Liang Emlyn Yang · Hans-Rudolf Bork
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Socio-Environmental Dynamics along the Historical Silk Road

GRADUATE SCHOOL AT KIEL UNIVERSITY
human development in landscapes

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Chapter 5
Quantitative Evaluation of the Impact on Aral Sea Levels by Anthropogenic Water Withdrawal and Syr Darya Course Diversion During the Medieval Period (1.0–0.8 ka BP)

Renato Sala

Abstract Paleo-climatic, environmental, archaeological studies and historical accounts concerning the behavior of the Aral Sea during the last 2000 years point to a number of water level regressions similar or deeper than the modern one. This article is focused on the causes of such regressions, which are variously attributed to climatic change, diversion of river courses and anthropogenic water withdrawal. The first factor has been researched by several geo-specialists and its potential impact has been preliminarily evaluated. The second factor has been considered only in the case of the Amu Darya river. The third factor—water withdrawal for irrigation purposes—has been hypothesized, though never deserved specific analysis. The article provides a quantitative evaluation of the total hectares covered by the medieval urban systems of the Syr Darya and Amu Darya river basins, and of the coefficient of water use per hectare of walled towns during the X-XII centuries AD. Estimates of annual volumes of anthropogenic water withdrawal allow the investigation of the complex interaction of the three factors above in determining the hydrological conditions of the Aral Sea. On the basis of the calculation of possible scenarios of water mass balance, the occurrence of transmission losses by medieval diversions of the Syr Darya course has been suspected as the main cause of lake regressions, which is supported by geological considerations, archaeological data and historical accounts.

Keywords Aral Sea · Lake water level change · Water subtraction
Medieval urbanization · Syr Darya course diversion

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5.1 Introduction

Tectonic depression at the modern Aral Sea and Sarykamysh basins formed during the Neogene final stage of the Tethys paleo-ocean evolution. From the Middle Pliocene to the start of the Pleistocene the depression was filled up to +73 m a.s.l. by the Akchagyl and Apsheron transgressions of the Caspian Sea; and, during the Pleistocene, it entered a continental phase characterized by a local erosional river network and shallow saline lakes.[1]

The Aral Sea depression started hosting a small lake around 140 ka BP when reached by the Syr Darya river, and a lake similar to the Aral Sea of year 1960 (Aral-1960[2]) only during the post-glacial period as soon as reached by both the Syr Darya and Amu Darya courses. The modern history of the Aral Sea begins with the Holocene, always concerned by water level fluctuations of high amplitude, with regressions down to total disappearance and transgressions up to 54–56 m a.s.l.,[3] forced by climate change and/or by diversion of river courses. Most significant are switches of the Amu Darya course between the Aral Sea and Sarykamysh basins. (Berg 1908; Maev et al. 1983; Mamedov 1991; Micklin et al. 2014; Sects. 3 and 5)

Accordingly, the reconstruction of the multi-millennial behavior of the Aral Sea requires the consideration of geological events (climate changes and deviations of river courses out of tectonic and sedimentary activity) happening in both the Aral Sea and Sarykamysh basins. Starting from VI century BC,[4] must be kept into account also the anthropogenic water withdrawal from the Amu Darya and Syr Darya rivers (Fig. 5.1).

By the end of the article it will be clear that, in order to reconstruct the historical evolution of the Aral Sea water volumes, such consideration must be extended to all the existing and *highly variable evapo-transpiration spots of the complex hydrology of the Aral Sea basin, inclusive of lakes, lakelets, marshes and…irrigated fields*.

5.2 Regressions of the Aral Sea During the Last 2000 Years

5.2.1 Modern Crisis and Parameters of the Aral Sea and Its Feeding Syr Darya and Amu Darya Rivers

In 1960 the Aral Sea is characterized by high water level stand: an average water volume of 1083 km^3, water surface 67,000 km^2, evaporation 63 km^3

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[1] About the tectonic and sedimentary processes driving the geological history of the Aral Sea basin, see: Kes and Klyukanova (1999); Letolle and Mainguet (2003).

[2] In this article, when considering the Aral Sea conditions in a specific year (for example year 1960), the lake will be shortly referred as Aral-1960.

[3] This is the altitude of the divide between the Aral Sea and Sarykamysh basins.

[4] In the present article, centuries will be referred by roman numerals (VI century BC = VI BC) and years by Arabic numerals (1890 year AD = 1890 AD).

Fig. 5.1 The Aral Sea basin in 1960

(940 mm/year), input +63 km^3 [net[5] river inflow 53 km^3 + local precipitation 8.9 km^3 (133 mm/year) + groundwater-infiltration balance +1–2 km^3 (inflow +2–3 km^3, infiltration −1–2 km^3)], water level at +53 m a.s.l. (with lake bottom at −13 m a.s.l., max water depth of 69 m and average depth of 16 m) and coastal salinity 10 g/l. Within the basin the total runoff totaled 114 km^3, irrigated area 4.7×10^6 ha, and annual water withdrawal 61 km^3 (Fig. 5.2).

During the following 50 years, the number of people living in the basin grew by four times, the irrigated area almost doubled to 8×10^6 ha and so did the water withdrawal up to 105 km^3, causing a progressive reduction of annual river inflow that by 2007–2012 dropped to less than 10 km^3, accompanied by a correspondent

[5] River inflow decreased by 8–10 km^3 of water losses in the deltas.

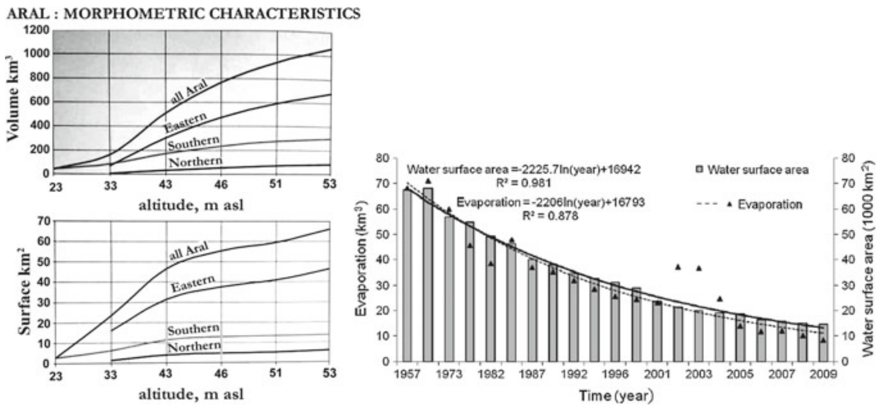

Fig. 5.2 Left: Aral Sea morphometry (*source* Nazionalnyi Atlas Respubliki KZ 2010). Right: evolution of water surface and evaporation volumes, 1957–2009 (*source* Gaybullaev and Chen 2012)

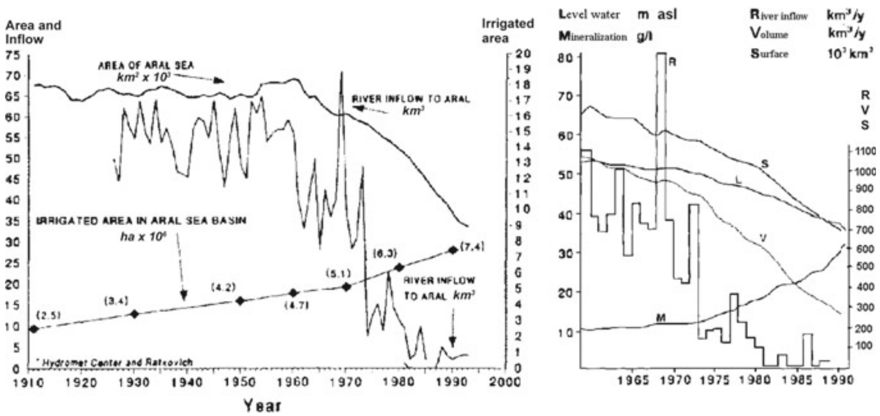

Fig. 5.3 Aral Sea. Left: evolution of water surface, river inflow and irrigated area within the basin (1910–2000) (*source* Micklin and Williams 1996). Right: water volume and mineralization from 1960 to 1990 AD (*source* http://archive.unu.edu/unupress/unupbooks/uu14re/uu14re0a.htm)

huge contraction of the lake water volume (down to 70 km^3) and surface (down to 8000 km^2) (Fig. 5.3).

During the years 2003–2008 the regression trend crossed two topographic thresholds, making the Aral Sea disappearing, first divided into two (Lesser and Greater) and then into three basins: Northern, Eastern and Southern. The northern (Northern Aral Sea, abbr. NAS) and the southeastern (Eastern Aral Sea, EAS) basins, because of infilling with sediments from the Syr Darya and Amu Darya rivers, are both quite shallow with basal elevations at +23 and +24 m a.s.l. respectively. The southwestern basin (South Aral Sea, SAS) is the deepest, with lake bottom at −11 m a.s.l..

The **NAS** is the main recipient of the Syr Darya inflow and is connected with the EAS through the Berg straight at +37 m a.s.l. In 1992, as the Aral Sea water level dropped towards +37 m a.s.l. (which would have cut off the small Aral Sea from the Syr Darya's flow completely), a dam (Kokaral dam) was built in order to catch the Syr Darya inflow, so that by 2006 the NAS water level rose to +41 m a.s.l. (water depth of 18 m).

The **EAS**, the largest basin, is the main recipient of the Amu Darya inflow and is connected to SAS through the Kulandy straight at +27–29 m a.s.l. Deprived of the Syr Darya inflow by the Kokaral dam and of the Amu Darya inflow by extreme water withdrawal, in 2009 the EAS went dry and in the following years intermittently reappeared as a salty pond.

The **SAS**, after becoming in 2006 totally isolated from the EAS and only fed by groundwater, had water levels dropping to +26 m a.s.l. (max water depth of 37 m) and salinity rising above 100 g/l.

The NAS, EAS in particular, and SAS basins are now very variable year by year: in 2017 they respectively present average water volumes of 53.5, 0.9 and 26.7 km^3 and water surfaces of 4.0, 1.0 and 3.3×10^3 km^2 ($\pm 30\%$).

Significant for the present study are some modern hydrological parameters (annual average of 2007–2012) of the Syr Darya and Amu Darya river basins given here.

Amu Darya: total surface runoff within the basin: max 97.4/min 52.8, av. 76 km^3; total irrigated area 5.09×10^6 ha; water withdrawal 72 km^3; terminal inflow 1–2 km^3.

Syr Darya: total surface runoff within the basin: max 72.5/min 18.3, av. 38 km^3; total irrigated area 3.1×10^6 ha; water withdrawal 31 km^3; terminal inflow 4–6 km^3.

As a whole, the Amu Darya has almost twice the values of the Syr Darya in terms of surface runoff, irrigated area, water withdrawal and, until 1980, of terminal inflow in the Aral Sea (in 1960, of the total 53 km^3 of river inflow into the lake, 36 km^3 came from the Amu Darya and 17 km^3 from the Syr Darya). Then, after 1980, on the account of water withdrawal, the annual terminal inflow of the two rivers decreased in different ways: the one of the Amu Darya has been almost nullified, the one of the Syr Darya was reduced to 4–5 km^3.

5.2.2 Historical Water Level Fluctuations of the Aral Sea

An unstable behavior characterized the Aral Sea throughout the Holocene. Regressions down to +24 m a.s.l. and transgressions above +55 m a.s.l. have been recorded by several authors from different disciplines: by climatologists analyzing abiotic and biotic climate and paleo-environmental proxies; by archaeologists documenting settlement patterns; and in historical sources.

Geological, climate and hydrological studies of the evolution of the Aral Sea basin during the last 2000 years have been produced by Soviet scientists such as L. Berg, A. Kes, I. Gerasimov, B. Fedorovich, E. Maev, S. Nikolaev, etc. (summarized in: Sevastyanov et al. 1991); and then have been continued by modern international specialists like P. Tarasov, P. Micklin, R. Letolle, I. Boomer, P. Sorrel, H. Oberhänsli, etc. (summarized in: Krivonogov et al. 2014).

Geomorphological data are still presenting low chronological resolution and contradictions. More robust and integrated data sets for modeling lake behavior are provided by reconstructions based on lithological, chemical and paleo-environmental analyses of proxy samples retrieved through lake coring: climate data (precipitation, seasonal evaporation and river inflow) are inferred from palynological analyses; lake water levels from analyses of abiotic (lithological and mineralogical) and biotic components (dinoflagellate cysts and diatoms) identifying salinity changes and water volumes.

In the present article the main references for paleo-climate and paleo-environmental conditions are the reports concerning the analyses of sediments from the composite core (CH2/1) retrieved in 2002 (Southern Aral Sea water level at +31 m a.s.l.) at the Chernyshov bay in the northern part of the southwestern basin (Sorrel 2006; Sorrel et al. 2006, 2007). The core is 10.79 m long with head at +9 m a.s.l. (water depth of 22 m) and base at −2 m a.s.l., representing a time span of 2000 years (Fig. 5.4).

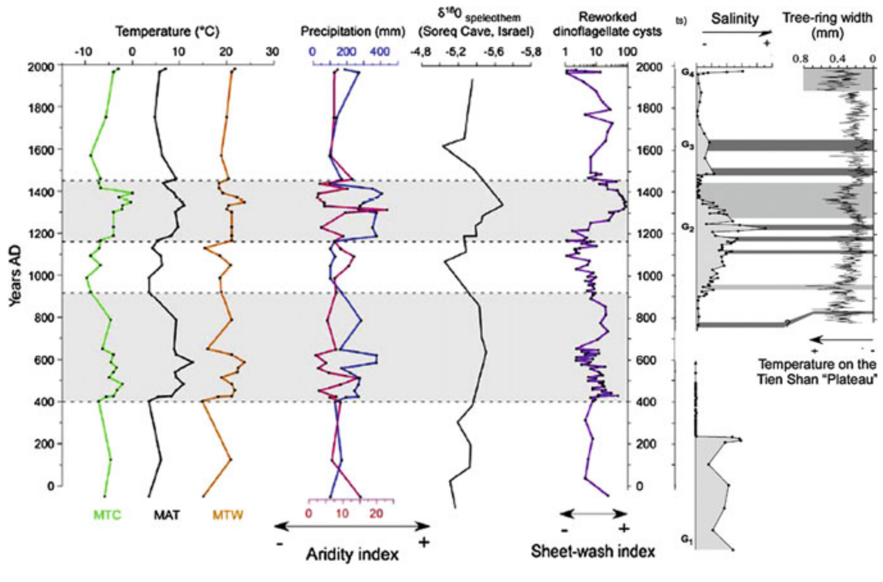

Fig. 5.4 Southern Aral-2002, Chernyshov bay, core section CH2/1: climate parameters T (MTC, MAT, MTW refer to Mean T during Coldest, Annual, and Warmest month respectively) and P, reconstructed from palynological analyses (blue line: Amaranthaceae-Chenopodiaceae; red line: Poaceae); sheet-wash index derived from relative abundance of reworked dinoflagellate cysts; salinity level estimated from relative abundance of L. machaerophorum. Grey shadings represent periods of increased T and P. Sheet-wash index directly points to water levels: low levels are documented at 2.1–0.6, 1.1–0.7, 0.6–0.4, 0.3 and 0.05–0 cal ka BP (*source* Sorrel et al. (2006, 2007). Tree ring record from Tienshan plateau (*source* Esper et al. 2002)

Archaeological surveys of monuments along the lake shore and river delta distributaries began in Soviet times with the works of S. P. Tolstov and continued after perestroika. They provide information about building and abandonment phases and, indirectly, about local paleo-hydrological conditions. Most significant has been the recent discovery of the Kerderi settlement dated to the XIII - early XIV AD, located at +34 m a.s.l. on the NE part of the Aral Sea evidencing a water level regression below +31 m a.s.l. (i.e. the water level of Aral-2002),[6] and the detection of a synchronic phase of inundation of the Sarykamysh lake (Boroffka et al. 2006; Boroffka 2010).

Accounts on the part of medieval Muslim geographers and historians are even more dramatic, quoting the disappearance of the Aral Sea at 1417 AD due to diversions in both the Amu Darya and the Syr Darya courses.[7]

Concerning the last 2000 years there is good agreement among authors in detecting four periods of relevant low lake level stands at: 0–400, 900–1230 (Medieval Warm Period), 1400–1650, and after 1960 AD. The first regression at 0–400 AD, which left peat layers at +10 m a.s.l. in the central part of the SAS lake, has been the most relevant; the second ended at 1250 AD with what seems to be an abrupt short event more extreme than modern, i.e. lake level stands below +26 m a.s.l.; and around 1400 AD the lake level dropped below +31 m a.s.l. Lesser regressions are suspected at 600 and 1800 AD. Regressions are intercalated by transgressive phases at 400–550, 650–900 and 1230–1400 AD.[8] (Boomer et al. 2009) (Fig. 5.5).

Figure 5.6 shows the tentative reconstruction of the evolution of Aral Sea water levels during the last 2000 years by synthesizing and attuning data from several sources and authors, in particular synoptic reconstructions of Aral Sea lake level changes (Boomer et al. 2009; Krivonogov et al. 2014). Lake level trends are compared with temperature and precipitation values from Sorrel et al. (2007).

T and P trends evolve in direct correlation (T amplitude between 4 and 12 °C, P between 100 and 400 mm/y) at the exception of the IX–XII and XVI–XVIII AD intervals where are diverging or converging.

Lake levels are characterized by a long regressive trend between 100 BC and 1600 AD, accompanied by fluctuations only partly correlated with climate, i.e. showing regressions in coincidence with T+P+ and transgressions with T+P−. The regressions in particular present most anomalous characters, witnessing the action of forcing factors other than climate: the strong regression culminating in 400 AD is correlated

[6]In proximity of the Kerderi settlement, satellite images show traces of a paleo-distributary of the Syr Darya delta flowing down to +30 m a.s.l., 100 km west from the shore of Aral-1960 (Krivonogov 2009).

[7]Hafızi-Abru, geographer at the Timurid court of Shah Rokh, in 1417 AD writes about the disappearance of the Aral Sea, which attributes to the diversion of both the Syr Darya and Amu Darya flow into the Caspian Sea (Tolstov 1948, 285). This account has been overseen by L.S. Berg and V. Barthold but hastily considered an overstatement (Krivonogov 2009).

[8]These transgressions are documented by the stratigraphy of shore sediments of the Karaumbet outcrop and the chronology of the Pulzhai settlement in the Aibugir Bay at the SW corner of the lake (Krivonogov et al. 2010, 560) and by the relative abundance of dinoflagellate cysts and freshwater algae from the Chernyshov Bay Core CH2/1 (Sorrel et al. 2007).

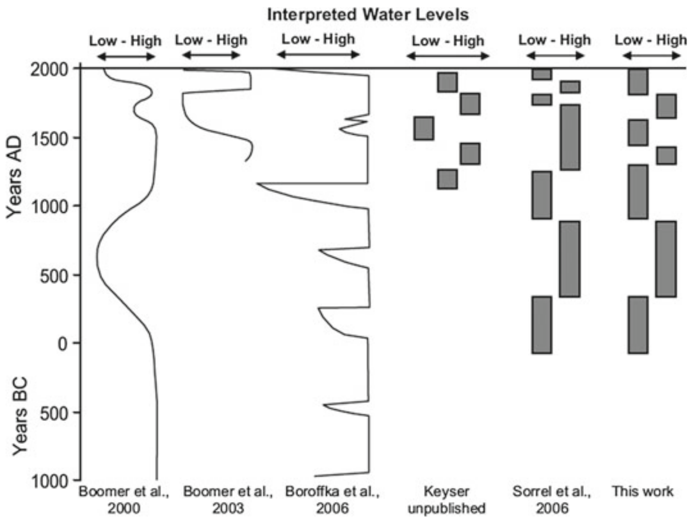

Fig. 5.5 Aral Sea: reconstructions of water level transgressions and regressions during the last 3000 years by different authors (*source* Boomer et al. 2009). The unpublished evaluation of Dietmar Keyser is based on ostracods analyses of two short cores from the Tschebas Bay (Boomer et al. 2009, 82)

with relatively stable T and P trends; the regressions of 1250 and 1300–1450 AD are anomalously related with high T and P values and remarkable by their extreme and abrupt character intercalated by relevant transgressions.

5.2.3 Causes

The above reconstruction, like any existing reconstruction of the multi-millennial behavior of the Aral Sea, is preliminary and must be continuously updated by new data. But even more controversial is the determination of the causes of the Aral Sea behavior, and of their interaction within a dynamic model, which constitutes the main subject of this article. The task is made difficult by the lack of data and by the entanglement of several events in the backdrop of the hydrology of the Aral Sea basin, in particular the complex and changeable behavior of tributary rivers exposed to transmission losses by natural and anthropogenic water subtraction.

Extreme Aral Sea regressions have been variously attributed to three different (and certainly concomitant) driving factors: climate change, river course diversion, anthropogenic water withdrawal. During the last 2000 years these three factors are most often acting together, with relative impact varying at different times. Each factor by itself may be able to induce a severe regression: annual precipitation can drop to less than 50 mm (1/3 of the average value) for prolonged periods (which mainly happens during cool phases but occasionally can coincide with rising temperature, like in 900–1200 and 1400–1550 AD), reducing the glacial and nival deposits that

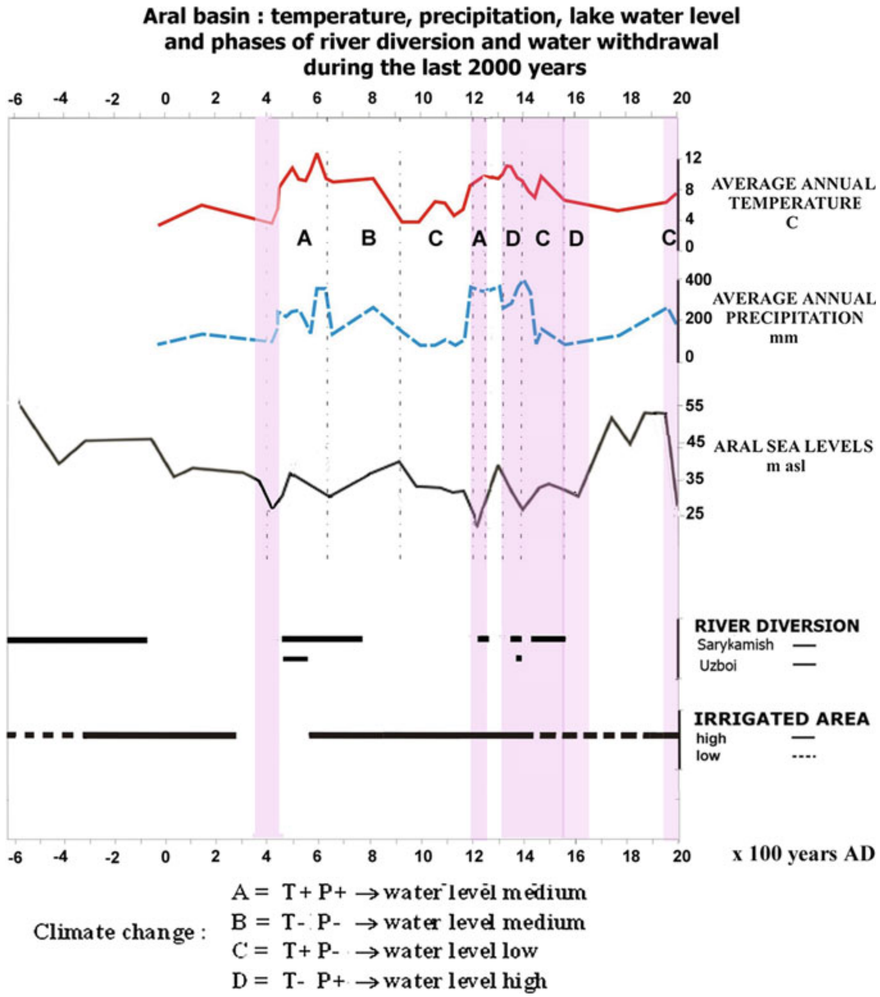

Fig. 5.6 Correlation of temperature, precipitation, lake water levels and phases of river course diversion and anthropogenic water withdrawal during the last 2600 years. A, B, C, D classify four types of climate changes and their potential impact on lake levels. Marked bands: periods of climatically anomalous water level fluctuations. T and P trends adapted from Sorrel et al. (2007); Aral Sea water levels elaborated by R. Sala by synopsis of different sources

constitute the main source of the river runoff; the diversion of the Amu Darya course can be almost total, lowering the river inflow by more than 50%, and relevant diversions probably happen also in the Syr Darya (see below Sect. 5.2); the increasing water withdrawal of the last 60 years has in itself been the determinant cause of the modern disappearance of the Aral Sea.

5.2.3.1 Climate Change to Very Arid Conditions

Climatologists and paleo-environmentalists who detected the severe Aral Sea regressions of the last 2000 years tend to underline their coincidence with negative NAO phases weakening westerly winds and precipitation (Sorrel et al. 2007; Hill 2017). Synchronous with these phases is the establishment of a series of events that all together point to global atmospheric teleconnections: palynological dry phases in the Aral Sea region at 900–1150 and 1450–1550 AD; decreasing tree ring width in the Tienshan and Pamirs ranges (sources of the almost totality of the rivers' runoff) at 1250, 1400, 1500 AD (Fig. 5.4); similar water level fluctuations in other Central Asian lakes like the Balkhash, Issykul, Bosten, etc. (Chen et al. 2008; Endo et al. 2012); and drought in the Near East.

All the above cases seem related to low P values, but the forcing effect of cold phases must be also considered. The regression of the 1450–1650 AD coincides the Little Ice Age when lower T values contributed to the decrease of river discharges in two ways: by lessening atmospheric transport and precipitation and by enhancing ice accumulation in the Tienshan and Pamir mountains (Krivonogov 2009).

5.2.3.2 River Course Diversion

Reconstructions based on archaeological studies and historical accounts tend to explain the most extreme Aral Sea regressions by a diversion at the head of the Amu Darya delta to the west through the Daudan Darya and Darialyk (Kunya Darya) channels into the Sarykamysh basin. The channel cross-section at Daudan Darya and Daryalyk could not carry more than 20–30 km^3 per year, so that the diversion of the Amu Darya flow can never be total and a residual inflow would always reach the southern part of the Aral Sea (Letolle et al. 2007).

The Sarykamysh basin covers an area of 11,000 km^2 with the potential to accommodate, between −38 and +54 m a.s.l., a max. water volume of 250 km^3 (1/4 of Aral Sea at its max capacity at +54 m a.s.l.) exposed to annual evaporation of 11 km^3. In case the Sarykamysh lake water level would grow above +54 m a.s.l., its emissary Uzboi channel would be activated towards the Caspian Sea. The annual discharge of the Uzboi channel cannot be higher than 10 km^3 so that the eventual water excess would be diverted and dissipated in the dunes of the Zaunguz desert (northern part of the Karakum desert). Besides the Amu Darya diversion, geomorphological features indicate that the Uzboi would be activated also in case the Aral Sea would enter into extreme transgressive conditions with water levels at +54–56 m a.s.l. and merge with the Sarykamysh (Tolstov and Kes 1960; Kes and Klyukanova 1999; Letolle et al. 2007).

A longstanding filling of the Sarykamysh lake and activity of the Uzboi channel is documented between 5000 and 2000 BC by the presence of numerous Neolithic sites, after which, due to the damming of the Daryalyk channel for irrigation purposes, Uzboi water regimes started decreasing and ended around IV BC. In subsequent times, except for short abrupt events that left no geological or archaeological traces,[9] the Uzboi was never reactivated and changed into a series of ponds that could host a caravan road but could not support the establishment of large agricultural settlements (Tolstov 1948, 295; Tolstov and Kes 1960).

Amu Darya diversions continued intermittently, filling incompletely the Sarykamysh lake during III–I BC, IV–VIII AD and XIV–XV AD.[10] After VIII AD the lake never reached level stands above +8 m a.s.l. (Krivonogov et al. 2014, 297), whereupon any further diversion of the Amu Darya course would have had just an abrupt and ephemeral character supporting average Sarykamysh lake stands and evaporation losses quite similar to modern.

The Amu Darya diversions of last 2000 years, which saw the anthropogenic embankment of the western distributaries of the Amu Darya delta, were necessarily related to the destruction of dams by natural hazards or wars: undocumented flash-floods or earthquakes at 1208, 1389, 1405 AD (Melville 1980), the Hephtalite Huns invasion during 380–400 AD, the Mongol invasion at 1221 AD, the Timurid wars at 1372–1388 AD.[11]

Besides the lower course of the Amu Darya, the middle and lower course of the Syr Darya are also characterized by a very unstable watershed where sedimentary and/or technogenic factors can easily induce abrupt events of water diversion (see below Sect. 5.2). In the first half of the XIV AD the Arab geographer ibn Fadl Allah al-Omari (d. 1349) heard from oral sources that the "*Seyhun (Syr Darya) flows among reeds and sands below the city of Jend (on the Janadarya) at the distance of three days travel and here it disappears*". (Barthold 1902, 55). As quoted above (note 7), also Hafizi-Abru in the early XV AD describes the Syr Darya delta (or at least its southern branches) merging with the Amu Darya, and both rivers avoiding the Aral Sea and flowing together to the Caspian Sea (Barthold 1902; Boroffka 2010). The Timurid ruler Babur (1483–1530) in his 'Memoirs' speaks about the Djihun (Syr Darya) lost in sands far away downstream from the medieval town of Turkestan (see Sect. 5.2) (Babur 1530, 45; Crétaux et al. 2009, 285).

[9]The Persian geographer Hamdallah Kazwını in 1339 mentions the Amu Darya flowing via the Uzboi to the Khazarian (Caspian) Sea (Tolstov 1948, 285); and in 1392 Zahır-ad-dın al Maraschı describes a trip taking place by ship up the Uzboi (Boroffka 2010, 292).

[10]In 1417 AD Hafızi-Abru wrote about the disappearance of the Aral Sea (see note 7). In 1558 the English merchant and traveler A. Jenkinson, while residing in Sellizure (Vazir) on the shores of the Daryalik channel, witnesses its progressive desiccation due to upstream anthropogenic implementations: "*the water that serveth all that country is drawn by ditches out of the river Oxus, unto the great destruction of the said river, for which cause it falleth not into the Caspian Sea* (in reality the Sarykamish lake) *as it hath done in times past; and in short time all that land is like to be destroyed and to become a wilderness for want of water, when the river of Oxus shall fail*" (Jenkinson 1558). Few years later, Abu al-Ghazi (1603–1663), khan of Khiva, reported that the Amu Darya was flowing to the southwest until the 1573 after which switched its course into the Aral Sea (Tolstov 1948, 285; Boroffka 2010, 293).

[11]All authors tend attributing the Amudaya diversion events of the last 2000 years to the destruction of technogenic dams built across main distributaries of the delta. Historical sources support that hypothesis (Barthold 1902). According to general Gloukhovsky (1893), between 1310 and 1575 AD the dams and irrigation systems of the Amu Darya delta were disrupted at the point of diverting its main current into the Sarykamysh depression and further, through the Uzboi channel, into the Caspian Sea (Boroffka 2010).

5.2.3.3 Anthropogenic Water Subtraction by the Agro-Irrigational Urban Complexes of the Amu Darya and Syr Darya Basins

Concerning the anthropogenic water subtraction by the medieval urban and irrigation systems of the Syr Darya and Amu Darya basins, its possible impact is evident today in the fact that water withdrawal for irrigation purposes has been by far the main cause of the present Aral Sea desiccation; and most of the authors quoted above suspect that, from the III BC to the XX AD, it has always been a concomitant factor, together with climate and river diversion, of Aral Sea water level fluctuations.[12] Referring to historical-archaeological accounts, on the lower Amu Darya the presence of large urban systems and irrigation practices have been documented initially between 300 BC and 300 AD and then again between 600 and 1300 AD. Their presence on the Syr Darya is basically ignored.

If up to now water withdrawal has not been subject of scientific investigation and quantitative evaluation, this is due to three main reasons: absence of a database of the urban systems of West Central Asia, underestimation of their size and potential environmental impact, and lack of geoarchaeological field studies needed for elaborating coefficients of past water use.

This article tries to answer those questions and confronts the problem of the interactive effect of the three casual factors spoken above on the evolution of Aral Sea water levels, focusing on the time span of the Medieval Warm period. Research methods are explained in Sect. 3, research results in Sect. 4. Eventually the quantitative evaluation of annual anthropogenic water subtraction is sorted out, allowing a preliminary reconstruction of the complex interaction of the three forcing factors in determining the Aral Sea water levels during the Medieval Warm Period (Sect. 5).

5.3 Medieval Water Withdrawal: Research Methods

The quantitative evaluation of water withdrawal by the medieval agro-irrigational urban complexes of the Syr Darya and Amu Darya basins and of its impact on Aral Sea water volumes is a difficult task, therefore the present study proceeds through average estimates and extrapolations, leading to approximate and debatable results. The method itself is original, developing through three main steps: documentation of the size of the urban systems of the Aral Sea basin during a specific period (century); elaboration of a coefficient of water use per urban hectare in a specific

[12] "However, the degree of lake level lowering may have been amplified by humans responding to changing environmental conditions. Irrigation systems were probably extended during periods of more arid conditions" (Sorrel et al. 2007). "Therefore a similar effect as the modern one, a major regression of the Aral Sea caused by man, may be presumed especially towards the end of Antiquity, when long-term results of intensive irrigation took effect" (Boroffka 2010). "Irrigation activities were at a maximum between 300 BC and AD 300 (Classical Antiquity) and between AD 800 and 1300 (Medieval Age) and after AD 1960" (Oberhänsli et al. 2007).

region; calculation of the ratio of agro-urban annual water subtraction from the virtual runoff of the Syr Darya and Amu Darya rivers during the chosen period.

Modeling starts analyzing the agro-urban complexes of the Syr Darya basin (Sects. 4.1–4.3) and sorts out hydraulic coefficients concerning the region. Such coefficients are then extrapolated to the Amu Darya region, allowing the evaluation of the total impact of irrigational water withdrawal in the entire Aral Sea basin (Sect. 4.4). In Sect. 5 the insertion of those data within a simplified model of the Aral Sea bathimetry and water balance provides the evaluation of the Aral Sea water levels under two different scenarios, i.e. two different values of terminal river inflow, in absence or in presence of river diversion. In detail:

a. **Documentation of all the walled units of the urban systems of the Syr Darya basin**, with particular focus on their geographical location, size in hectares and chronological attribution of their occupation by century.

The database of these monuments has been elaborated by the Laboratory of Geoarchaeology of Almaty during several research seasons. It includes all the walled towns (and a few very large and visible villages) of the Syr Darya river valley, recorded in archaeological reports and in the *Svod Pamiadnikov Istorii i kulturi Respubliki Kazakhstan.*[13] Small unwalled villages are omitted, by being in general badly explored, most often undetectable, and in any case covering a relatively small total area heterogeneously in different urban regions.

b. **Selection of a particular historical period and of a particular urban region** for documenting the irrigation schemes (general structure, length and profile of canal distributaries) active in that region during that period.

As *historical period*, for this study has been selected the X century AD, due to four convenient characters: (1) it is included within the recession phase of the IX-XII AD, which ends with the extreme low water stand of the early XIII AD; (2) its climate has been evaluated as similar to modern, though slightly cooler and drier,[14] suggesting an estimate of precipitation and evaporation rates and virtual river runoff in the Aral Sea basin as 10% less than in modern times, i.e. 104 km^3, 33 km^3 in the Syr Darya basin and 71 km^3 in the Amu Darya[15]; (3) in the X AD, historical records quote the Aral Sea as receiving the entire discharge of the Amu Darya river,

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[13] A large part of the urban units has also been documented by aerial photography and explored by land surveys for filling entries of environmental character. A few tens of urban structures have been discovered anew.

[14] The Sorrel reconstruction of Fig. 5.4 infers for the start of X AD average temperature values 3 °C cooler and annual precipitation 40 mm lesser than modern, and T and P rising to modern conditions by the end of the century and during the following XI and XII centuries. The time span falls within the so-called Medieval Warm Period, which apparently in Central Asia has not been exceptionally warm.

[15] Together with values of virtual river runoff, also values of terminal river inflow into the Aral Sea would be decreased by 10%. This is in agreement with measurements and dating (by archaeological findings and few radiocarbon analyses) of re-deepened river channels in the foothill zone, implemented in Soviet times by E. D. Mamedov and G. N. Trofimov, suggesting for the XI AD a total terminal river inflow in the Aral Sea of 49–50 km^3 increasing in the following century to modern

which excludes anomalies attributable to Amu Darya course diversion and allows inferences about diversions of the Syr Darya course; (4) and, most importantly, the X AD corresponds to the peak of urbanization in West Central Asia, which shows a plateau of homogeneous total urban area between the VI and XII AD.

As *study polygon* for hydraulic analyses has been selected the Otrar oasis, located on the Arys delta at its confluence with the middle Syr Darya (Fig. 5.10), for several reasons: its monumental heritage has been object of several decades of archaeological study and chronological attribution; the oasis shows evidence of six generations of clearly detectable irrigation schemes; and its environment has been object of palynological analyses and paleoclimate reconstruction.

c. **Structural analysis of a significant irrigation scheme**, evaluation of the total volume of annual water withdrawal through the use of specific agro-hydraulic models, and calculation of the coefficient of annual water use by occupied urban hectare.

The hydraulic system under study, the Altyn irrigation scheme of the X–XIII AD, runs in the central part of the Otrar oasis and has been analyzed in the context of the project INTAS/2002-2005. The canals' length, bed width, side slope, bed slope and berm width have been measured in order to reconstruct trapezoidal canal cross sections and calculate their carrying capacity. These data have been simulated into a hydraulic model using the US Corps of Engineers River Analysis System software HEC-RAS 2009. CROPWAT software (UN-FAO) provided additional estimates of water requirements in mm/day based on consideration of crop type, effective rainfall and soil moisture deficit (Clarke et al. 2010).

d. **Extrapolation of the Otrar water use coefficient to the whole agro-urban systems of the Syr Darya**, resulting in the evaluation of the total volume of annual water withdrawal from the entire Syr Darya river basin.
e. **Evaluation the virtual river runoff of the Syr Darya during the chosen period** on the basis of the climate esteems quoted at Sect. 3b, and calculation of the ratio of water withdrawal versus water runoff.
f. **Extrapolation of the ratio of water withdrawal calculated for the Syr Darya to the water runoff of the Amu Darya basin**, and evaluation of the total volume of water withdrawal and residual runoff of both rivers.

The resulting values of water withdrawal are valid without significant error for the X–XII AD. In fact the period under study is the X AD, the total area of the Syr Darya settlements between VI and XII AD is stable (±3.6%) (Fig. 5.8), and the Otrar Altyn irrigation scheme chosen for sorting out hydraulic coefficients has been active from X to XIII AD.[16]

regimes of 56.9 km^3 (Trofimov 2003, Table 3). As a whole, these esteems point for the X–XII AD to an arid climate supporting nival-ice deposits and river discharges slightly lower than modern.

[16]The values of medieval urbanization and correspondent water withdrawal given for the X–XII AD start decreasing only from XIII AD when West Central Asia, following the Mongol invasion, entered a period of pastoralist conversion reducing agricultural activities and a longstanding cooling climate phase lessening water requirements.

By tendency the above procedure underestimates the resulting amounts of water withdrawal: on one hand they are lowered by the discounting of unwalled villages and still undiscovered urban units, and on the other by the extrapolation of values calculated for the Syr Darya to the Amu Darya basin which, being more arid and historically more crowded, would better hold higher coefficients.

5.4 Medieval Water Withdrawal: Research Results

5.4.1 The Urban Complexes of the Syr Darya Basin

The urban system of the Syr Darya basin as a whole develops from the VI to the XX AD (Fig. 5.7) and blossoms during the VI–XII AD. The X AD represents the urbanization peak with around 400 occupied walled towns covering, together with an additional 25% of large unfortified villages, a *total urban area of 2350 ha* (Figs. 5.7 and 5.8).

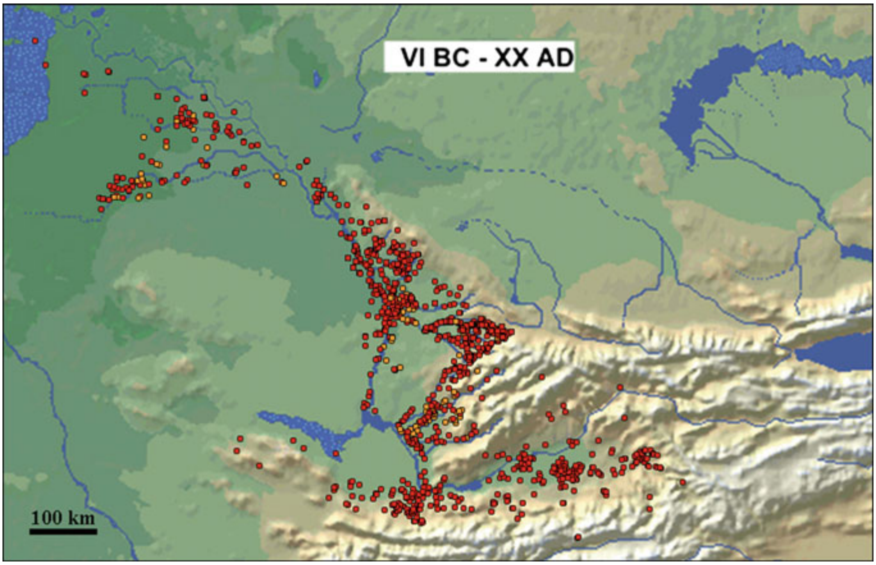

Fig. 5.7 Total urban units in the Syr Darya basin from VI BC to XIX AD. More than 1050 walled towns have been documented, covering altogether around 3500 ha. Red dots = settlement units. Settlements built after the XIX AD are not included

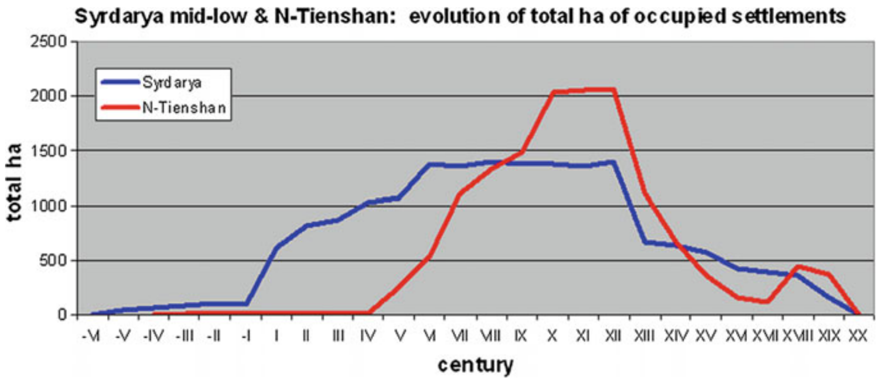

Fig. 5.8 Evolution of occupied urban area (ha) of walled towns in the middle-low Syr Darya basin (Fergana not included) and in N-Tienshan piedmonts from VI BC to XIX AD. Settlements built after the XIX AD are not included

5.4.2 *Coefficient of Water Use in the Otrar Oasis in X–XII AD*

In the X-XII AD, the central part of the Otrar oasis, covering an area of 15 × 15 km (Figs. 5.9 and 5.10), hosts 12 occupied walled towns totaling an urban area 46.76 ha and watered by a third generation irrigation system, the Altyn scheme, that had been operational during X–XIII AD. By measuring the carrying capacity of the canals' network and the seasonal needs of cultivated crops, "*we calculated peak irrigation water requirements as 7.64 mm/day, equivalent to a continuous canal flow of 0.88 l/s for each hectare of crop at the peak of the growing season*" (Clarke et al. 2010). This corresponds to an annual water subtraction of 0.24 km^3 and a *coefficient of annual water use of 0.0051* km^3 *per urban ha*.[17]

5.4.3 *Annual Water Withdrawal in the Syr Darya Basin During the X-XII AD*

Volumes. The coefficient of water use of central Otrar, when extrapolated to the 2350 ha of the entire urban system of the Syr Darya during X AD, corresponds to an *annual water withdrawal in the Syr Darya basin of* $0.005 \times 2350\ km^3 = 11.9\ km^3$.[18]

[17]The coefficient of water use could be calculated referring to values other than urban hectares, like irrigated ha or number of inhabitants, which are less convenient objects because of difficult or indirect recognition. Anyhow, these three objects can be put in correspondence: geo-archaeological considerations suggest that, in medieval urban complexes, 1 urban ha averagely corresponds to 400 inhabitants and to 161.63 ha of irrigated agriculture (Clarke et al. 2010).

[18]In Medieval times, this amount of water withdrawal from the Syr Darya basin would correspond to an irrigated area of 0.4×10^6 ha. For irrigating the same agricultural area, the modern surface basin-irrigation systems of the Syr Darya region, thanks to the implementation of sealed canals,

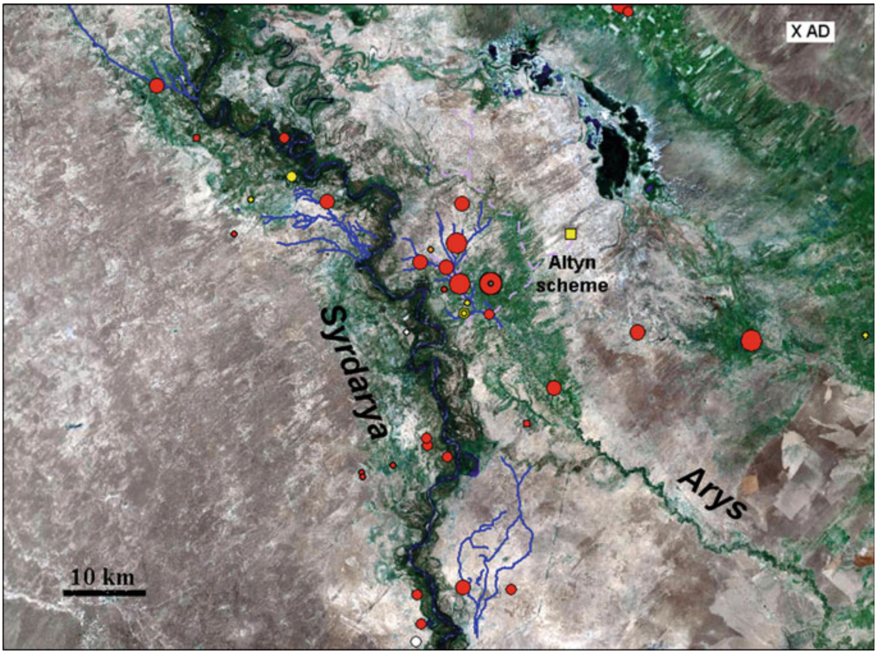

Fig. 5.9 Otrar oasis during the X century AD. Dots = settlements: red = occupied; yellow = newly built after the start of the century; white = just abandoned before the start of the century. Dots' size is proportional to the areal dimension of the urban unit. Blue lines = canals of the Altyn irrigation scheme (center) and, south and northwest of it, of its contemporary Shubara and Ak-Aryk schemes

Ratios. Supposing for the X–XII AD climatic conditions slightly cooler and drier than modern and virtual river regimes 10% lower, the virtual annual surface runoff of the Syr Darya basin would be 33 km^3 (see Sect. 3b), of which the *annual water withdrawal of 11.9* km^3 *represents the* $11.9 \times 100 : 33 = 36.0\%$.

5.4.4 Total Annual Water Withdrawal in the Syr Darya and Amu Darya Basins During X–XII AD

Currently, a complete data base of the medieval settlements of the Amu Darya basin is not available. In order to evaluate the anthropogenic water withdrawal within this basin, the same ratio of water subtraction calculated for the Syr Darya has been applied to the virtual surface runoff of the Amu Darya (71 km^3; see Sect. 2b), resulting in an *annual water withdrawal from the Amu Darya basinof* $36.0\% \times 71 = 25.5$ km^3.

water drainage and return flow, would use only half of the water volume calculated here for Medieval times.

Therefore, during the X AD the *total annual water withdrawal from the entire Aral Sea basin (Syr Darya+Amu Darya) would be 11.9+25.5=37.4 km³*.[19]

A water withdrawal of 37.4 km^3 represents around 1/3 of the total runoff of the two rivers (104 km^3), leaving a total residual river flow of 66.6 km^3, 45.5 km^3 in the Amu Darya and 21.1 km^3 in the Syr Darya. And it corresponds to around half of its value in the 1960,[20] the year that saw the last modern high stand of the lake (+53 m a.s.l.) before the following catastrophic recession.

5.5 Discussion

5.5.1 Controlling Factors of the Aral Sea Water Balance During X-XII AD

The water mass balance equation of the Aral Sea, which is deprived of emissary, is a function of few hydrological variables characteristic of the lake, expressed in water volumes (km^3/year):

$$\mathbf{f}_0:\ dV/dt = R_t(v_t - d_t - a_t) + P_t + G_t - E_t$$

where V = lake water volume, t = time, R = river inflow, P = local precipitation, G = groundwater-infiltration balance, E = local evaporation. R is function of virtual runoff (v), river course diversion (d) and anthropogenic annual water withdrawal (a). P, E and v depend strictly on climate. The equilibrium state, where the lake hydrological system is uniform throughout, corresponds to dV/dt=0.

For example, the water balance equation of Aral-1960 is:

$$\mathbf{f}_1:\ \mathbf{Aral-1960}\quad R[v(114) - d(0) - a(61)] + P(9) + G(1) - E(63) = 0\ \text{km}^3/\text{year}$$

Let's work out the water balance equation of the Aral Sea at X AD (Aral-1000) in two steps, under two scenarios.

[19]In Medieval times, this amount of water withdrawal from both the Syr Darya and Amu Darya basins would correspond to an irrigated area of 1.15×10^6 ha (see note 17), against the 10×10^6 ha of the modern land under irrigation. During Classical Antiquity (IV BC–IV AD), according to Tolstov and Andrianov (1968) and Gerasimov (1978), the network of canals detected in just the Amu Darya basin would 'allow' to irrigate more than 5×10^6 ha (Oberhänsli et al. 2007, 177). In fact, the actual extent of yearly irrigated area was most probably 3–4 times lower (Tolstov 1948) and submitted to fallow cycles longer than modern, in that way approximating the evaluation of irrigated land given above for the entire Aral basin during medieval times.

[20]This double modern value of water withdrawal matches the fact that by 1960 the Soviet regime quadrupled the former medieval irrigated area of the Aral Sea basin from 1.2 to 4.7 million ha, introducing in the same time technical advances as sealed canals, drainage and return flow that improved the performance of the irrigation systems and halved the water requirements per ha.

The two scenarios are similar in supposing the same climate and the same amount of water withdrawal as evaluated above. Climate conditions are slightly more arid than modern,[21] so that precipitation and evaporation rates in/from the lake and run-off values within the basin are evaluated as 10% lower than modern (Sect. 3b). The value of annual anthropogenic water withdrawal (a) is 37.4 km^3, as calculated in Sect. 4.4. The two scenarios differ on values of terminal river inflow R, in absence or in presence of water subtraction by river course diversion.

a. The **first scenario** considers the terminal river inflow as the residual flow of Sect. 4.4: $R = v(104) - a(37.4) = 66.6$ km^3 (45.5 from the Amu Darya and 21.1 from the Syr Darya), i.e. without additional water subtraction by river diversion, i.e. $d(0)$.

A river inflow of 66.6 km^3 corresponds to hydrological parameters of Aral-1000 higher than today, at the top of the lake's bathymetric capacity: water volumes above 1100 km^3, water surface of 75600 km^2, local evaporation volumes 75.6 km^3, local precipitation 8 km^3, and lake level at +55 m a.s.l. Under this scenario the resulting water balance equation for Aral-1000 would be the following:

$$\mathbf{f}_2: \ \mathbf{Aral-1000(1)} \quad R[v(104) - d(0) - a(37.4)] + P(8) + G(1) - E(75.6) = 0\ \mathrm{km}^3/\mathrm{year}$$

The hydrological parameters related to this first scenario (a river inflow of 66.6 km^3) are in disagreement with the values suggested for the same period by the paleo-environmental reconstructions quoted above: physico-chemical analyses of lake cores indicate for Aral-1000 higher salinity levels and lower water volumes than for Aral-1960 (see Sect. 2.2, Figs. 5.4 and 5.5); and geomorphological surveys of relict channels suggest a much lower inflow of 49 km^3 (see note 16).

b. The **second scenario** considers a river inflow into the Aral Sea of 49 km^3 in agreement with the estimations of river inflow and lake water volumes suggested by paleo-environmental studies. A river inflow of 49 km^3 would correspond to lake water volumes of 820 km^3, water surface of 57,000 km^2, local evaporation volumes of 58 km^3, local precipitation of 7 km^3, and lake-water level at +49 m a.s.l.

But in order that $R = f\ (v - d - a) = 49$ km^3, with values of climate (virtual river runoff) and anthropogenic water withdrawal set as the preconditions spoken above [$v(104)$ and $a(37.4)$], an additional $(104 - 37.4 - 49) = 17.6$ km^3 of water subtraction must be attributed to a still undetected event of river diversion: $d(17.6)$.

$$\mathbf{f}_3: \quad \mathbf{Aral-1000(2)} \quad R[v(104) - d(\mathbf{17.6}) - a(37.4)] + P(7) + G(1) - E(58) = 0\ \mathrm{km}^3/\mathrm{year}$$

[21] For the start of X AD have been evaluated annual temperature values 3 °C cooler and precipitation 40 mm lower than modern, and T and P trends rising to modern values by the end of the century (see Sect. 1.1, Fig. 5.4, note 14).

Being excluded switches of Amu Darya course (see Sect. 2.3.2), the additional water subtraction of 17.6 km^3 must be attributed to some still undetected transmission losses along the poorly explored course of the Syr Darya river.

When analyzing this possibility, it has been noticed that the Syr Darya has hydrological parameters averaging half of the values of the Amu Darya but at the same time a much more meandering and undefined course, "*frequently changing its bed, forming channels that often lose themselves in the sands, and overflowing its low banks at flood*",[22] ending up in constituting a deltaic floodplain one-and-half times wider and potentially exposed to higher transport losses. Have also been found archaeological data and historical accounts (quoted in Sect. 5.2) testifying the occurrence of medieval switches of the Syr Darya course relevant enough to divert the quasi totality of the 21.1 km^3 residual flow of the river, matching in that way the hydrological scenario inferred by geo-environmental reconstructions and described by the water balance equation $\boldsymbol{f}_3$.

5.5.2 Water Diversion Events Along the Syr Darya Course

Significant events of water diversion from the middle and low Syr Darya course during antiquity and, specifically, during medieval times are documented by geological studies, archaeological data, and historical accounts.

Concerning *geological studies*, the susceptibility of the Syr Darya to switches of river course into paleo-beds ending in neighboring depressions to now has been underestimated. Most exposed to diversions are four points of the middle-low course:

- The first diversion occurs from the left bank at the exit of the Fergana valley, feeding the Arnasay lowland and, today, the man-made Aydar-Arnasay lake. It has become very relevant only in the last few decades after been enhanced by Soviet technogenic implementations.[23]
- The second occurs from the left bank of the Chardara river segment towards the sand dunes of the Kyzylkum desert where a relict delta 100 km long with front 60 km wide is detectable. This diversion happened during the period under consideration at a scale that seems to be of medium size.[24]

[22] See: *Syr Darya*, Encyclopedia Britannica 2011.

[23] The Arnasay lowland, formerly a dry salt pan and ephemeral lake (Tokzan lake), in the 60ies started to be used as a flood control basin and grew into a lake with water surface of 3000 km^2 and water volume of 44 km^3 (Aydar-Arnasay lake system). In that way an 'unintentional byproduct of Soviet planning', by subtracting annually 10% of the Syr Darya water flow (3 km^3), became one of the main causes of the subsequent shrinking of the Aral Sea. As a whole, the total water surface of useless Soviet evaporation basins amounts to 10,000 km^2 (Ashirbekov and Zonn 2003, 16). Today, in spite of the fact that only 500 families inhabit the Aydar-Arnasay region, the restoration of the former hydrological conditions is impeded by transboundary water conflicts.

[24] Today the areas paralleling the left bank of the Chardara river segment are concerned by seasonal floods totally harvested within irrigation schemes, so that the Chardara paleodelta itself is almost desiccated. This was not the case between the IX and XII AD when some of its distributaries were

- The third, just at the head of the delta at +154 m a.s.l., is the right bank diversion of the Telikol channel that during the period under consideration, after running northward for 100 km, could have flooded the Daryalyk plain and the Ashikol depression located between the Syr Darya course in the south and the Ulytau mountains in the north, forming the so-called Telikol (or Gorguz) lake (Fig. 5.10).

Fig. 5.10 Main diversions of river courses in the Aral Sea basin. The Syr Darya course presents four main points of diversion, from SE to NW: Aydar-Arnasay, Chardara, Chiili, Zhanadarya. Most of these points correspond to large historical and modern irrigation oases fed by catching floodwaters (flood-basin irrigation schemes). The Telikol (Gorguz) lake was apparently covering the Daryalik plain and Ashikol depression. White dot and arrow: point and direction of river course diversion. Background: Bing satellite image, year 2000

surely active, as witnessed by the chronology of the ruins of 6 large villages aligned along the Josely paleochannel (Asylbekov et al. 1994).

- The fourth and only diversion event clearly quoted by historical accounts (note 12) and considered by some authors (Barthold 1902; Boroffka 2010) is the diversion of the Zhanadarya delta distributary into the sands of the Kyzylkum desert. The event occurred together with the reactivation and re-colonization between XII and XVI AD of the formerly dry Zhanadarya course (Fig. 5.12) and is not related to the period under study.

Most significant for the present discussion is the Telikol diversion, due to its chronology, size and location. The Telikol is today an artificial canal, but the existence of a past natural diversion is evidenced by relict paleo-distributaries 100–200 m wide diverging at Chiili from the Syr Darya right bank to the north for 100 km until merging with the Sarysu and Chu river deltas. From there a multi-channel river course established a large lacustrine system in the Daryalyk plain and the Ashikol depression, and then flowed out to the west until merging with the terminal segment of the northernmost distributary of the Syr Darya delta. "*Finally, a curious observation comes from the Memoirs of Sultan Babur (Babur 1530), a solid diary of events in Central Asia at that time, who wrote "in my time, Djihun (Syr) was lost far away in the sands". This would imply that at least a good part of the Syr water did not fetch the Aral. In fact, at the NW of Kzyl Orda, exists a large area of about 50,000 km^2 covered with gypsum and lake sediments, at the past junction of Syr Darya and the Chu river (these lakes are shown on nineteenth century maps), which could have evaporated most of the Syr Darya water. This does not seem to have been investigated in detail, and could have consequences on reconstructions of the past of Aral Sea*." (Cretaux et al. 2009, 285).

Given the geomorphological characters of the plain, the Telikol water basin could only have been a system of lakelets, brackish ponds and evaporation flat and salt playas occasionally gathering into large basins, functionally similar to the Sarykamysh, shallower but much larger by size and evaporation potential.[25] Geological studies concerning the region are scanty and up to now the full extent of the Telikol diversion and lake have not been geologically documented and chronologically attributed.

Better grounded are *archaeological data*. The head of the Syr Darya delta during the VIII-X AD sees the sudden development of the Chiili oasis, with the building of 13 walled towns[26] and a large agro-irrigational system covering around 44,000 ha

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[25]The Syr Darya course diversion into the Daryalyk plain would have surely caused, if not a large lake, in any case high transmission losses, which "*are relatively low when flow is confined to the primary channels, but increase at higher stages as lesser channels and the floodplain are activated…exacerbated here by the exceptionally long distance and unusual multichannel form of the channel/floodplain system*" (Knighton 1994, pp. 137–142).

[26]The medieval walled towns of the Chiili oasis are in number of 13 and cover all together an area of 44 ha. Signak, the largest (26 ha), is dated to the VI–XIX AD, 3 other towns to the VIII–XII AD, and 8 to the X–XIV AD. Eight additional large villages covering together around 10 ha appeared between the XIV–XVI AD. The Telikol channel has surely been active from the VIII until the XII–XIV AD, after which is documented an enhance regime of the Zhanadarya distributary and of the main course of the Syr Darya delta (Kerderi branch) in the context of low lake level stands (Krivonogov 2009).

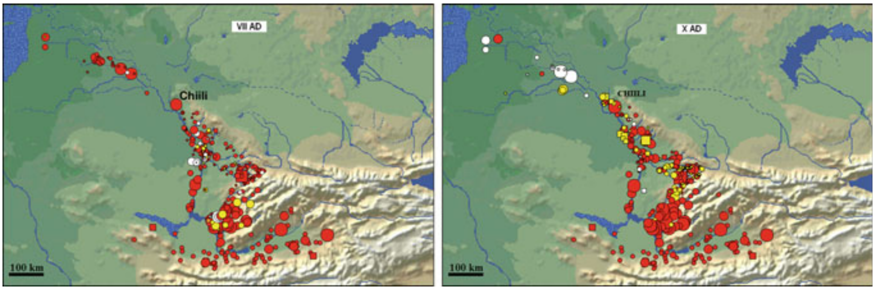

Fig. 5.11 Walled towns along the Syr Darya during VII (left) and X (right) AD. Dots = towns: red = occupied; yellow = newly built after the start of the century; white = just abandoned before the start of the century

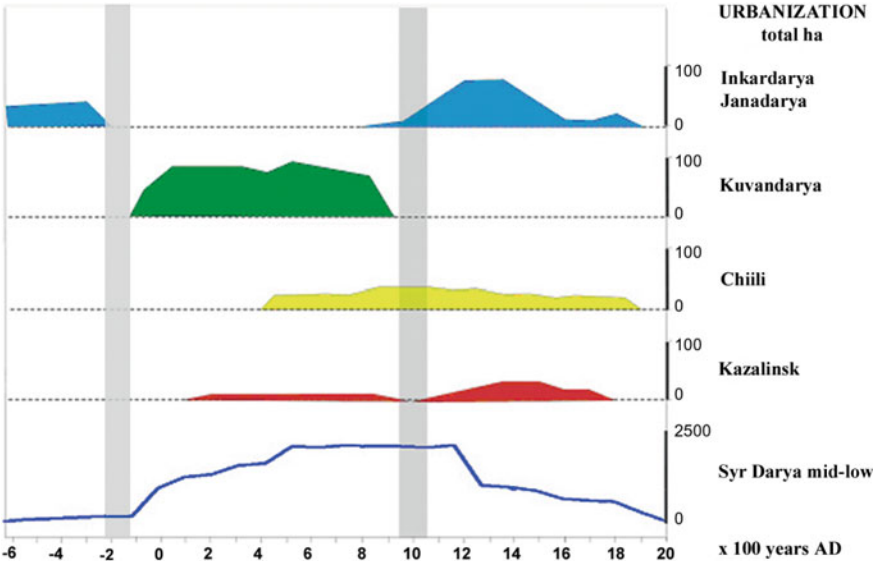

Fig. 5.12 Phases of urbanization along different distributaries of the Syr Darya delta. Two discontinuities in the urban development are detected at II BC and X AD (grey bands), both accompanied by drying delta distributaries and peaking upstream urban development (*source* Sala 2012)

along the Telikol paleo-distributary and its diverging branches. Synchronous with the urban development of the Chiili oasis is the progressive abandonment between the VIII and X AD of the agro-urban structures of the lower Syr Darya delta,[27] apparently as result of critical upstream water subtraction along the mid-Syr Darya course (Figs. 5.11 and 5.12).

[27]This process of urban contraction represents the last phase of the longstanding Jety-Asar culture established in the II century BC along the Kuvandarya delta distributary.

Referring to *historical accounts*, the existence of a very large lake called Gorguz in what seems corresponding to the Daryalyk plain is quoted in the "*Kitab Nuzhat al-Mushtaq*" ('Book of pleasant journeys') of the medieval Muslim geographer Muhammad Al-Idrisi (1100–1165 AD): "*the Gorguz lake…bigger than the Aral Sea.…similar to an ocean*".[28] Even the words of the Timurid ruler Babur quoted in Sects. 2.3.2 and 5.2 could refer to the Telikol diversion (Babur 1530, 45).

The presence of a lake (or of a system of lakes) named Telikol in correspondence of the Daryalyk plain and Ashikol depression still figures in several maps of the XVIII–XIX centuries (Schraembl 1792; Pansner 1816; Von Humbold 1843).

Among the modern specialists supporting the establishment of a large lake in that region during medieval times are counted the English orientalist Miller (1926) and the Soviet ethnographer Vaynberg (1999). B. Vaynberg, who during the 40ies and 50ies was member of the Tolstov's multidisciplinary expeditions involved in the ethno-archaeological study of the ancient civilizations of the Amu Darya and Syr Darya deltas, says: "*To the east of Kzyl-Orda there is an extensive takyr plain (Daryalyk-takyr) where, apparently, in antiquity and perhaps in the Middle Ages, there was a lake into which flowed the Sarysu and Chu rivers and part of the Syr Darya runoff. It is possible that this was the same lake marked on ancient and medieval Chinese maps and mentioned by medieval Muslim travelers (Bichurin 1851, tome III, annexes; Agadzhanov 1969, p. 65 and further). The Inkardarya and the ancient Janadarya courses, which have origin at the south of this region, did not flow into this lake, but undoubtedly into the Daryalyk-takyr "poured" a number of right bank paleo-distributaries clearly discernible in the Chiili region and dated by archaeological material from the early Iron Age to the Middle Ages*." (Vaynberg 1999, pp. 52–57).

The Telikol diversion and the flooding of the Daryalyk-Ashikol evaporation basin could have subtracted, for few centuries around the turn of the I millennium, a large part (17.6 km^3) of the residual river stock of the Syr Darya (21.1 km^3), in agreement with the evaluated total annual river inflow into the Aral Sea of 49 km^3 (3.5 km^3 from the Syr Darya and 46.5 km^3 from the Amu Darya).

The "*Telikol hypothesis*" is certainly debatable but does raise a new significant factor in the complex puzzle of the Aral Sea water levels: diversions of river course along the middle-low Syr Darya. In particular, it introduces a diversion event that during X–XII AD put in correspondence the evaluation of the anthropogenic water withdrawal of 36.54 km^3 as calculated in Sect. 4.4 with the Aral Sea terminal river inflow of 49 km^3 and water level at +49 m a.s.l. inferred by paleo-environmental analyses (Sect. 2.2 and note 16).

[28] Such quotation has been resumed by two subsequent Muslim geographers, Ibn Kaldun (1332–1406) and Ibn Iyas (1448–1522). Ibn Kaldun is adding that the lake is fed from the north by "*several streams originating from the Mrgar mountains*" (Ulytau mountains?) (Agadjanov 1969, 70).

5.6 Conclusions

As conclusion it must to be admitted that, in modeling the interaction of the driving factors of the hydrological parameters of an internally draining basin located in an arid zone, the main difficulty encountered is that here rivers are flowing in wide flat floodplains with discharges decreasing significantly downstream with high annual and centennial anomalies, so that the "*…modeling of flow regimes requires data on the spatial and temporal distribution of* (natural and anthropogenic) *transmission losses…due to infiltration to channel store and/or floodplain soils, evapotranspiration, and ponding in terminal storages, such as ephemeral pools, channels and other wetlands…*" (Costelloe et al. 2003).

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