern side of this area limestone exposures are found, which are separated by the lake's sediments layers. Northward the plain is covered by a layer of gravel and pebbles combined with takyrs and solonchaks. Many sandy ridges are found, some of which stretch up to 20 km long. The height of the Aeolian products decreases northward until approximately 3 m around the center of the Sarykamysh depression. This situation implies that the longer the area is exposed, the greater the Aeolian accumulation will be. Figure 5 presents a description of the landscape, by dividing the depression to eight landscape units separated by age and geomorphology.

2.6 Soil, Flora and Fauna

The presence of arid-land vegetation is connected not only to geomorphological history and other habitat conditions but also to lithography formation, soil types, salinity, groundwater level and its salinity. All parameters mentioned form a complicated spatial soil pattern (Fig. 6), which varies significantly from one point to another in the depression. Hence, the vegetation appears in patches.

The central part of the depression is dominated by solonchaks, where only halophytic vegetation can thrive in this environment. In most of the flooded area (1991) the vegetation is covered. The vegetation population is represented by species of *Halocnemum*, *Salsola*, *Suaeda*, and *Tamarix* [21].

Another common type found in the depression is *Haloxylon*, of two species: *Haloxylon persicum* is found more on the thick Aeolian deposits, while *Haloxylon aphyllum* is found on heavier and saltier soils. Another noticeable species in this habitat is the *Carex physodes*. The vegetation is quite sparse, 40–50 individuals per hectare, coupled with subshrubs, the vegetation cover does not exceed 20–40%. Overgrazing is affiliated as one of the underlying causes of the low vegetation cover. The *Haloxylon*'s ability to thrive is thanks to the close groundwater, and to the subsurface slope from the Amu-Darya toward the Sarykamysh.

Thin pebbly soils and relatively high groundwater are found in the Caplarkir, and in some areas in the south part of the depression that supports vegetation to the height of 1.5 m.

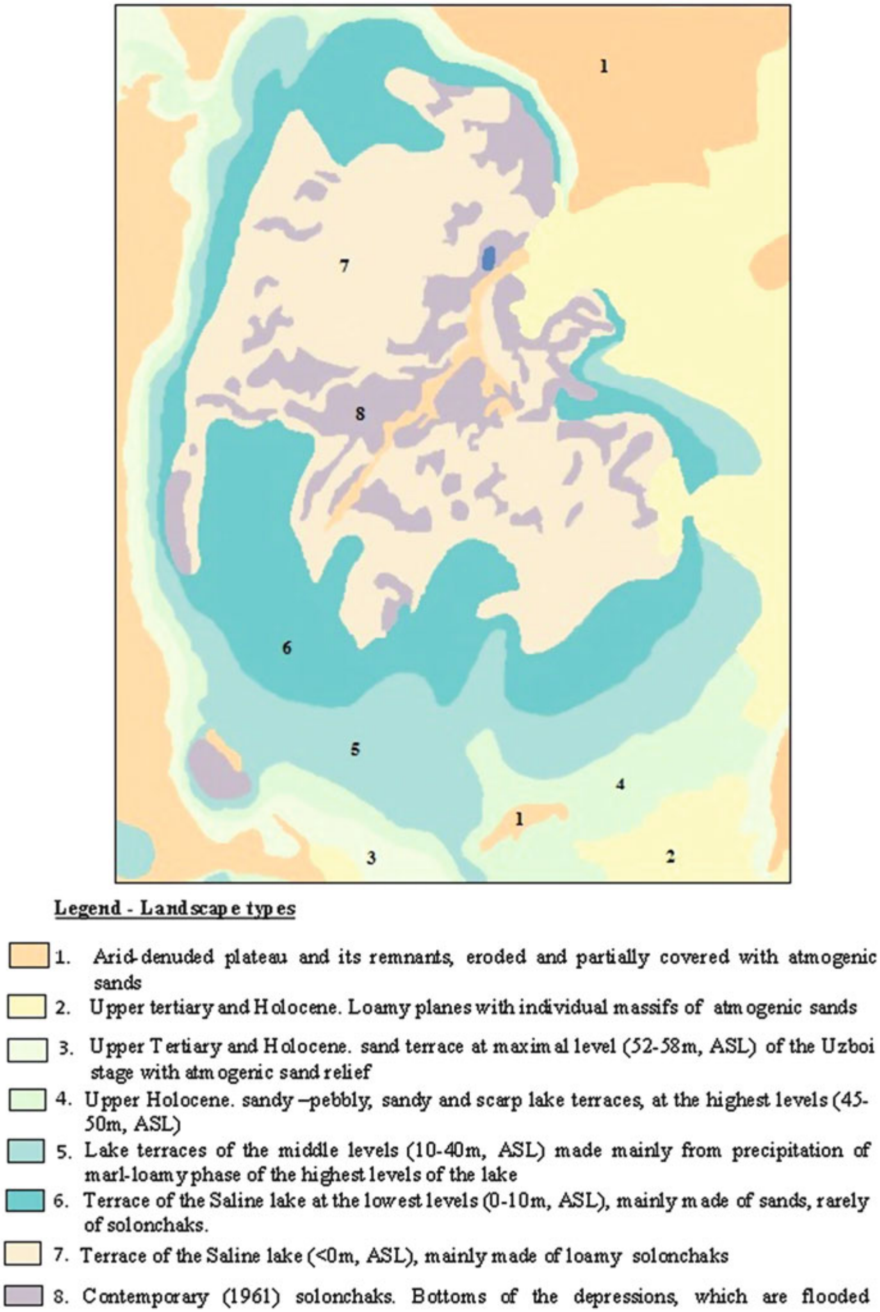

Fig. 5 Landscape map of Sarykamysh depression (after Tolstov and Kes' [5])

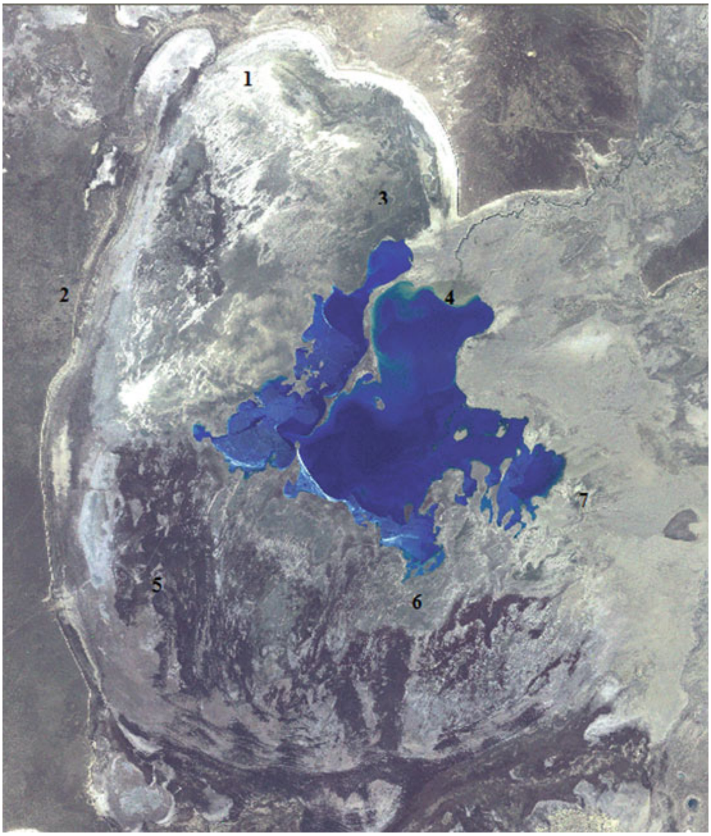

Fig. 6 Soil and landscapes types in the Sarykamysh depression as can be identified in Landsat MSS image (1973): (*1*) sands; (*2*) gypsum plateau; (*3*) sands and takyr-like soils; (*4*) alluvial sediments; (*5*) sands and solonchaks; (*6*) solonchaks; (*7*) takyrs. Satellite image view was obtained from Earth-Explorer, USGS

On gray-brown soils, which are closer to the depression's slopes, *Artemisia terrae albae* and *Salsola arbuscula* can be found. In areas with clay deposits *Artemisia diffusa* and *Salsola orientalis* can be found. *Anabasis salsa* occurs in moderately salinized soils. On the Ustyurt slopes the *Haloxylon aphyllum* stands out in its density over the area (10–50 m between individuals). *Salsola arbuscula* and *Atraphaxis spinosa* can be found in small "sinks" on the slopes of the Ustyurt. In this area the vegetative population is quite poor. Significant ephemerae presence is represented by: *Bromus tectorum*, *Alyssum aureum* and *Salsolae* semi-shrubs.

The southern plain is characterized by a large variety of soils that form a mosaic of patches between the base rock exposures. These patches are inhabited by *Artemisia kemrudica*, *Salsola gemmascens*, and *Salsola rigida* with ephemerae and annual *Salsolae*. The vegetation cover in this part of the depression does not exceed 40%. Wherever there is a thick sandy cover, the *Salsola arbuscula* and the *Haloxylon aphyllum* are dominant. With them the vegetation population is also represented by *Reaumuria fruticosa*, *Artemisia terrae-albae*, and *Alyssum aureum*. Ephemerae are represented by *Ferula assafoetida* and *Carex physodes*. The old-tugai residual-humus soils coincides with the ancient coastal sandy terraces, where *Haloxylon aphyllum* can be found mixed with *Haloxylon* growth, and with *Carex physodes,* which can also be found in the lower layer. The puffy solonchaks are bare apart from their edges where *Halocnemum strobilaceum* and *Kalidium caspicum* can be found. The sandy hills are inhabited by *Carex physodes*. In the northern area of the upper Uzboi Corridor, in the inter dunar area, biogenic crust is found which is created mainly by *Tortula desertorum*.

Generally, before and after the flooding the fauna in the Sarykamysh is very rich, with a large variety of species: from herbivores through all the food chain up to wolves and other carnivores. Previous to the flooding the fauna was represented by a long list of arid-land species. The list included birds from the Ustyurt, while the solonchaks area and the central lake "Gurluk-Kul" were inhabited by hydrophilic birds and invertebrates. The remoteness of the Sarykamysh and the very few connecting routs enabled the establishment of endemic species, such as of antelope (*Saiga tatarica*), gazelle (*Gazella subgutturosa*), and wild sheep (*Ovis ammon*). Since the area has become accessible to motorcycles, the individual's numbers have significantly decreased.

The birds population includes species such as Houbara Bustard (*Chlamydotis undulata*), Stone Curlew (*Burhinus oedicnemus*), Crested Lark (*Galerida cristata*), Finsch's Wheatear (*Oenanthe finschii*), Red-headed Bunting (*Emberiza bruniceps*), and the Eurasian Eagle Owl (*Bubo bubo*). The last species nests mainly on the Ustyurt cliffs but can be found in some places in the depression.

The reptile population includes species such as: Steppe Ribbon Racer (*Psamophis lineoletus*), Naked-toed Geckos (*Gymnodactylus russowi*), and Russian tortoises (*Testudo horsfieldi*). Among the invertebrates, rough woodlouse (Porcellio scaber) and snails (*Radula tridentata*) can be found.

The center of the depression had some uniqueness in terms of the species that inhabit it. Among these species the sand cat (*Felis margarita*) and wild cat (*Felis silvestris ocreata*) could be found together with rodents such as the Five-toed Pygmy Jerboa (*Cardiocranius paradoxus*), the European ground squirrel (*Spermophilus citellus*), and the marbled polecat (*Vormela peregusna*).

The poorest list of fauna is of the solonchaks: Plovers (*Charadrius*), and of the birds, the Common Pratincole (*Glareola pratincola*), and of the reptiles, the Reticulated toad-headed agama (*Phrynocephalus*).

2.7 Sarykamysh: Contemporary State

The modern anthropogenic stage of the Sarykamysh Lake started at the end of 1950s – beginning of 1960s – with active involvement of virgin lands to agricultural production. Until 1955 the Sarykamysh consisted of five small lakes (Fig. 7a) with

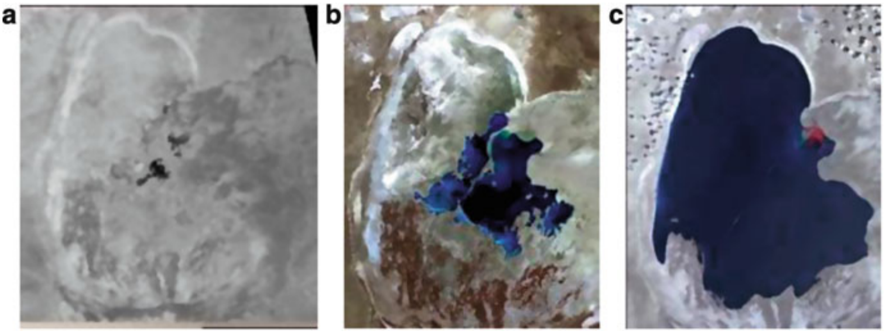

Fig. 7 Sarykamysh evolution as seen by satellite imagery from different years: (**a**) Corona (1962), (**b**) Landsat MSS (1973), (**c**) Landsat TM (2000). Source: Earth-Explorer, USGS

salinity that varied between 75 and 300 g/L. Although drainage water was dispatched with the Daryalyk channel toward the depression, no water reached the water body of the Sarykamysh (on-surface) before 1962, probably due to percolation and evaporation. Today, the Sarykamysh (Fig. 7c) is a vast water body within the area of 3,955 km^2 (2006) that receives inflow of 5.8–7.48 km^3/year.

Pavlovskaya [22] reported a lake's salinity of 12–14 g/L enabling a marine ecosystem to thrive, thanks to the natural supporting conditions and forced by natural pressure resulting from the Aral Sea desiccation.

Fishery in the Sarykamysh started in 1966, with the climax amount recorded being 2,500 tons in 1981–1985 [23]. According to Pavlovskaya [22] the Sarykamysh marine environment is optimal for a significant number of species. Thirteen species were identified as a potential base for commercial fishery. The Lake also carries problems, which are related to its sources. The water being drained from the cultivated areas contain 3% of the defoliants (used mainly over cotton), 2–3% of the pesticides, and 10–15% nutrients. The following three facts make the accumulation process more problematic since: (1) Sarykamysh is a terminal lake. Hence, all the chemicals entering do not leave; (2) the contaminated water carries the chemicals from a large number of fields; (3) an excessive usage of chemicals (20–54 kg per hectare), in the whole Amu-Darya basin.

Obviously the presence of these chemicals damages the fisheries potential. Finally the chemicals are accumulated in the water body, or may sink on its bed, or are absorbed in the biotic system. Many fish develop abnormalities, mainly in their reproduction systems, and suffer many diseases as a result of exposure to these chemicals.

There are very few studies available regarding the modern Sarykamysh Lake, or studies that focus on attempts to model the lake and its behavior, in spite of the fact that the Sarykamysh behavior is expected to cause a significant regional impact.

Alimokhamedov et al. [24] analyzed images of glaciers and lakes (including Sarykamysh) and achieved a satisfying estimation of the physical parameters for local market needs.

Between 1973 and 1985, Nuriddinov [25] monitored changes in the Sarykamysh shore line using Soviet remote sensing images, and defined remote sensing as the preferable method of monitoring lakes of this scale. The author reported that areas identified as being waterlogged on earlier images were identified as flooded by the lake on later images. Therefore, it was concluded that there is a possible subsurface flow involved in the lake's growth. This conclusion correlates with the description offered by Tolstov and Kes (1960) of sand dunes apparent in a large part of the depression.

Kikichev et al. [26] estimated evaporation from the Sarykamysh during 9 months using radioisotopic analysis. The study analyzes the distribution of natural tritium in the Lake's feeding sources, the Lake itself and the atmosphere above it. One of the advantages of this method is the achievement of definite values of estimation regardless of the Lake's size parameters.

Kes' [16] published a summary of the studies, as well as field surveys reports, and in situ data; all of which were conducted prior to the current flood. A significant part of the knowledge is based on field surveys published in a set of expedition reports regarding the Khoresm oasis by Tolstov and Kes' [5]. These surveys are highly important since they are the only scientific description of the dry Sarykamysh depression. In her description, Kes' includes a comprehensive analysis of the geology and geomorphology of the depression, climate, biotic system, and human history. Kes' also brings a mathematical analysis of the depression.

Pavlovskaya [22] studied the potential of irrigation systems and fishery according to the current state (early-mid 1990s), and the changes that irrigation water bodies and fishery have gone through. The study reveals a disturbing level of pollution and salinity within the drainage water systems where fishery takes place. The author concludes that any potential for fisheries will be terminated, unless a general drainage water system rehabilitation program is implemented.

Nezlin et al. [27] estimated the Amu-Darya flow on the basis of global atmospheric precipitation data. In their study they followed Sarykamysh water level changes (among other water bodies) using T/P data and found a correlation between precipitation patterns and trends in the lake's water levels.

This study suggests a model, which will cover the missing patch of Sarykamysh behavior under different scenarios.

3 Materials

3.1 Maps

A set of topographic maps, compiled in the 1940s (prior to the modern flood) were collected (in scale of 1:200,000). The topographic maps enabled basic delineation of the study area according to the identification of the depression and its borders. A soil type map (in scale of 1:600,000) was also collected enabling us to follow the descriptions of the geomorphologic processes in the depression.

Table 1 The list of satellite images used for the retroactive analysis of the Sarykamysh Lake

Image ID	Acquisition date	Satellite platform	Sensor	Spatial resolution (m′)
DS09034A038MC043	18 May 1962	Corona	Film camera B/W	104 m
DS09058A008MC040	29 Aug 1963	Corona	Film camera B/W	96 m
DS09065A024MC042	15 June 1964	Corona	Film camera B/W	133 m
(LM)1174031007306090	01 March 1973	Landsat	MSS	79
LM2174031007513190	11 May 1975	Landsat 2	MSS	79
LM2174031007724690	3 Sep 1977	Landsat 2	MSS	79
LM3174031008016890	16 June 1980	Landsat 3	MSS	79
LT5162031008613910	19 May 1986	Landsat 5	TM	30
(LT)4162031008920310	22 July 1989	Landsat	TM	30
(LM)5162031000024210	29 July 2000	Landsat	TM	30
LT5162031000619410	13 July 2006	Landsat 5	TM	30

Source: Earth-Explorer-USGS

Table 2 Landsat sensors and their bands

	Sensor			
Range	MSS		TM	
Blue			Band 1	0.45–0.52
Green	Band 1	0.5–0.6	Band 2	0.53–0.61
Red	Band 2	0.6–0.7	Band 3	0.63–0.69
IR	Band 3	0.7–0.8	Band 4	0.75–0.90
IR	Band 4	0.8–1.1		
Mid IR			Band 5	1.55–1.75
Short-wave IR			Band 7	2.09–2.35
Thermal IR			Band 6	10.4–12.5

Source: Earth-Explorer-USGS

3.2 Satellite Images

The only data sources available to perform a temporal survey on the development of the lake over the past 40 years were images taken over the Lake from airborne or spaceborne platforms. The earliest images available for the Sarykmysh depression area are analog images taken by Corona Satellite (declassified in 1996). Three Corona images of the Sarykamysh area were collected (1962, 1963, and 1964), which were acquired shortly after the Daryalyk has reached the Sarykamysh depression in 1961, and reflect the early stages of the development of the lake. Tables 1 and 2 show the images collected and their basic parameters.

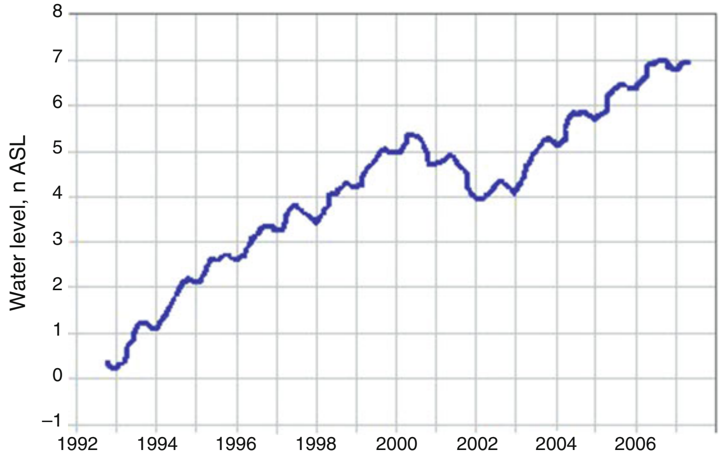

Fig. 8 Altimetry data of Lake Sarykamysh (after LEGOS, online database)

Table 3 Summary of satellite altimetry general characteristics

Satellites	Operation period	Orbital cycle	Accuracy	Minimum target area and width	
ERS2	1995–2002	35 days	>9 cm rms	>100 km^2	>500 m
ENVISAT	>2002	35 days	>9 cm rms	>100 km^2	>500 m
T/P	1992–2005	10 days	>3 cm rms	>100 km^2	>500 m
Jason-1	>2002	10 days	>3 cm rms	>100 km^2	>500 m

Source: Cretaux and Birkett [28]

3.3 Altimeters

The collected images allowed following the development of the lake at least twice in each decade since the early 1960s. There is a missing step in the sequence during the 1990s, since no images of the Lake could be found among commercial imagery suppliers. In order to complete the data sequence we used spaceborne altimeters data collected between 1992 and 2005. Spaceborne altimeters are active radar systems designed to measure altitude of ground or sea surfaces above a certain level. The measured range (R) of the altimeter from the target is calculated based on the time difference (t) between a signal and its returning echo, and the light velocity (C) as can be described by Eq. (1):

$$R = t/2 \times C \tag{1}$$

Altimetry data of the Sarykamysh (Fig. 8) were collected at the LEGOS web database. The altimetry data are an updated average of the four altimeters (Table 3).

Fig. 9 Collecting water samples from Daryalik CDW. Photography: L. Orlovsky (March 2007)

3.4 Local Data

The following local archive data had been collected with the help of the Turkmen National Institute of Deserts, Flora and Fauna, and with the Courtesy of the Turkmen National Meteorology Agency: (1) precipitation for 1953–2006 (measured at Shakhsenem station); (2) water level of Sarykamysh Lake for1970–2000; (3) surface area and volume (1962–2002); (4) CDW inflow to the Sarykamysh (1970–2002), (5) lake's salinity, salt stocks and inflow's salinity (1970–2002).

3.5 Water Samples

Water samples were collected from two areas in the Lake (one close to shore and the other in deeper water). In addition, samples were collected from the two main tributaries of the feeding CDW: the Daryalyk (Fig. 9) and the Ozerny. It is important to note that samples were collected in March 2007, prior to the irrigation and seeding seasons, during the soil washing season, when water used to wash the soil is drained into the CDW. Samples were analyzed for inorganic content and total dissolved solids (TDS) content at the Zukerberg Institution for Water Research of the Bluastein Institution for Desert Research, Ben-Gurion University of the Negev, Israel.

4 Methods

4.1 Topographic Structure Analysis

In order to predict the lake's behavior a retrospective analysis of the development of the lake over the past four decades was performed. The topographic maps were scanned and rectified. The topographic isolines were digitized and a Digital Elevation Model (DEM) was produced (Fig. 10). The plane area was calculated and volume (under the defined plane) for every height in the DEM range.

In order to estimate the accuracy of the DEM, the area and volume of the lake were used as a function of height (level) together with parallel functions based on the local measurements. In addition, nonlinear fit curves were extracted for each of the functions to enable expression of the lake parameters, based on local height measurements or forecasted ones.

4.2 Morphological Development of the Lake

The area of the Lake was extracted by supervised classification (Fig. 11) and was applied onto the DEM to extract the water level and volume of the lake at the time of image acquisition.

As seen in Table 1 there is an 11 years gap between 1989 and 2000. In order to fill up this gap the altimetric data covering most of the temporal gap have been used. Altimetry data were applied onto the DEM to derive the area and volume of the lake and fill in the gap in the images sequence.

4.3 Water Balance

The morphological changes of the lake along the years are a function of the lake's water balance. Asmar and Ergzinger [29] presented a water balance (after [30]), which they used in the analysis of the behavior of the Dead Sea. Based on their study a water balance was defined for Sarykamysh case (Eq. 2):

$$\frac{\Delta V(h)}{\Delta t} = Q_t + S(h)_t\,(P_t - E_t) + \mathrm{GW}_t \qquad (2)$$

in which ΔV is the total additional volume added in time Δt (Δt will always be considered as 1 since our calculation is annual); Q represents the total inflow to the lake during time t; S represents the lake's area at time t; P and E are the total precipitation and evaporation at time t, respectively; GW represents the total inflow volume added (or reduced) by ground water. The volume and area can be described

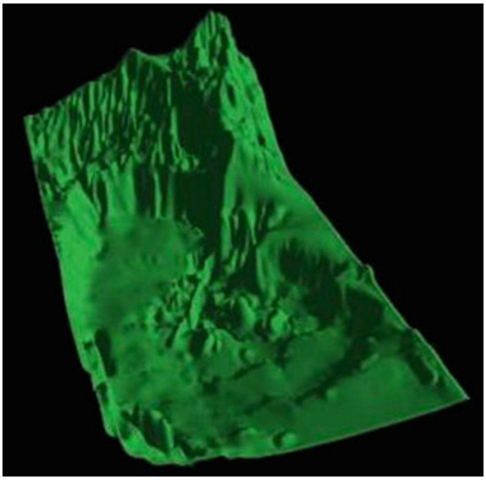

Fig. 10 A 3D view with vertical exaggerations of the Sarykamysh depression produced from topographic maps

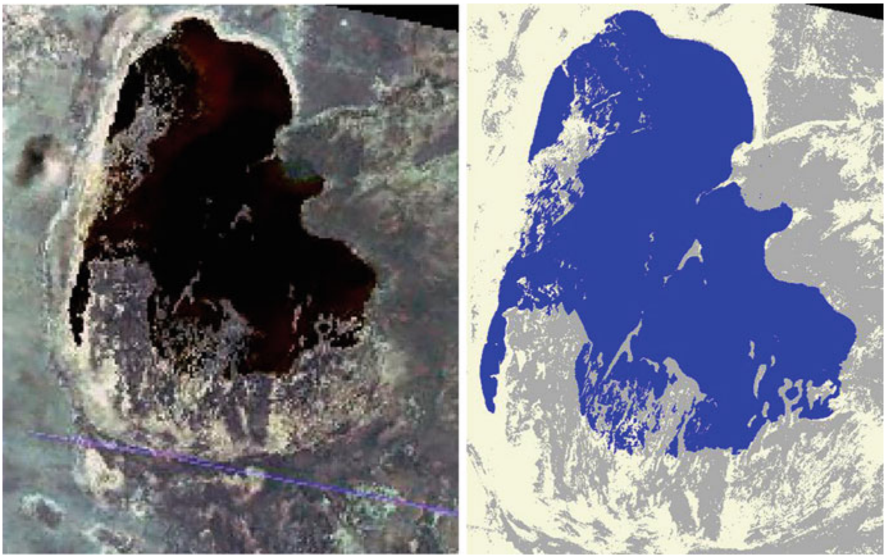

Fig. 11 Sarykamysh Lake in the 1980 MSS imagery (*left*), and supervised classification product (*right*). The flooded parts can be easily identified

as functions of the water level; inflow and precipitation data were used from the local measurements data set, mentioned previously. According to Kes' [16] the contribution of groundwater is negligible; therefore, this part of the water balance was ignored. The only element missing in the balance is evaporation. Applying all available elements into Eq. (1) enables extracting evaporation values for each year. Comparing the calculated evaporation rates with those of other authors enables evaluating the water balance and DEM.

In order to correctly compute the evaporation in the forecast one should take into account the changes in water mass that will affect salinity, which, in turn will affect the evaporation rates [31, 32]. In order to correctly calculate the salinity it is necessary to identify the elements constituting the salt balance. Glazovsky [33] and Benduhn and Renard [34] have presented a salt balance in the following way (Eq. 3):

$$\frac{\Delta SV}{\Delta t} = (S_r\ Q_r) + \left(S_{gw}\ Q_{gw}\right) + A_L\left(S_p\ P_t - S_E\ E_t\right) - e_t \tag{3}$$

where S is the water salinity; V is the lake's volume; ΔSV represents the change of total salt in the lake during time t; S_r and Q_r represent the river's (or canals') salinity and their total volume, respectively; S_{gw} and Q_{gw} represent groundwater salinity and its total volume, respectively; A represents the lake's area in time t. This variable is used as a factor to estimate the salt exchange between the lake and atmosphere together with the following parameters: total precipitation during time t (P_t) and precipitation salinity (S_p), and total evaporation (E_t) and its salinity (S_E). e_t represents the gain and loses of the total salts, which are not included in the calculated addition by inflow. For convenience this value will be referred as "residuals."

Glazovsky [33] found that atmospheric salt absorption through precipitation and loss of salt as aerosols to the atmosphere are two processes that balance each other, and therefore both can be neglected. As was mentioned previously the contribution of groundwater to the lake is negligible. Consequently, the salt balance can be expressed in a simplified way (Eq. 4):

$$\frac{\Delta SV}{\Delta t} = (S_r\ Q_r) \pm e_t \tag{4}$$

Amer [32] defined the relation between evaporation from saline water and evaporation from fresh water as a function of salinity (Eq. 5):

$$\frac{E_{sal}}{E_{fw}} = 1.0 - 0.22S \tag{5}$$

where, E_{sal} is the evaporation rate from saline water; E_{fw} is the evaporation rate from freshwater under the same conditions, S is the salinity in ds/m units. Using this expression we can calculate evaporation rates, calibrate them to freshwater evaporation values, and compare them with multi-annual averages, as measured by Orlovsky [35]. The expected evaporation values in the forecast can be calibrated for every year using the salinity values.

The forecast included applying precipitation and evaporation values together with inflow according to the scenario, and the parameters of the lake. This is defined by the functions based on local measurements or based on our DEM. Precipitation and evaporation values can be fed differently according to climate change expectations.

The last part of the salt balance is the residuals estimation. As explained, residuals will include the following: salt precipitation on the lake's bed, additional salt inflow from surrounding streams that wash in salts during floods, and salts washed from the atmosphere by precipitation, being lost by the spray into the atmosphere. The total salt stock (TSS) difference can be represented as (Eq. 6):

$$\mathrm{TSS}_t - \mathrm{TSS}_{t-1} = (S_\mathrm{r}\ Q_\mathrm{r})_t \tag{6}$$

where TSS_t represents the total salt stock accumulated in the lake (and on its bed) until time t, and TSS_{t-1} refers to the previous year; $(S_\mathrm{r}Q_\mathrm{r})_t$ represents the total inflow of salt in year t. The TSS can be defined as (Eq. 7):

$$\mathrm{TSS}_t = SV_t + \sum_{i=1}^{t} e \tag{7}$$

where $\sum_{i=1}^{t} e$ represents a sum of residuals: all salts precipitated till year t, and all gains and losses during year t. SV_t represents the total salt dissolved in the lake in time t. Using the expression of TSS (Eq. 7) in the TSS difference expression (Eq. 6) gives us (Eq. 8):

$$\left(SV_\mathrm{t} + \sum_{i=1}^{t} e\right) - \left(SV_{t-1} + \sum_{i=1}^{t-1} e\right) = (S_\mathrm{r}\ Q_\mathrm{r})_t \tag{8}$$

Therefore (Eq. 9):

$$e_t = \ \Delta SV_t - (S_\mathrm{r}\ Q_\mathrm{r})_t \tag{9}$$

Values of positive salts residuals will be found in years when more salt was gained than lost (mainly to precipitation) and vice versa – negative values will reflect years in which more salt was lost than gained. A multi-year average (1972–2000) of the residuals stands on 1.5% of the inflow salts per each year. Since the relative part of the residuals is very small, and due to the complexity of quantifying all the residuals components, we chose to refer to it as a negligible element in our salt balance.

5 Results and Discussion

5.1 Water Analysis

TDS analysis of the collected water samples showed that the lake water is brackish with a total salinity of 11.4 g/L, both in the costal water and in the deeper area. The TDS values in the CDWs were significantly smaller, with 2.8 g/L in the Daryalyk and 3.1 g/L in the Ozerny. Pavlovskaya [22] reported that water samples taken from the Sarykamysh contained toxic chemicals. Table 4 presents the concentration

Table 4 Representative toxic chemicals in the Sarykamysh Lake

Chemicals	Concentration found in the Sarykamysh (mg/L)	Maximal concentration recommended by WHO (mg/L)
Hexachlorine	2.5	0.0006
DDT	6.4	0.001
Organochlorine	0.0021–0.0059	0.00003

Source: Pavlovskaya [22], WHO [36]

Table 5 Summary of water sample analysis and their recommended values by WHO and US-EPA (all units in mg/L)

	Sarykamysh		CDW		MCL	
Place	Deep	Shore	Daryalik	Ozeorniy	WHO[a]	US-EPA[b]
pH	7.25	6.39	7.39	7.06		6.5–8.5
EC (mS)	17.4	17.7	4.59	5.13		
TDS	11,453	11,445	2,857	3,173	1,000	500
Cl	4,080	4,038	728	912	250	250
SO_4	3,710	3,716	996	1,028	250	500
Br	0	0	15.2	0	0.01	
NO_2	0	0	0	0		1
NO_3	3.16	3.20	3.70	7.75	50	10
CO_3	0	0	0	0		500
HCO_3	148	152	282	266		
Na	2,268	2,260	470	610		200
K	35.0	37.0	7.83	10.05	10	20
Ca	656	674	212	200		250
Mg	553	565	143	139		200
PO_4	0	0	0	0		0
$CaCO_3$	121	125	231	218		200–500

[a]Source: WHO [36].
[b]Source: US-EPA [37].

values of important chemicals and their maximal recommended concentration in drinking water, according to the World Health Organization (WHO).

Water samples from the Sarykamysh, the Daryalyk, and the Ozerny were analyzed for their major solids contents. Table 5 presents a summarized comparison of the samples with values recommended by the WHO and the US Environment Protection Agency (EPA). The results suggest that the water samples content significantly exceeds the maximal contaminant level (MCL). Since the lake accumulates the water with all their substance, the ions measurements hold higher values in the lake than in the CDWs. Obviously, both the water in the CDWs and in the lake is undrinkable, but it is important to note that the MCL values presented are relevant for drinking water only. The water can still be used for agriculture, which permits higher levels of contamination. Three components in the list stand out in

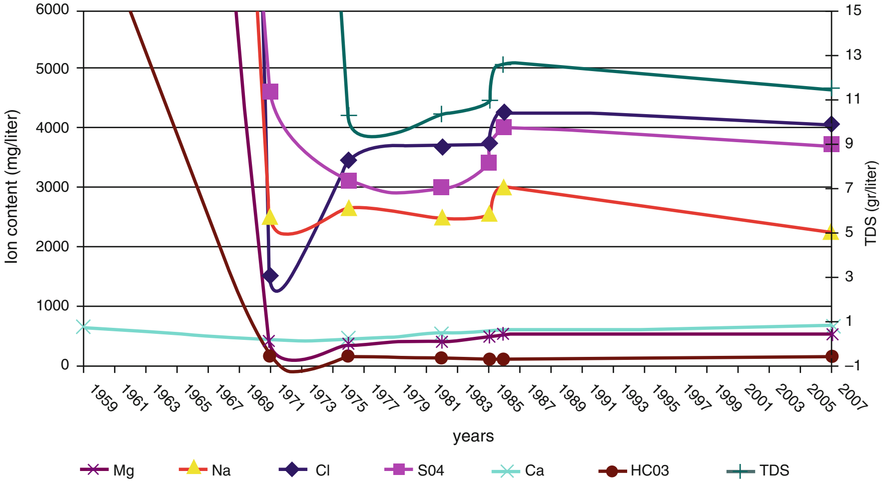

Fig. 12 Ionic content in the Sarykamysh in1959–2007

their extreme value: chloride (Cl^-), sulfate (SO_4), and sodium (Na^+). Since these ions are highly toxic [38], their extreme values can explain the cessation of fishery in the lake and in other irrigation water bodies [22].

Water samples were collected during March 2007, when water in the CDW is most likely soil washing water. Contamination values are expected to be higher during the irrigation seasons, due to the presence of fertilizers and pesticide residues.

A comparison of the ionic content reported in the Sarykamysh since 1959 (Fig. 12) indicates the existence of a few trends. There is a sharp decrease in ions content between 1959 and 1971. This decrease can be explained by the fact that drainage water, which has significantly lower salinity values, reached the Sarykamysh only in 1961 and diluted the lake's water. Between 1985 and 1986 there is a small decrease in the concentration of three ions: Na^+, SO_4^+, and Cl^- as well as in the TDS values. A retrospective analysis of the inflow and inflow's salinity of that period did not show any corresponding trends. If there was no change in the sampling and measuring methods, it is possible that the additional ionic content came from solonchaks that were covered by the lake's water at this period. Since we were not able to obtain data of water analysis between 1986 and 2007, the lack of any major changes in these ions concentrations should be considered with care.

Although there are more than a few definitions of salinity boundaries for brackish water, the Sarykamysh water is almost at the salinity level of the Caspian Sea (TDS: 12,666 mg/L) and higher than the salinity of the Aral Sea (TDS: 10,500 mg/L), as measured in 1950.

5.2 Retroactive Analysis

In order to examine the model's reliability the DEM-derived area and volume values as a function of the lake's water level (height plotted) were plotted, enabling to compare these plots to those of local measurement dataset (Fig. 13).

As seen in Fig. 13, the resemblance between the volume series is easily noticeable. However, in the area series there is a gap of up to 900 km^2 in the mid values between the local measurements and the model derivations (22% of the lake's current area). This gap is related to the water level measurements observed during the early 1970s to the mid-1980s. The gap between the two area datasets decreases, until around the height of -2 m ASL and onward the datasets are almost identical. The differences between the two datasets correspond with heights of -9 to -12 m ASL. In our DEM we can identify a topographic "shelf" or a "shoulder" between these heights, although this shelf is undetectable in the local measurements dataset. The high resemblance between the two datasets, which can be seen in the other ranges, suggests that the observed gap is not related to calibration. It is highly likely that this is a result of data loss due to differences between the sampling and measurements methods used in this study and those used in the topographic surveys of the maps (Fig. 14).

The general deviations between the two datasets can be explained in the following ways:

- Measuring methods: while computations in the present study are based on the DEM, local datasets are a collection of in situ measurements with an interpolation between them. These measurements involved field surveys in a very low spatial resolution and thus a lot of the spatial information was lost.
- During this study a wide variety of data were collected. In some of the cases not all the details regarding this data are clear. For example, the assumption was that the vertical datum used for our in situ measurements was in Krasnovodsk at the shore of the Caspian Sea (Turkmenbashi nowadays). However, at a certain stage the Soviet Union adopted a unified cartographic system, and nowadays the Baltic system is used as a vertical datum. Due to technical difficulties of finding this kind of details, it was impossible to perform a perfect calibration to the in situ data or to the topographic data. Similar difficulties occurred in the collaboration of the DEM data (Gauss-Kruger system, Krasovsky's Spheroid and Datum which is probably Pulkovo-1942) with the Landsat Data, because some spatial information would have been lost in the transfer from one system to another if one doesn't have all the cartographic details.
- A wide set of in situ measurements which runs over 30–40 years was most likely collected in more than one method, since knowledge and experience evolve. In many cases a dataset sequence is broken due to a method change, a formulae or a measuring tool.

In order to simplify the use of the database, a nonlinear regression to the DEM data has been derived, i.e., volume as a function of height (fourth order courier regression,

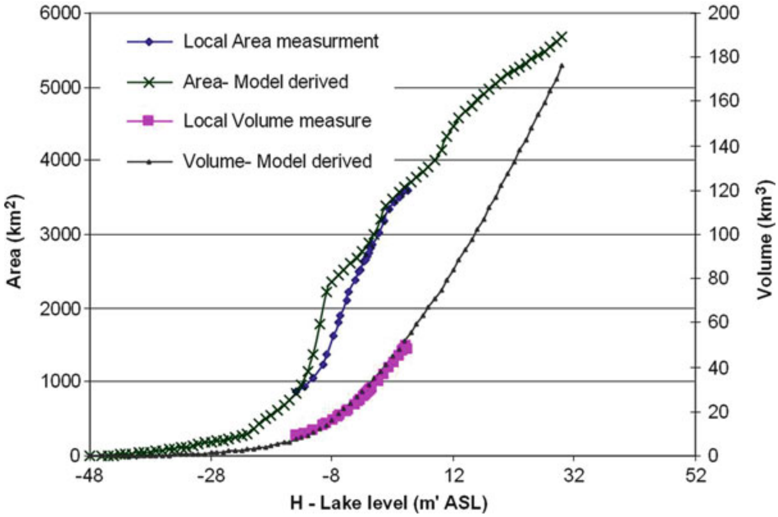

Fig. 13 Lake's area and volume as a function of water level (height), local measurements data vs. DEM produced data. It is possible to see that there is resemblance between volume series. However, a gap can be noticed between two series of area

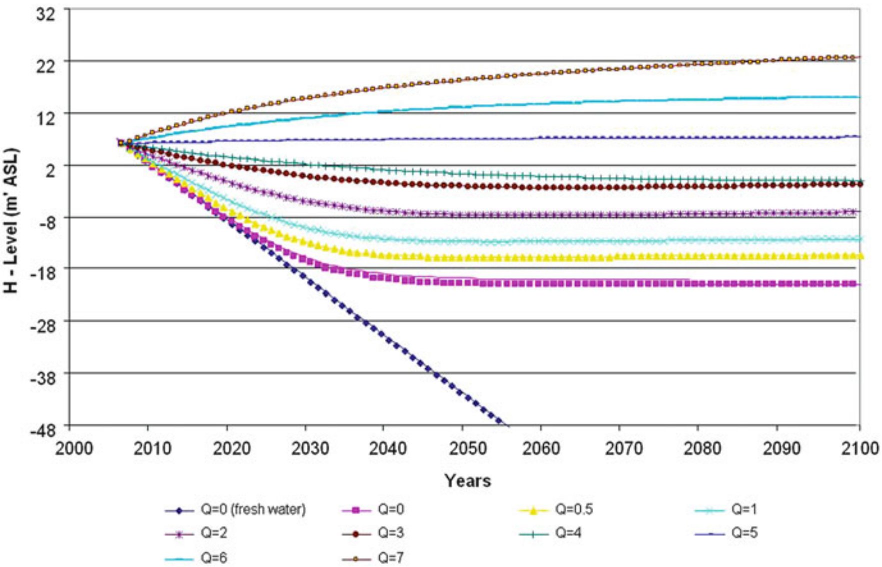

Fig. 14 The Sarykamysh Lake water level forecast till 2100, according to different inflow scenarios

Table 6 Multi annual evaporation rates as calculated with different water level database in different area and volume functions (local dataset or DEM based) and satellite imagery classification

	Area and volume derivation method					
H source	S(h)-Local dataset regression	V(h)-Local dataset regression	S(h)-DEM-regression	V(h)-DEM-regression	S- Sat. classification (interpolation)	V(h)-DEM-regression
Local gauges	Saline water: 1.428 Fresh water: 1.48					
Satellite classification derived			Saline water: 1.162 Fresh water: 1.253		Saline water: 1.190 Fresh water: 1.282	
Altimeters			Saline water: 1.276 Fresh water: 1.332		Saline water: 1.242 Fresh water: 1.297	

$R^2 = 0.9999$) and area as a function of height (ninth order polynomial, $R^2 = 0.998$). The same regressions were produced for the local measurements dataset: Area (described by third polynomial order achieved $R^2 = 0.9981$) and volume (described by exponential function $R^2 = 0.9972$). The values of the functions were used in the water balance equation (Eq. 2), presented earlier, to calculate evaporation values. Table 6 presents multi-annual evaporation values from the lake, according to the function source and the height variable source. The evaporation values based on local height measurements and with local data derived functions are very close to the evaporation values presented by Orlovsky [35]. Orlovsky explained that evaporation from the Sarykamysh must be smaller than the values he presented, because his evaporation measurements were done with a 20 m^2 water tank, and there is an opposite relationship between the volume of the water body and its heat exchange. Kikichev et al. [26] presented their calculations regarding evaporation values using isotopes analysis: from May 1986 to September 1987 they calculated an evaporation of 0.95 m. Relative calculations for this period, which were based on the DEM, showed evaporation loss of 0.93 m. The evaporation rates of the Aral Sea ranged between 0.97 and 1.05 m/year [34]. A comparison of evaporation values between the results obtained from Orlovsky [35], Kikichev et al. [26] and Benduhn and Renard [34], and the results of calculations of water balance in the current study reveal that the evaporation rates based on the local datasets are probably too high. This statement is consistent with the gap observed between the model-derived area calculation and the local area datasets (see Fig. 13). It is possible that the area values found in the local datasets are lower than the actual values, and hence the calculated evaporation values came out too high. Higher values of evaporation can explain lower growth of the dimensions of the lake. The fact that the evaporation rate based on local measurements is too high suggests that the evaporation rates based on presented in this paper datasets (DEM, classification, and altimeters) are closer to the true values of evaporation from the lake. Therefore, it is possible to refer to presented datasets as more reliable forecasts.

5.3 Forecast

Based on all the elements presented so far (water balance, salinity, and evaporation processes), a future water balance was calculated with iterations to predict the behavior of the lake until 2100. The iterations were repeated with different scenarios of inflow, inflow's salinity, annual evaporation, and total precipitation (Fig. 14), while all other parameters were kept stable along these iterations. The results of the water balance forecast suggest that the factors influencing the lake's final level are annual inflow volume, total annual evaporation, total precipitation, and inflow's salinity, in a decreasing order. Furthermore, it can be seen that in all scenarios relative stability is achieved at different levels. In all scenarios where inflow was lower than 3 km^3/year, there is a sharp decrease in the water level in the first 30–40 years, which is followed by relatively stable levels. Stable water level is achieved because the evaporation's total volume balances the annual inflow. The stability is defined as relative, since while the water gain and loss is almost balanced there is still constant addition of salt that increases the salinity values and reduces the total evaporation values, thus creating moderate fluctuations of the water level. The forecast for the lake's behavior was examined according to several aspects, i.e., no inflow scenario, lake's expansion scenario, borderline across the lake, Lake's viability and climate change.

5.3.1 No Inflow Scenario

If the inflow to the lake will cease completely, the expected salinity will reach 268 g/L around the year of 2065. The value is expected to be relatively stable (very moderate increase) since the loss of water by evaporation will be limited by the salinity. The edition of salts by inflow to the system will create an almost negligible change (around 0.2 g/L per a year).

Running the model with no salinity considerations at all can suggest that some of the natural inflow creates the original 5 small lakes. The information was collected from a variety of sources, regarding the water lake level prior to the current flooding. Kes' (1960, [16]) quotes a field survey in which the water level rests in −33 m ASL. It is possible to achieve such a level of stability by running the model in an inflow scenario of 0.17 km^3/year. The fact that the lake was observed when there was no artificial inflow leads to the inevitable conclusion that the water source is natural, i.e. precipitation or ground water. The lake's volume calculation, as observed in 1962 (when the inflow first reached the lake), is 0.6 km^3. Taking into account an average annual precipitation (100 mm) it was calculated that a drainage basin of 6,000 km^2 is required in order to accumulate such a volume of precipitation (not taking into account percolation and evaporation processes). Therefore, it is possible to suggest that the sources of the natural lakes in the Sarykamysh are ground water and springs coupled with the contribution of precipitation.

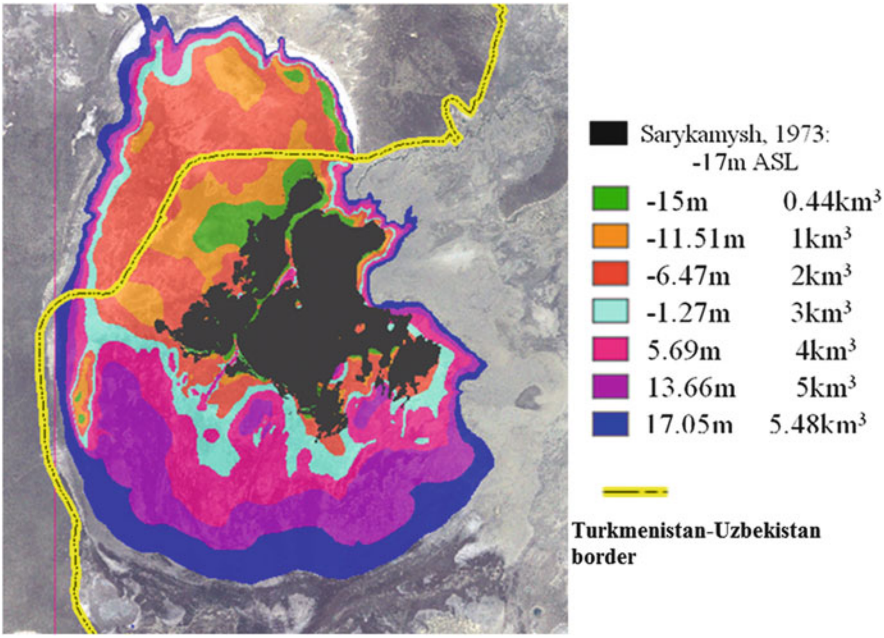

Fig. 15 Sarykamysh depression. Water area expected in the year 2100 according to the different inflow scenarios. In the middle (in *black*), the lake as seen by Landsat MSS (1973)

5.3.2 Lake's Expansion Scenarios

In a scenario of inflow of 5 km^3 per a year with the same inflow's salinity, water level and salinity in the lake will reach 13.66 m ASL and 27.6 g/L, respectively, by 2100. At this height the lake will cover an area of 7,823 km^2.

5.3.3 International Border Exposure

If the inflow to the Sarykamysh will stand on 0.44 km^3/year, the water level will drop down to −15 m ASL. This implies that the entire borderline with Uzbekistan, which crosses the Sarykamysh depression, will dry out. The salinity in this case will reach 159 g/L, inevitably defining the Sarykamysh as an unviable ecosystem. Figure 15 presents possible lake dimensions as a result of a few possible scenarios.

5.3.4 Lake's Viability

In a terminal lake the most acute process in the accumulation is salts accumulation. The total salt stocks in the lake will always increase as long as there is inflow. Since the lake's viability depends primarily on the lake's salinity two possibilities to

Table 7 Lake viability duration according to different inflow scenarios

Maintaining salinity lower than 16 g/L		Maintaining salinity lower than 35 g/L	
Total inflow (km^3 per a year)	Viability duration	Total inflow (km^3 per a year)	Viability duration
0	2008[a]	0	2016
1	2008[a]	1	2019
2	2009[a]	2	2026
3	2010	3	2041
4	2013	4	2085
5	2020	5	Beyond 2099
6	2041	6	Beyond 2099
7	2070	7	Beyond 2099

[a]Value has low significance.

preserve the lake as a viable ecosystem were checked: (1) maintaining the lake's salinity under 16 g/L, which will enable the existence of the brackish water ecosystem; (2) maintaining the lake's salinity under 35 g/L, which will turn the lake into an ocean-like ecosystem. Table 7 presents the duration of lake's viability according to different scenarios of inflow. The basis for all the calculation was inflow salinity of 3.5 g/L which is the average reported inflow's salinity.

According to the results, a salinity increase above the current values will take place in a couple of years. Maintaining the current inflow to the Sarykamysh (around 5 km^3/year) will keep the lake under a salinity level of 16 g/L until 2020. Beyond this stage salinity is expected to pass the salinity threshold. An attempt to maintain the Sarykamysh as an ocean-like ecosystem (in terms of salinity) is feasible for longer duration. Maintaining the current inflow to the Sarykamysh will enable salinity values lower than 35 g/L even beyond 2099.

6 Conclusions

In order to forecast the behavior of the Sarykamysh Lake, a model was produced based on 1940s topographic maps. Using satellite images, Satellite Altimetry data and the Lake's morphological characteristics collected over the years in situ, the morphological changes of the lake in the past 40 years have been studied. By applying water and salt balances the evaporation rates from the lake during this period was calculated. Evaporation rates calculated by the model were compared with evaporation rates based on local measurements and with rates calculated by other scientists. These comparisons proved the reliability of our model. The model was applied to several controlled inflow scenarios to the lake, and lake's parameters were derived. Furthermore, the lake's behavior was examined in scenarios of different parameters such as inflow's salinity, annual precipitation, and annual evaporation rates.

In almost all scenarios water level stability is achieved around 40 years from today in different levels. A total disconnection of the lake from its feeding canals will probably not bring the lake into total desiccation, at least not until the year of 2100, but salinity values will be so high (268 g/L) that life could not exist in it. The environmental impact of the salinity issue is severe since the expected loss is of species that were forced out of the desiccating ecosystem of the Aral Sea area toward the Sarykamysh where they found a suitable ecological niche.

The water level according to the different scenarios is not perfectly stable. It is moderately fluctuating around certain levels. These fluctuations occur because there is constant inflow of salt (though total inflow and total evaporation balance each other).

Multiannual salt residuals average was calculated and stands on 1.5% of the lake's salinity. Due to the complications in calculating each of the residuals elements, and due to the minor size of the residuals, we chose to refer the residuals part as negligible in our salt balance.

The expected drop in the Sarykamysh water level hides severe consequences regarding the exposure of the lake's bed, which carry dust and sands sediments together with chemicals and salts. The additional Aeolian exposed substance might lead to severe regional environmental and health hazards [39–41]. Possible future research should focus on an analysis of soil exposure, based on the presented model, and an analysis of the potential contribution to Aeolian activity for risk assessment process.

Maintaining the current inflow (around 5 km^3/year) will lead to a rise of the water level up to 13.66 m ASL, and an expansion of the lake's area up to 7,823 km^2, more than twice of the lake's area today. By the year 2100 the salinity will rise up to 27.6 g/L.

The meaning of the salinity increase (even with maintaining the lake with ocean like salinity) is the loss of the Sarykamysh as an ecological refuge for many species that have migrated from the Aral Sea during the last four decades.

A scenario in which an inflow of 0.44 km^3/year is kept will lead to a decrease of the water level down to -15 m ASL. The importance of this level is a complete exposure of the borderline between Turkmenistan and Uzbekistan in the Sarykamysh depression.

References

1. CAWATERinfo – Aral Sea Basin (2012) http://www.cawater-info.net/aral/geo_e.htm. An internet site of CAREWIB. Accessed 03 July 2012
2. Ziyadullaev SK (1990) Use of land and water resources in Central Asia and Southern Kazakhstan. Probl Desert Dev 2:1–3 (in Russian)
3. Chembarisov E (1988) Hydrochemistry of irrigated areas (on example of the Aral Sea). FAN, Tashkent, Uzbekistan, 104 p (in Russian)
4. Nikitin A (1987) The lakes of Central Asia. Gidrometeoizdat, Leningrad, 105 p (in Russian)

5. Tolstov SP, Kes' AS (eds) (1960) Low Amudarya River, Sarykamish, Uzboi. History of formation and population. Materials of Khoresm Expedition, vol. 3. Academy of Sciences of the USSR, Moscow, 347 p (in Russian)
6. Kiyatkin A, Sanin MV (1989) The Lake Sarykamish – the largest accumulator of collector and drainage water. Amelioration and Water Industry 1:20–24 (in Russian)
7. Mansimov M, Glazovsky V (1988) Sarykamysh depression: problems and perspectives. Probl Desert Dev 4:71–72 (in Russian)
8. Anisimov V, Staroverova B (1982) The modern state and perspective of fishery in the Sarykamysh Lake. Vestnik Karakalpakstan branch of Academy of Sciences of Uzbekistan 3 (89):47–52 (in Russian)
9. Shaporenko SI (1987) The effect of hydrological regime on fish productivity of salinized water bodies (using the example of the Aral Sea, lakes of the Arnasai system and Sarykamysh) [Vliyaniy gidrologicheskogo rezhima na ryboropoduktivnost' osolonyayushikhsya vodoyemov (na primere Aralskogo morya, ozer Arsanajskoi sistemy i Sarykamysh)]. *Avtoref na soisk uch. step.k.g.n.* (Moscow)
10. Djumaniyazov K (1978) Lake Sarykamish. Proc SANIGMI 59(140):67–73 (in Russian)
11. Vitkovskay T, Mansimov M, Shekhter L (1985) Dynamics of Sarykamysh Lake by remote sensing data. Probl Desert Dev 6:38–43 (in Russian)
12. Gorelkin N, Mansimov M (1990) Hydrometeorological regime and water/salt balance of the lake Sarykamysh. Proc SANIGMI 133(214):70–84 (in Russian)
13. Mansimov M (1987) Lake Sarykamish and its influence on the adjacent environment. Probl Desert Dev 2:65–68 (in Russian)
14. Mansimov M (1994) Dynamics of landscape and ecological conditions in the zone of influence of the Sarykamysh Lake. Probl Desert Dev 3:32–38 (in Russian)
15. Saparov U, Golubchenko V (2001) Turkmen Lake in the Karakum Desert. Probl Desert Dev 1:46–51 (in Russian)
16. Kes' AS (ed) (1991) Lake Sarykamysh and water bodies collectors of drainage water. Nauka, Moscow, 150 pp (in Russian)
17. Aladin N (2000) Water and environment health – historic evolution of the Aral Sea system. Water security – opportunity of development and cooperation in the Aral Sea area. A SIWI/RSAS/UNIFEM Seminar, Stockholm, 2000
18. Grigoryev AA (1955) The Sate of Soviet Geography. Geogr J 121–124:429–439 (in Russian)
19. Countryturkmenistan (2005) Information portal accessed on http://countryturkmenistan.tripod.com/index.blog?start=1118403201
20. Aladin N, Letolle R, Micklin P, Plotnikov I (2005) Uzboy and the Aral regressions: an hydrological approach. International conference on rapid sea level change – a Caspian perspective, Rashat, Iran
21. Sanin M et al (1991) Sarykamysh Lake and water bodies-collectors of drainage waters. Nauka, Moscow, 149 p (in Russian)
22. Pavlovskaya LP (1995) Fishery in the lower Amu-Darya under the impact of irrigated agriculture. FAO Fisheries Circular No. 894, 42–57. FAO, Rome
23. Petr T (ed) (2003) Fisheries in irrigation systems of arid Asia. FAO Fisheries Technical Paper. No. 430. Rome, FAO, 2003, 150 p
24. Alimokhamedov MA, Lesnik IUN, Timoshenko AM (1982) The use of space photographs in the mapping of glaciers and water bodies. Geodeziia i Kartografiia, May 1982, 24–30 (in Russian)
25. Nuriddinov OS (1989) Use of remote sensing in the study of the changing shoreline of Sarykamysh Lake. Sci Remote Sens 26(1):74–77 (in Russian)
26. Kikichev KG, Kostyyukovsky VI, Sanin MV, Shevtsov LA, Shkarin BI (1990) Assessment of evaporation off the surface of the Sarykamysh Lake from Radioisotope data. Int J Radiat Appl Instrum Part E Nucl Geophys 4–1:91–98

27. Nezlin PN, Kostianoy AG, Lebedev SA (2004) Interannual variations of the discharge of the Amu Darya and Syr Darya estimated from global atmospheric precipitation. J Mar Syst 47:67–75
28. Cretaux JF, Birkett C (2006) Lake studies from satellite altimetry. CR GeoSci 338:1098–1112
29. Asmar BN, Ergzinger P (1999) Estimation of evaporation from the Dead Sea. Hydrol Process 13:2743–2750
30. Brutsaert W (1982) Evaporation into the atmosphere: theory, history and applications. D. Reidel Publishing Company, Dordrecht
31. Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc Royal Soc Lond Series A 193:120–145
32. Amer MH (1992) Fayoum Oasis of Egypt. A Ph.D Thesis work. Water Research Center, El Kanater, Egypt
33. Glazovsky NF (1995) The salt balance of the Aral Sea. GeoJournal 35(1):35–41
34. Benduhn F, Renard P (2004) A dynamic model of the Aral Sea water and salt balance. J Mar Syst 47:35–50
35. Orlovsky NS (1971) Evaporation from the small water bodies of Turkmenistan. Ashgabat, Ylym, 96 pp (in Russian)
36. WHO (2003) Background document for preparation of WHO guidelines for drinking-water quality. Geneva, World Health Organization (WHO/SDE/WSH/03.04/17)
37. US-EPA (2003) Drinking water contaminants list on the US Environment Protection Agency web site: http://www.epa.gov/safewater/contaminants/index.html#mcls. Accessed on 18 Oct 2007
38. Pescod MB (ed) (1992) Wastewater treatment and use in agriculture no. 47 Series title: FAO Irrigation and Drainage Papers. Food and Agriculture Organization of the United Nations, Rome, 1992
39. Gill TE (1996) Aeolian Sediments generated by anthropogenic disturbance of Playas: human impacts on the geomorphic system and geomorphic impacts on human system. Geomorphology 17:207–228
40. O'Hara SL, Wiggs GFS, Mamedov B, Davidson G, Hubbard RB (2000) Exposure to airborne contaminated with pesticide in the Aral Sea region. Lancet 355:627–628
41. Orlovsky L, Orlovsky N, Durdyev A (2005) Dust storms in Turkmenistan. J Arid Environ 60:83–97
42. IFAS (2000) State of environment of the Aral Sea Basin: regional report of the Central Asian States. Portal accessed on http://enrin.grida.no/aral/aralsea/index.htm. 13-4-2005
43. LEGOS, Hydrology from space, Cretaux JF (ed). Database portal accessed on http://www.legos.obsmip.fr/en/soa/hydrologie/hydroweb/12-8-2007
44. Allmetsat – online weather and climate database. http://www.allmetsat.com. Accessed 23 July 2007
45. Earth-Explorer, Earth Resources Observation & Science (EROS) USGS. http://www.earthexplorer.usgs.gov/. Accessed during Mar 2005 to Oct 2007
46. Roll G, Alexeeva N, Aladin N, Sokolov V, Sarsembekov T (2004) The Aral Sea – management, experience and lessons learned. A status report on the portal: International Waters Learning Exchange and Resource Network. http://www.iwlearn.net/publications/ll/aralsea_2005.pdf/view