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Review paper

History of Aral Sea level variability and current scientific debates

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ABSTRACT

The Aral Sea has shrunk drastically over the past 50 years, largely due to water abstraction from the Amu Darya and Syr Darya rivers for land irrigation. Over a longer timescale, Holocene palaeolimnological reconstruction of variability in water levels of the Aral Sea since 11,700 BP indicates a long history of alternating phases of regression and transgression, which have been attributed variously to climate, tectonic and anthropogenic forcing. The hydrological history of the Aral Sea has been investigated by application of a variety of scientific approaches, including archaeology, palaeolimnological palaeoclimate reconstruction, geophysics, sedimentology, and more recently, space science. Many issues concerning lake level variability over the Holocene and more recent timescales, and the processes that drive the changes, are still a matter for active debate. Our aim in this article is to review the current debates regarding key issues surrounding the causes and magnitude of Aral Sea level variability on a variety of timescales from months to thousands of years. Many researchers have shown that the main driving force of Aral Sea regressions and transgressions is climate change, while other authors have argued that anthropogenic forcing is the main cause of Aral Sea water level variations over the Holocene. Particular emphasis is made on contributions from satellite remote sensing data in order to improve our understanding of the influence of groundwater on the current hydrological water budget of the Aral Sea since 2005. Over this period of time, water balance computation has been performed and has shown that the underground water inflow to the Aral Sea is close to zero with an uncertainty of 3 km^3/year.

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1. Introduction

The Aral Sea is a closed lake located in an active graben structure in Central Asia to the south of the Ural Mountains, between the Usturt Plateau to the West, the Karakum Desert to the South, and the Kyzyl Kum Desert to the East (Fig. 1B). Two main rivers feed it: the Syr Darya and the Amu Darya that together represented almost 80% of the total inflow to the Aral Sea in the first half of the 20th century. The climate of the Aral Sea basin, which encompasses more than 2 million km^2, is of arid/semi-arid type and characterised by instability over various timescales ranging from years to millennia. The Aral Sea

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was not always a terminal lake (Létolle and Mainguet, 1997) as since the last glaciation it has changed from an exorheic to an endorheic state. During the Holocene the Aral Sea underwent several phases of regressions and transgressions, the latest being the contemporary shrinkage starting in the mid 20th century. At that time, it was the fourth largest lake in the world, while today it is divided into four small water bodies with a water level decline of about 25 m since 1960 (Kouraev et al., 2009).

The limnological and geomorphological history of the Aral Sea before the 20th century is for the most part detailed in Russian literature, and was, until the beginning of the 21st century poorly referenced with respect to the dozens of articles relating to the last Aral Sea dessication that started in 1960. To reconstruct the hydrology of the former Aral Sea until now, several sources of information may now be used: geomorphological and sediment analysis of lake terraces and shorelines; palaeolimnological reconstruction of past environmental and climate changes from analysis of lake sediment cores; and analysis of the distribution of archaeological settlements and measurements on crustal vertical deformations (Boomer et al., 2009; Micklin, 2010). For the Holocene period, accurate information was gained by Russian scientists to elaborate a scenario of the history of Aral Sea hydrology that was derived from a 3.5 metre core extracted from the centre of the Aral Sea, North West of Vozrojdenia Island (Fig. 1A). Radiocarbon dating allowed dating the bottom of the core to an approximate age of 11,000 +/− 1000 BP (Rubanov, 1982; reported in Létolle and Mainguet, 1997). From absence of Gypsum at early Holocene it was shown that the Aral Sea was exorheic at that time, and from further successive layers of gypsum or mirabilite deposits observed in this core, a first dating of episodes of high and low lake-level stands until recent times was performed. It was completed by several studies on the ancient terraces of the Aral Sea's western shoreline (Snitnikov, 1983; reported in Boomer et al., 2000) that allowed a description of the different phases of the lake over late Pleistocene and Holocene. Interpretation of Aral Sea hydrology over this long period was generally attributed to natural causes until 4000 BP, and then mainly to anthropogenic origins: irrigation, devastation of infrastructure, and diversion of the rivers (Létolle and Mainguet, 1997). Research on Aral Sea palaeolimnology severely declined after the collapse of the Soviet Union in 1991.

In 2002, an expedition of several scientists from different countries, using the framework of the CLIMAN project, was carried out in the North West of Large Aral, and two sediment cores were extracted providing information over the last two millennia. The scientists who participated in the project describe a different scenario of Aral Sea history for at least the last 5000 years. The dating of phases of regressions and transgressions and the causes of this variability conflicted with previous studies.

The CLIMAN project also involved archaeologists, climatologists, and historians who completed and sometimes contradicted the main results derived from the core sediment analysis. We will detail in the next sections the controversy deriving from these recent studies.

In Section 2 we will describe the history of the Aral Sea over the Holocene with emphasis on the different results and interpretations made in the literature. We will separate the Holocene into two main periods of time, from the late Pleistocene to the end of the Lavlakian period (5000 BP) during which the Aral Sea became an endorheic lake (Section 2.1), and then up to the modern Aral Sea crisis in 1960 (Section 2.2). For the first period of time we will describe the Aral Sea evolution including a brief overview of the history of the rivers and insight into the debate on the maximum lake level ever reached. For the second period, we will highlight the recent controversy on the causes of Aral Sea level evolution.

In Section 3 we come to the last regression, more commonly known as the modern crisis of the Aral Sea, and will present different results obtained by several authors regarding one of the new scientific debates concerning the existence of significant underground water that has the potential to counterbalance Aral Sea shrinkage. We will demonstrate that current satellite remote sensing instruments can provide very accurate data to calculate the water balance of the Aral Sea over a timescale ranging from years to decades.

One objective of this study is to stimulate the various discussions on Aral Sea hydrology over time, considering that a very accurate assessment of water balance for the present-day, inferred from a combination of remote sensing and in situ data analysis, could open or re-open questions about the history of Aral Sea evolution in terms of water resources. Recent scientific studies on the relative impact of climate change and irrigation since 1960, during which the last regression was very intense, also provide important new findings regarding this issue over the past 2000 years.

2. History of the Aral Sea over the Holocene[1] period

2.1. How the Aral Sea became an endorheic lake; insight into history of the Central Asian rivers after the Last Glacial Maximum (LGM)

Aral Sea level variations are strongly dependent on river inflow, which varied greatly in the past (Létolle and Mainguet, 1993; Boomer et al., 2000) and is therefore fundamental when investigating the history of Central Asian rivers over a long time-span. Our aims are to understand Aral Sea level variability over the geological time-span and to provide realistic scenarios of the past evolution of its level. However, both large rivers of this region, the Amu Darya and the Syr Darya, were affected over the geological time period by several changes and alterations in their downstream courses (Létolle and Mainguet, 1997; Létolle, 2008).

The climate in the Aral region during the upper Zyriankan glaciation period (22,000–11,700 BP) was more arid than it is today. During that time the Aral depression received very limited amounts of water (Arkhipov, 1986), most likely from Siberian plains in the north through channels (in the Tourgai depression) that were created by aeolian erosion and from direct local snow melt (Gorodeshkaia, 1970; Létolle and Mainguet, 1997; Micklin, 2010). Precipitation over the Pamir and Tien Shan mountains was likely feeding only the glacier cap. In fact, fluvial sedimentation from Amu Darya and Syr Darya was very small at the LGM (Létolle and Mainguet, 1997; Boomer et al., 2000), the Aral Sea was a very small water body, and Lake Sarykamish was completely dried up (Mamedov, 1991; Boomer et al., 2000). Aeolian erosion may have been important at that time (Gerasimov, 1931).

At the end of the last LGM the Aral Sea was exorheic and already allowed external export of water to Sarykamish. It has been demonstrated from analysis of a core made by Rubanov (1982) collected in the middle of the Aral Sea that no gypsum was found during early Holocene.

From 11,700 BP to 9000 BP, during the Paskevich terrace, the climate changed from warm/wet to cold/dry conditions (Vinogradov and Mamedov, 1991). At that time, the Aral Sea was fed only by the Syr Darya, which was able to transport enough sediment to fill the former bed of the Northern and Eastern parts of the Aral Sea. Meanwhile, the south-western basin, separated by the Vozrojdenia ridge was protected from sedimentation. The Aral Sea water level was at that time about 31 m a.s.l. (Micklin, 2010). This may easily explain why the deepest part of the Aral Sea depression is located in the western basin, being submitted to a sedimentation rate of around 0.5 mm/year while the eastern part receives around 2 mm/year (Zenkevitch, 1947; Brodskaya, 1956). At this rate of sedimentation, the Aral Sea would be completely filled by sediment in 30,000 years, a phenomenon which should have occurred in the past if export mechanisms like fluvial and aeolian erosion were not operating (Létolle and Mainguet, 1997). Amu Darya was flowing to the Sarykamish depression during the Paskevich period (Micklin, 2010).

[1] Holocene is the last period of the geological history, and began at about 11,700 years BP.

When the climate became warmer and wetter (9000 BP), the Turanian glaciers (Pamir and Tien Shan) started to thaw (much later than the retreat of Siberian ice caps during the early Holocene), exporting large fluvial sediments and water downstream (Micklin, 2010) and contributing to the diversion of many riverbeds (Grosswald et al., 1994; Boomer et al., 2000). This period is named the Lavlakian phase and was marked by a large discharge of Amu Darya. Progressively, after deglaciation and during this Lavlakian phase, the Amu Darya carried out considerable quantities of fluvioglacial sediments that had filled the depression between the Aral Sea and Lake Sarykamish at a rate of around 30 mm/year (Létolle, 2008).

Vertical crustal uplift may also have enhanced the formation of a natural dam between both basins. Meanwhile, part of the water from Amu Darya flowed into the Sarykamish (SW), part into the Aral Sea, and part eastward towards the Akcha Darya Valley (Boomer et al., 2000).

During this first phase of deglaciation, the river discharge into the Aral Sea may have reached around 200 km^3/year, largely compensating for evaporation and allowing the lake level to rise up to 58 m above sea level (Létolle and Mainguet, 1997), while extending to the east.

Simultaneously, water overflowed easily from the Aral Sea to Lake Sarykamish, and then into the Uzboy Channel (Boomer et al., 2000) through water erosion of the sill in formation. This 750 km long channel joins Lake Sarykamish and the Caspian Sea. Based on geological considerations (Létolle, 2000) it has been established that, due to climate changes or anthropogenic actions, the Uzboy Channel has carried out water from Amu Darya to the Caspian Sea several times since the LGM (Létolle, 2000). This assertion was however subjected to a large debate among historians and scientists, most of them considering that Uzboy could not carry the whole water flux (ranging from 30 km^3/year to 70 km^3/year) of the Amu Darya to the Caspian Sea (Létolle et al., 2007). In all probability a large part of Amu Darya water flow was running, evaporating and infiltrating into the Zaunguz Desert through interdune channels (Kes' and Klyukanova, 1999). A part was evaporated by Lake Sarykamish and other small parts evaporated in lagoons in the south east Aral basin following the former Akcha Darya riverbed.

Until the end of the Lavlakian phase, the water discharge had decreased to approximately 90 km^3/year and the lake became endorheic at around 7000 BP (Létolle and Mainguet, 1997). At this point, Aral Sea level fluctuations were fully driven by discharges into evaporation from the sea. Direct precipitation is very negligible in arid regions.

The modern delta of Amu Darya was formed during this period of alluvia filling. The sill reached an altitude of 58 m and it seemed to take around 3 to 4 millennia to definitively close the Aral Sea basin (Létolle and Mainguet, 1997). Because of a larger watershed it seems probable that Amu Darya had a greater contribution to the fluvioglacial sedimentation of the Aral Sea basin than Syr Darya, the latter having formed its current delta only during the last Holocene period (Boomer et al., 2000).

Although this scenario seems to be well accepted by a large community, there is still debate concerning the maximum level reached by the Aral Sea until the end of the Lavlakian period (mid-Holocene, around 5000 BP). In order to calculate the lake level at different stages, the altitudes of the 7 terraces on the shoreline of the Aral Sea (principally observed on western and northern coasts) were used as an indicator of Aral Sea level since the LGM (Boomer et al., 2000). Based on the altitude of the first terrace (labelled as I) authors (Epifanov, 1961; Hondkarian, 1977; Fedorov, 1980; reported by Boomer et al., 2000) estimated that it should have been around 72–73 m above sea level until the end of the Lavlakian pluvial phase. The assumptions of those authors were also enhanced by the discovery of bivalves originating from the Caspian Sea near the shoreline of terraces I (72–73 m) and II (57–58 m), which tends to confirm the connection between the Caspian and Aral seas in the mid-Holocene. Such a connection is possible only if the water level of the Aral Sea reaches very high values, thus confirming the high stand deduced from the altitude of terrace I.

However, more recent articles have proposed different interpretations of terrace altitude and past scenarios of Aral Sea level (Boroffka et al., 2006; Létolle, 2008). Firstly, it has been shown that the altitude of the higher terrace could be attributed to tectonic vertical displacement of the Earth's crust, which reached more than 10 m from its origin to now (Kirioukhin et al., 1966). More recently, Nurtaev (2004) has shown that vertical crustal movement reached a rate of 12 mm/year (equivalent to 13–14 m since the early Holocene). This needs to be taken into account in the reconstruction of Aral Sea level variations over a geological time-span on the basis of the altitude of the terraces. Moreover, Boroffka et al. (2006) conducted archaeological investigations on Neolithic (7000–5000 BP) settlements around the Aral Sea at an altitude of around 58–59 m above sea level. They found no lacustrine traces at this elevation. Also considering geomorphological and satellite observations they concluded that an Aral Sea level of 72–73 m in the Lavlakian phase was unrealistic, and even a level of 58 m as assumed by other authors (Létolle and Mainguet, 1997) was probably never reached during the Holocene. They proposed a maximum elevation of no higher than 54–55 m which has been confirmed by Reinhardt et al. (2008) from sediment analysis. They have also assumed that during this period of post deglaciation the Amu Darya had principally flowed directly to the Uzboy Channel and not to the Aral Sea or Akcha Darya Valley as assumed elsewhere. This led them to consider that the level of the Aral Sea was low.

2.2. Current issues and controversies on the history of Aral Sea level changes from the end of the Lavlakian period (5000 BP) to the modern Aral Sea crisis (1960)

2.2.1. From 5000 BP to 2000 BP

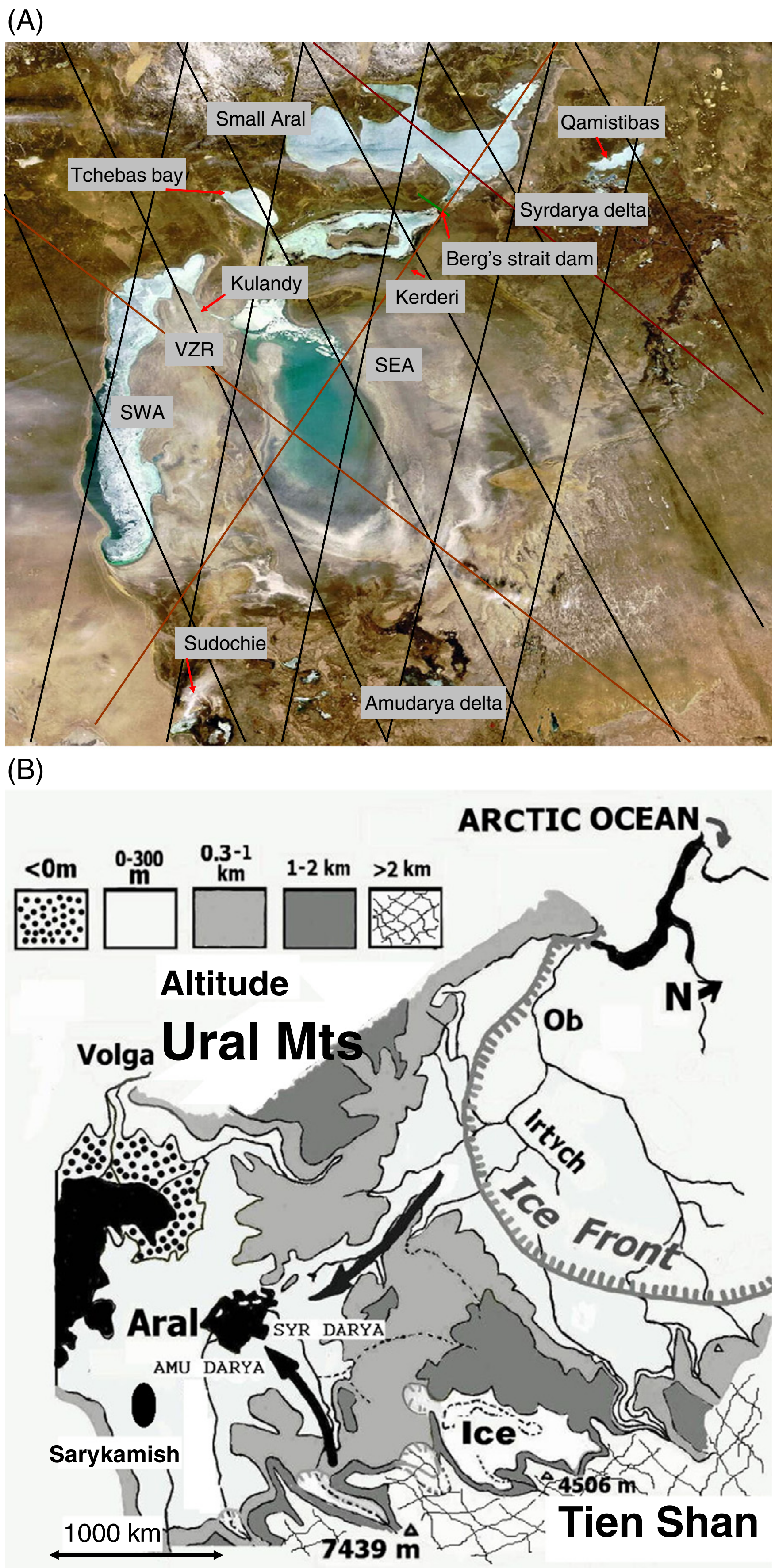
From the end of the Lavlakian period to 2000 BP the information available for dating the regression and transgression phase is based on radiocarbon dating of a 3.5 m core collected by Rubanov in the centre of the lake.

Archaeological data providing information on human settlements and irrigation activities and dating of terraces on the west coast of the Aral Sea give additional information on Aral Sea water levels in the past and possible causes of water level variations.

It can be gleaned from gypsum deposits in Rubanov's core that a brief episode of low water level took place at around 4950 BP (+/− 140) before the existence of irrigation and was most probably due to natural conditions (Létolle and Mainguet, 1997). Another gypsum bed was detected at 3600 BP (+/− 140), again corresponding to a low water level. However, the main results from that particular sediment core analysis were that this 3000-year period was characterised by high water levels (Rubanov, 1982; Maev et al., 1991; Létolle and Mainguet, 1997). However, a short one/two hundred year period at around 3600 BP may have broken a long period of transgression.

Archaeological studies of irrigation and river diversion during the Bronze Age (3000–4000 BP) corroborate the findings of other scientists. Boroffka (2010) found that irrigation along the Amu Darya River and the Horezm delta started at around 3900 BP with the highest period of activity between 2400 BP and 1600 BP. In the case of the Syr Darya River, irrigation activity started much later (900 BP). These archaeological findings confirm both the dating of terrace II at 3500 BP and the assumptions made by Andrionov (1969) and Kes' (1978) that the 3600 BP regression was mainly due to irrigation. It has also been found (Micklin, 2010) that the westward diversion of the Amu Darya to the Sarykamish and then to the Caspian Sea through the Uzboy Channel also occurred episodically during this period.

Considering Rubanov's sediment core analysis (two short periods of low water level during a 3000 year period of transgression) irrigation was probably slight. In addition, the climate probably remained wet and warm over this period of time. In contrast, Boroffka (2010) and Boroffka et al. (2006) discovered new regression periods during the Bronze and Iron ages (3000–4000 BP and 2500 BP) at a 42–43 m level


(A)
Small Aral
Qamistibas
Tchebas bay
Syrdarya delta
Berg's strait dam
Kulandy
Kerderi
VZR
SEA
SWA
Sudochie
Amudarya delta
(B)
ARCTIC OCEAN
<0m
0-300 m
0.3-1 km
1-2 km
>2 km
Altitude
Ural Mts
Volga
Ob
N
Irtych
Ice Front
Aral
SYR DARYA
AMU DARYA
Sarykamish
Ice
4506 m
Tien Shan
1000 km
7439 m

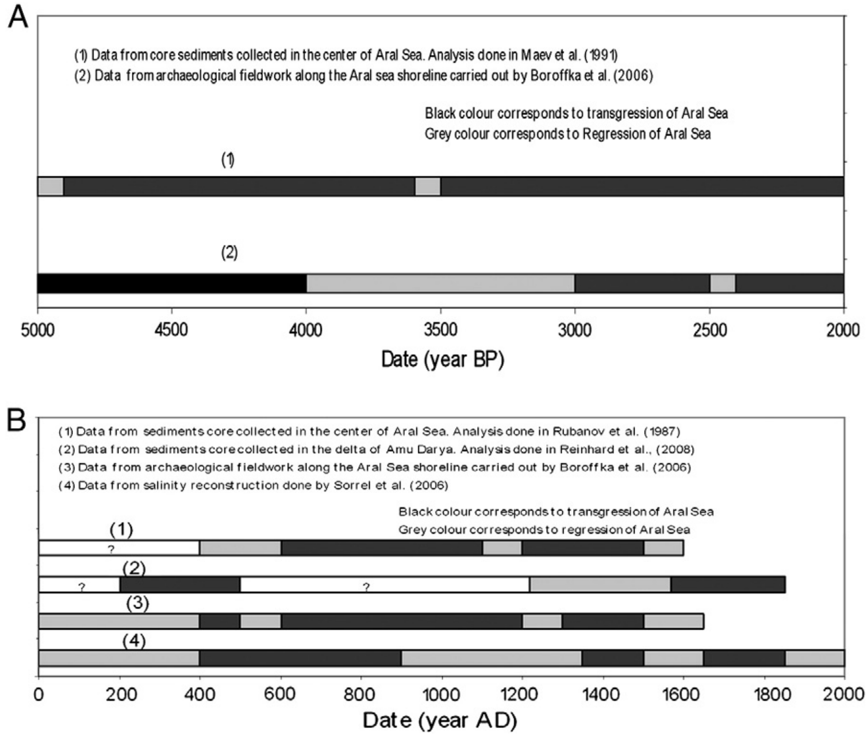


Fig. 2. Chronology of water level variations from different authors (A) from 5000 to 2000 BP (B) from 2000 BP to 20th century.

not detected in the core. The conclusions of Boroffka (2010) and Boroffka et al. (2006) were based on archaeological discoveries along the Aral Sea shoreline.

Fig. 2A demonstrates the two main scenarios that can be drawn from these studies over the period 5000–2000 BP. We can see how they differ between 3000 and 4000 BP and at around 2500 BP.

2.2.2. From 2000 BP to 1960

The ensuing 2000 years until the present is better documented in various recent articles (Hondkarian, 1977; Rubanov, 1982; Maev et al., 1991; Kes' and Klyukanova, 1999; Boroffka et al., 2006; Sorrel et al., 2006, 2007; Austin et al., 2007; Boomer et al., 2009; Krigonov, 2009; Oberhänsli et al., 2011). They have been able to achieve either full or partial reconstruction of Aral Sea level fluctuations.

However, an important question has been addressed by several authors concerning the exact causes of the past phases of regression and transgression over this period of time. Tectonic activities have certainly influenced Aral Sea level variability in the Pleistocene and early Holocene. The authors have for the most part debated the two main sources of Aral Sea level cycling over the last 2000 years, namely climate changes and human action upon the drainage system in the river basins (through river diversion and irrigation development). Historical information and deltaic and lacustrine sediment data were used to reconstruct the palaeolimnology of the Aral Sea (Boomer et al., 2000). As shown in the following, they also differ in terms of dating of regression and transgression phases.

Rubanov (1982, 1987) and Maev et al. (1991) analysed lacustrine sediment cores collected in the central Aral Sea using ^{14}C radiocarbon dating. They identified ancient sediments (including gypsum and mirabilite deposits) indicating that phases of high evaporation occurred from 5000 to 2000 BP and is associated with low-level stand of the Aral Sea.

With regards to the last 2000 years they found a gypsum deposit dating to 970 BP. Létolle and Mainguet (1997) linked this deposit to devastation of the Amu Darya delta by Genghis Khan. A final regression phase was detected in this core and may correspond to destruction caused by Tamerlan in 710 BP (Bortnik, 1999; Kes' and Klyukanova, 1999). Rubanov also found a peat bed in the central Aral Sea of 35 mm thick at 1600 BP. It is known from historical sources (Létolle and Mainguet, 1997; Krigonov, 2009) that irrigation infrastructures were completely destroyed during the Hun invasions, a scenario confirmed by Klige et al. (1995). According to Maev et al. (1991), there was nevertheless a long period of 800 years between 2000 BP and 1200 BP, of low water level stage of the Aral Sea (23–27 m a.s.l.). Boroffka et al. (2006) reported that Amu Darya was diverted to the Sarykamish and Uzboy channels during this time, until at least 1400 BP. From Micklin (2010) and Krigonov (2009) we can see that the Syr Darya was likely diverted southward into the Kyzyl Kum Desert or was even connected to Amu Darya and did not reach the Aral Sea until the late middle ages.

Reinhardt et al. (2008) proposed another interesting scenario. They detected a short, but intense period of transgression (with elevation of 54 to 55 m) of the Aral Sea around 1800 BP. By extracting a 2.5 m sediment core from the Amu Darya delta and performing ^{14}C radiocarbon dating of organic matter (shells) they were able to couple the information to palaeoshoreline elevation data derived from satellite measurements (SRTM) and GPS field vertical profiles. One of their main results was the detection of a high transgression of the Aral Sea during the 4th century, a period regarded by others as a low level stand of the Aral Sea.

Fig. 1. (A) Satellite image of the Aral Sea from March 6, 2008. The red line corresponds to Topex/Poseidon, Jason-1 and Jason-2 satellite tracks, and the black ones to the Envisat tracks. (B) Overview of the physical map of the Aral Sea basin during the LGM. Ice caps on the front corresponds to the South Siberian Islandis border, which were close to Aral depressions. Black arrows represent main wind directions.

For other authors the scenarios are still different. In particular, they consider that the most important factor of regression is climate change with potential amplification from human activities (Boroffka et al., 2006; Sorrel et al., 2006, 2007; Oberhänsli et al., 2011). Their methodology is based on different records. Sorrel et al. (2006) reconstructed salinity variability (derived from analysis of relative abundance between different species of dinoflagellate cyst in the core retrieved in the Northwestern part of Large Aral). In the end, the salinity time series was linked to water level changes with a 10 to 20 year time resolution. In 2007, the same authors derived pollen-inferred temperature and precipitation estimates to reconstruct climate change at a resolution of 50 years over the last two millennia. They discriminated between cold, arid phases alternating with warm, wet ones. Palaeoconductivity of diatom was recorded by Austin et al. (2007) and used to reconstruct Aral Sea level variations over the last 1600 years. Boroffka et al. (2006) reconstructed the Aral Sea water balance over the last 2000 years from relative Ca abundance in the sediment core. All of these studies were based on a sediment core taken in the Chernyshov Bay during the CLIMAN expedition.

Sorrel et al. (2007) correlated the chronology of climate change conditions over the Aral Sea to water level variability. They make the assumption that climate conditions over the Central Asian region are strongly controlled by both Siberian high pressure and the North Atlantic Oscillation (NAO) suggesting that when the NAO is negative, rainfall in Central Asia is controlled by the Eastern Mediterranean cyclonic system, while the Siberian high pressure drives temperature gradient. From their data, they investigated Aral Sea level fluctuations from high to low values with a periodicity of around 400 years over the last 2 millennia (Sorrel et al., 2007). The authors calculated that precipitation rates range from 0.3 m/year to 0.5 m/year from arid to wet climate. Their chronology is well correlated with climate changes observed by other authors in Israel and confirms their assumption of correlation between the Central Asian climate and Eastern Mediterranean. As for river discharge variability, which drives 80% of the water input of the Aral Sea (Boomer et al., 2009), it is highly correlated with melt water discharge of Pamir and Tien Shan glaciers (Oberhänsli et al., 2011).

Their analysis revealed high salinity signalling a regression phase during a cold, arid climate period between 2000 and 1600 BP followed by a transgression phase until 1100 BP. This contradicts data and analysis by Reinhardt et al. (2008) who found transgression of the Aral Sea between 1800 BP and 1600 BP, while Sorrel et al. (2006, 2007) and Boroffka et al. (2006) consider it to be in cold, arid and high salinity conditions. We know that this period was characterised by intensive irrigation along the Amu Darya and Horezm delta (Boroffka, 2010), which is in accordance with Aral Sea regression. Boomer et al. (2009) noted this contradiction and considered that there may be dating errors in the lacustrine sediment chronology of Reinhardt et al. (2008).

Irrigation in the delta probably stopped after the Hun invasion around the 5th century and may also explain further transgression of the Aral Sea. Looking at data published by Sorrel et al. (2006) we see (fig. 11 of their article) that just after 1600 BP there is an extremely steep decrease in salinity. As we will see further, it is difficult to believe that this sudden drop of salinity resulting in a dramatic water level increase could happen so suddenly (only a few years based on the data of Sorrel et al., 2006). Even very rapid climate change or abrupt inflow of fresh water to the Aral Sea from Amu Darya takes decades and is more likely to radically change its water balance. We believe that climate change and devastation of irrigation systems from the Huns have changed Aral Sea hydrology over a much longer time-span than observed by Sorrel et al. (2006). Our supposition is that regression stayed longer (which may corroborate other studies like those of Rubanov, 1987) but due to a warm, wet climate as shown in Sorrel et al. (2006, 2007) the Aral Sea progressively came back to a higher water level and lower salinity conditions until a new change started at around 1100 BP.

In fact, Rubanov (1987) detected low water level stands in the Aral Sea between 1400 BP and 1600 BP and Boroffka et al. (2006) revealed an Aral Sea regression at around 1400 BP. This is also in contradiction with the scenario of a drop in salinity in only a few years as suggested by Sorrel et al. (2006). Boomer et al. (2009) argued that the Ca abundance at 1400 BP measured by Boroffka et al. (2006) is uncertain but does not discuss Rubanov's sediment core analysis which agrees with low level stands of the Aral Sea during this period.

Sorrel et al. (2006) found other regressions between 1100 and 800 BP that they again considered to be climatically controlled perhaps reflecting a long-term decline of the Syr Darya and Amu Darya rivers (Boomer et al., 2009). Between 500 BP and 350 BP another regression occurred, which corresponds to the Little Ice Age (the last regression being the contemporary one). Between these two intervals they found decreasing salinity, corresponding to a high-level stand of the Aral Sea. This was well correlated with warmer and wetter climate conditions and confirmed by Boomer et al. (2009). Their climate change result is also in good agreement with a reconstruction of the past 1300 years of Central Asian climate based on tree-rings by Esper et al. (2002). Human activity is denied as having a major role but is acknowledged as having a slight influence on Aral Sea hydrology. The main argument is that changes between episodes of regression and transgression were very progressive and in their opinion are contradictory with a catastrophic event provoked by man (through riverbed diversion or dam destruction on the Amu Darya). Very recently, Oberhänsli et al. (2011) have shown using Aral Sea core sediments of 4.3 m collected in 2004 from the Eastern shore of the Chernyshov Bay in the Large Aral Sea, that the declining lake level over the past 2000 years is directly linked to climate change. They suggested that it principally resulted in large-scale snow cover changes over the Tien Shan and the Pamir that directly affected the river runoff into the Aral Sea. However, they recognise that Aral Sea regression has probably been enhanced by the fact that major historical changes in terms of long distance invasion were "*facilitated by reduced glacier extent and minimal annual snow cover*". Consequently, the damage done to the irrigation system is concomitant with climate changes.

However, an archaeological discovery from a settlement found on the East part of the Aral Sea basin named Kerderi proves that from the 13th to 14th century the lake was at a very low level of around 30 m above sea level (Reinhardt et al., 2008; Krigonov, 2009) which does not corroborate the scenario proposed by Sorrel et al. (2006), who found an earlier decline in salinity (around the year 1230) reflecting increasing Aral Sea water level.

In several expeditions and studies, Rubanov also found and analysed mirabilite deposits on the Aral Sea bed in three different areas: Small Aral at 25 and 26 m a.s.l., Tchebas Bay at 24 m a.s.l., and the Western part of Large Aral at −10 to 0 m a.s.l. (Rubanov, 1977, 1982, 1987, 1994). The presence of mirabilite, which precipitates at very high salinity, is another indication of severe desiccation of the Aral Sea as its deposits need several conditions: first is a regular and not too high input of external water; second is a low temperature in winter; and other specific conditions for mirabilite not to be re-dissolved in summer. Based on the position of deposits, and on a model developed by Cretaux et al. (2009) a scenario was proposed implying that the deposits found by Rubanov correspond to an absolute level of 30 m above sea level for the middle age regression.

If we look again at fig. 11 of Sorrel et al. (2006) we see a peak of salinity around the year 1200–1250 followed by a slight salinity decrease until the mid-14th century. We suggest that both interpretations of the observations are not completely contradictory. The high peak of salinity (20 to 30 year duration), which broke the slight long-term tendency of salinity variations (attributed to climate change) observed before and after 1220 may be attributed to the destruction of irrigation systems by Genghis Khan. As mentioned in Boroffka et al. (2006), not long after the devastation, large dams were reconstructed which resulted in the refilling of the Aral Sea and can be seen in fig. 11 of Sorrel et al. (2006) by a decrease of salinity just after 1220. It took a long time (about a century) to fill the Aral Sea and could explain why the Kerderi site was occupied during this time.

Krigonov (2009) also showed a long period of 300 years (between 700 BP and 400 BP) of regression phase of the Aral Sea and estimated from both fieldwork carried out on the eastern part of the Aral Sea and historical sources, that the water level during this period did not exceed 29 m a.s.l. This is confirmed by evidence of human settlement at an altitude of around 30 m a.s.l. on the East part of the Aral Sea at the Kerderi monument. Krigonov suggested that this site was occupied for roughly one hundred years, between the 13th and 14th centuries. Boroffka et al. (2006) found a low level stand of the Aral Sea between 700 BP and 780 BP (13th century) which is in partial accordance with this scenario of a 13th century Kerderi settlement. Both Krigonov (2009) and Reinhardt et al. (2008) agree on the fact that after 1573 the course of Amu Darya was no longer controlled by the population and its course turned towards the Aral Sea, and was followed by a transgression phase.

Historical reports from merchants in the mid-16th century also show that artificial diversion of the Amu Darya River to the Lake Sarykamish and then back to the Aral Sea occurred around the year 1570 AD. The Sultan Babur reported that the Syr Darya was diverted to the desert near the city of Turkestan (Babur, 1530). Several authors of the middle ages also documented that the Amu Darya River was flowing to the Uzboy Channel. In addition, evidence exists that during the regression episodes agriculture was developed in the western branch of the Amu Darya River delta (named Daryalyk) and around Lake Sarykamish with high inflow of freshwater from the Amu Darya River. Intake for irrigation has also been attested (Létolle, 2008). Sorrel et al. (2006) and Boomer et al. (2009) estimated that the following regression started around 500 BP to 350 BP. For this period we may consider that observations by Reinhardt et al. (2008) and historical sources corroborate those of Sorrel et al. (2006) as the time for the Aral Sea to refill after 1570 was not instantaneous, perhaps taking dozens of years.

We contest the argument given in Sorrel et al. (2006). Because their data shows a progressive change in salinity and water level they assume that the Aral Sea level cannot be triggered by catastrophic, sudden events, like those provoked by the destruction of infrastructure. This contradicts general theory on lakes reported by Mason et al. (1994). The time for a lake to reach a new equilibrium after a sudden change in one component of the water balance (sudden change of precipitation or runoff for example) is long.

We applied this theory to the case of the Aral Sea with a simple hypothesis: water level is about 31 m, precipitation (P) as reported by Sorrel et al. (2007) for the period 500 BP to 350 BP is 0.235 m/year, and evaporation (E) is 1.1 m/year (as it is currently). We assume that after a long period of diversion, Amu Darya was suddenly redirected to the Aral Sea. We also assume an annual runoff (R) of about 40 km^3/year (and that Syr Darya was flowing to the Aral Sea at that time, with an average runoff of 10 km^3/year). This is an arbitrary choice, but the objective is to calculate an order of magnitude for the time needed to refill the Aral Sea. With these hypotheses, we can calculate the new area of equilibrium of the Aral Sea given by the following equation:

$$A_{LE} = \frac{R}{(E-P)}. \tag{1}$$

A_{LE} with our hypothesis is: 58,000 km^2. From Mason et al. (1994) we may calculate the "equilibrium response time", τ_ε, to reach a fraction $(1 - 1/e)$, which represents 63% of the total area change.

τ_ε is given by the following equation:

$$\tau_e = \frac{1}{dA/dV(E_l - P_l)} \tag{2}$$

where dA/dV corresponds to the average slope of the bottom topography and is given by

$$dA/dV = (A_{LE} - A_0)/(V_{LE} - V_0) \tag{3}$$

where A_0 and V_0 are the area and volume of the Aral Sea at the time when the equilibrium was broken, respectively. Here for a level of 31 m, and from a digital model of the Aral Sea (Cretaux et al., 2005), $A_0 = 15{,}540\ km^2$, $V_0 = 91\ km^3$, and $V_{LE} = 960\ km^3$. From Mason et al., 1994, we also calculate the area of the Aral Sea at each time-span (yearly in our case) given by the following equation:

$$A_l(t) = A_0 + [A_{LE} - A_0]\left(1 - e^{\frac{-t}{\tau_e}}\right). \tag{4}$$

We have obtained for τ_ε, a value of 23.7 years, and from Eq. (4) the total time to reach the new equilibrium of 5800 km^2, is about 200 years. It reaches 63% of the surface in 24 years, and 95% in 65 years. We made the calculation with other values of runoff (+/−20 km^3/year in the total runoff), but the order of magnitude remains the same, i.e., at least 100 years are needed to reach the new equilibrium. Therefore, there is no objection to the fact that sudden change in the water balance conditions of the Aral Sea may take a long time before reaching a new equilibrium as invoked in Sorrel et al. (2006) to exclude the anthropogenic origin of Aral Sea level changes over the last 2000 years.

From these observations we may assume that the water level of the Aral Sea is triggered by both climate change and anthropogenic forcing. For example Reinhardt et al. (2008) noted that in 1570 water was diverted from Amu Darya to the Aral Sea because of irrigation. This coupled with dry climate conditions starting in 500 BP (Sorrel et al., 2006, 2007) which led to a very low water level of the Aral Sea in the 16th century. When Amu Darya again reached the Aral Sea and the climate became wetter, both effects led to a transgression of the Aral Sea after 1650.

In our opinion, there is only one period of roughly one hundred and fifty years that opposes both 'schools': the mid-14th–15th century is considered transgressive by Sorrel et al. (2006) and Boomer et al. (2009) and regressive by Reinhardt et al. (2008) and Krigonov (2009).

Reinhardt et al. (2008) consider that after this regression, which possibly stopped around the year 1650, an episode of high water level took place until the mid-19th century. This is also in slight disagreement with Sorrel et al. (2006) and Boomer et al. (2009) who believe that the level of the Aral Sea started to decline at the end of the 18th century.

They conclude that the control of Amu Darya has undoubtedly driven those regression and transgression phases during the last 2000 years, and that climate forcing is relatively minor. Others (Boroffka et al., 2006; Sorrel et al., 2006, 2007; Oberhänsli et al., 2011) interpret successive phases of regression and transgression over the last 2000 years as a direct consequence of climate change, with human activity having a very low impact. Moreover, the absence of gypsum and mirabilite in the core sediment analysed in Sorrel et al. (2006, 2007) during high regression in the middle ages is contradictory with the core sediment collected by Rubanov in the 1980s. Their argument to deny the role of anthropogenic effects is also erroneous as shown above, so climate changes alone cannot explain the changes occurring over the last 2000 years.

For some authors the sequence of regression and transgression is strongly correlated to the development of irrigation systems and their consequent destruction due to political crises (war). This places the role of human action as the dominant cause in Aral Sea fluctuations (Boomer et al., 2000; Létolle, 2008) even though climatic fluctuations may alter the Aral Sea level to a lesser extent (Létolle and Mainguet, 1997).

Because of the numerous contradictory records and assumptions, we agree with Reinhardt et al. (2008, page 315) who conclude that "*climatic interpretation of the Late Holocene lake evolution has to be treated with care*" adding that this controversial debate needs more study to be solved.

We can also assume that during periods of cold/dry climate conditions, irrigation is increased to compensate for low precipitation, and conversely, during warm/wet climate conditions, irrigation is diminished. More information on quantity of water withdrawal for irrigation over the last 2000 years would be necessary to better understand the real impact of climate change on Aral Sea level variability. New sediment core extraction close to the Lake Sarykamish would also provide unprecedented information on the linkage between this lake, the Amu Darya River and the Aral Sea.

With reference to the regression in the Middle Ages, differences in data interpretation are significant and remain a key issue needing further investigation. The period from 500 BP to 700 BP is considered as a transgression phase by advocates of the climate origin of Aral Sea water level variations. In contrast, it is clearly proven (from archaeological discovery and historical sources in particular) that there must have been a very low water level stage of the Aral Sea at least for the first half of this period. We believe that both anthropogenic action and long term climate change have acted together to alter the Aral Sea's water level. We defend this interpretation by providing the following examples: after the destruction caused by Genghis Khan in 1220 at a time when the climate started to be wetter, or during the 16th century when people lost control of the Amu Darya during a period of dry climate (following the conclusions of Sorrel et al. (2006, 2007)).

Fig. 2B illustrates the controversy discussed here.

3. Present-day Aral Sea level variability and water balance

3.1. The modern Aral Sea crisis

At the beginning of the 19th century the Aral Sea declined by around 2–3 m to an absolute level of about 50 m above sea level. This was followed by a succession of increasing and decreasing levels of 2–3 m until 1905 when it reached 53 m (Bortnik, 1999). Until the 1960s, river discharge provided on average 56 km^3/year (Bortnik, 1999) of fresh water to the Aral Sea which represented approximately half of their total runoff capacity flow. This was sufficient to maintain the lake level at +53 m above sea level (Zenkevich, 1963). The other half was lost by evaporation, underground infiltration and irrigation along the 3000 km length of river.

In 1960 the Aral Sea started to shrink drastically due to growth of water intake for irrigation and construction of water reservoirs along both the Syr Darya and Amu Darya rivers (Hollis, 1978; Micklin, 1988; Bortnik, 1999; Gaybullaev et al., 2012). In this arid zone, irrigation provided the means to reach the planned agricultural objectives of the Soviet Union. Large-scale development of ground infrastructure (irrigation channels, reservoirs) began and the extent of the irrigated area increased from 4 billion ha to 8 billion. For an arid lake like the Aral Sea, the water balance determines the equilibrium level of water and is strongly forced by the surface inflow from river discharge. Small changes in this component will thus significantly affect the water level since evaporation remains constant for a given climate condition where rainfall is generally very low and not sufficient to compensate for the evaporation.

Furthermore, the last few decades have been marked by global climate changes, which may have enhanced or diminished Aral Sea desiccation. This can somehow be seen as a projection of the debate about origin of transgressions and regressions over geological timescale (see Section 2.2) to the very contemporary issue on impact of global change on water resources in particular over the Aral Sea basin. Nevertheless, the question becomes more complicated by the fact that desiccation of the Aral Sea due to irrigation may also have positive feedback on the Aral Sea level as it may have changed the regional climate (Small et al., 2001). Therefore we may consider three different causes: irrigation, regional climate change and global climate change.

Climate change directly affects Aral Sea level variations through open water evaporation and precipitation changes, and indirectly through river runoff changes due to increased or decreased precipitation over the whole watershed of the Amu Darya and Syr Darya rivers.

Direct precipitation over the Aral Sea has been measured from 1930 to 1984. It reached on average 0.1 m/year +/− 0.01 m/year while annual evaporation derived from 15 stations on the former shorelines was on average 1.1 m +/− 0.1 m (Project More, 1990, reported in Létolle and Mainguet, 1997). Small et al. (2001) made estimations of climate change impact over the Aral Sea for the period 1960 to 1990 (based on water balance and evaporation models over the open water). These authors showed that over this period the increase of evaporation minus precipitation was about 0.15 m/year and therefore corresponded to an increase of Aral Sea desiccation by about 15% per year during this period. In this study, they have separated direct effects of global warming (around 0.1 m/year) from positive feedback of the desiccation itself (around 0.05 m/year). The influence of these phenomena should have further increased during the last twenty years, largely due to the increase in temperature.

More recently, other articles have investigated the role of irrigation on regional climate change and its impacts on water resources, at basin scale or only at the scale of the Aral Sea.

Aus Der Beck et al. (2011) calculated the water volume changes of the Aral Sea with and without water diversion for irrigation, and discovered that it should have been much higher without irrigation. They concluded that about 14% of Aral Sea shrinkage is due to climate change, which is in full agreement with the results given by Small et al. (2001).

Shibuo et al. (2007) showed that increasing evapotranspiration (ET) over the Aral Sea basin due to irrigation and heightening temperatures from climate change may have extensive consequences over the region's water resources. They showed that climate change alone over the period 1983–2002, would have slightly increased the runoff to the Aral Sea by about 6% instead of having contributed to its shrinkage. In addition, they demonstrated that irrigation has also enhanced the ET increase over the Aral Sea basin, with most of the water vapour flux in the atmosphere being transported to other regions outside of the Aral Sea basin. They also observed cooling in the region affected by irrigation.

Jarsjö et al. (2012) have continued this study by performing a projection on the impact of climate change (using mean global climate change ensemble analysis) on the Aral Sea basin and its different hydrological responses under two main scenarios: in the case where climate change is accompanied by continuous irrigation along the rivers for agriculture, and in the case without. Their main conclusion is that climate change projections agree together with an average increasing temperature of 1.5° for the period 2010–2039 over the basin. They showed that a small change in precipitation or temperature will lead to a large change of the total runoff of the rivers (5 to 15 km^3/year decrease over the whole basin), which may therefore contribute to the water balance of the Aral Sea itself. Moreover, they showed that if some global climate models predict increasing runoff the multi-model ensemble mean projection produces a decrease of the runoff.

Their most interesting conclusion with respect to the coupled effect of irrigation and climate change is that irrigation undoubtedly enhances the role of climate change through higher changes in evapotranspiration (ET). For example, in a scenario without irrigation, the Syr Darya River could sustain about a 50% temperature increase before yielding the same ET increase inferred from the scenario where irrigation is maintained. In other words, ET is highly sensitive to irrigation that amplifies the climate change impact. Together (climate change and irrigation at the current level) they will lead to a full depletion of total runoff over the basin in 40 years time.

Destouni et al. (2010) revealed that global climate change has only slightly modified runoff and evaporation from the Aral Sea, and that in 2002 runoff decreased by 83% due to water diversion for irrigation with respect to pre-1950s conditions and increased only by 3% due to climate change. They confirmed results from Shibuo et al. (2007)

regarding a relatively small cooling effect due to water diversion and irrigation (−0.6 °C) with respect to increased temperature due to climate change (+1.2 °C). They also calculated that the shrinkage of the Aral Sea has led to an average regional temperature increase of about 0.5 °C which compensates for the cooling effect of irrigation. This result seems to be in good agreement with those of Small et al. (2001) who have shown that the contribution of climate change to Aral Sea desiccation (mainly through increasing direct evaporation) is twice as high from regional manifestation of global climate change than from feedback from Aral Sea shrinkage. However, Destouni et al. (2010), accounting for the cooling impact of irrigation, conclude that the total increase of temperature over the Aral Sea is likely to be due in full to global climate change, and that the total impact of climate change on Aral Sea water level changes given in Small et al. (2001) is probably a little overestimated.

Other studies focus on the contribution of snow to river runoff feeding the Aral Sea, and also on observation of changes of snow cover and glaciers over the last several decades. In particular, the glaciers of Tien Shan and Pamir decreased up to 28% from 1960 to 2000 (Khromova et al., 2006; Niederer et al., 2007; Kutuzov and Shahgedanova, 2009). The direct effect of thawing glaciers is increasing river runoff in the Aral Sea basin. However, rising temperatures simultaneously lead to a decrease of snow cover (Groisman et al., 1994; Oberhänsli et al., 2011) with a consequent decrease of river runoff. Oberhänsli et al. (2011) estimated that since 1970 the mean annual snow cover extent was reduced by about 10%, and has therefore helped accelerate the desiccation of the Aral Sea.

Bortnik (1999) considers that after 1960, climate change (deduced from changes in P and E) would have provoked a decline of the sea of 2.3 m in 20 years. In fact, a much higher decline of 8 m has been observed. This calculation seems to slightly over-estimate the impact of climate change with respect to irrigation when compared to Small et al. (2001) and Oberhänsli et al. (2011).

This issue is still very much an open debate and needs more accurate quantification of total water volume variation, particularly in the mountain areas, even though it is clear that since 1960 a major part of Aral Sea desiccation has been coupled with a significant increase in irrigation (almost double since 1960) for both Kazakhstan and Uzbekistan. In addition, the most recent studies conducted on coupled climate change and irrigation impact on the Aral Sea have shown that they cannot be disconnected when attempting to explain its water level variability. What is true for the modern Aral Sea crisis should also be true for past phases of transgression and regression. From the different scenarios detailed in Section 2, there is an evident lack of investigation regarding exchange between climate change and human action.

From 1961 to 1970 the first consequence of reduced river runoff, particularly along the Amu Darya, was a decrease of the Aral Sea level by about 0.2 m/year (Bortnik, 1999). The following decade (1970s) was characterised by an enormous amplification of water intake, with only 17 km^3/year reaching the Aral Sea, compared to ca. 56 km^3 before 1960. Consequently, the decreasing water level rate was about 0.58 m/year.

The 1980s were dry years and it was the first time that Amu Darya could not reach the Aral Sea itself. Average water discharge during this period was about 4 km^3/year (Bortnik, 1999). Consequently, the Aral Sea separated into two distinct water bodies at the end of this decade: the North Aral (or Small Aral) and the South Aral (or Large Aral). Small Aral is fed by Syr Darya, while Large Aral is fed by Amu Darya. At the time of separation, the Aral Sea level was about 40 m above sea level (Aladin et al., 1995). Since that time the two seas have both evolved differently. At the beginning of the 1990s, the Amu Darya still supplied around 15 km^3 of water per year to the Large Aral Sea and its delta (Zholdasova, 1999) due to several years of high precipitation in the Pamir mountains. In the mid-1990s water runoff decreased again and the level of Large Aral in 2002 was 10 m lower than that of the Small Aral. Large Aral has continued to shrink at an average rate of 0.8 m/year until now. On account of runoff from the Syr Darya and the smaller surface of Small Aral, evaporation was also balanced by groundwater input and precipitation. Because of this and the construction of a dam in the Berg's strait in different epochs, the level of the Small Aral has more or less stabilised to an average value of 40 m above sea level, with periodic fluctuations due to seasonal and inter-annual climate changes. This dam has been destroyed and rebuilt during the last 15 years. Aladin et al. (2005) demonstrated that between 1993 and 1999 the existence of the dam allowed some restoration of the Small Aral. They calculated from water balance that during periods of the dam's absence, only 20% of the river runoff entering into the delta reached the sea. The rest was lost to evaporation in the delta and in the desert, to underground infiltration, and probably due to some inflow to Large Aral through the Berg's strait. They also showed that when the dam was in place, it allowed 80% water retention of the river runoff entering via the Syr Darya delta. This computation determined the correlation between the amount of water entering into the Syr Darya delta and the level of Small Aral (Aladin et al., 2005).

The differences in the hydrological regimes of the two lakes have thus led to the stabilisation of the Small Aral level while the Large Aral has continued to desiccate and salinize. All the above has been widely documented in several articles (Micklin, 1988; Aladin et al., 1995; Bortnik, 1999; Glantz, 1999; Letolle and Chesterikoff, 1999; Small et al., 2001; Aladin et al., 2005; Cretaux et al., 2005; Kouraev et al., 2009).

At the beginning of the 19th century the first systematic measurements of Aral Sea level started and in 1940 6 to 10 ground gauge stations were already functioning (Bortnik, 1999). In the mid-1990s there were no longer any stations in operation. From this time, the Aral Sea water level has been calculated from satellite measurements, through radar altimeter instruments, and via optical satellite imagery of the sea surface. The evolution over the last 15–20 years of Aral Sea level using radar altimetry has been described in several articles for Large Aral (Cretaux et al., 2005, 2009; Kouraev et al., 2009) and for Small Aral (Aladin et al., 2005; Kouraev et al.; 2009). With T/P, Jason-1, Jason-2, GFO and Envisat altimeters, it is possible to measure precisely the level variations of Large and Small Aral from 1992 until now. The elevation of the Large Aral reached a low value of +29 m in 2008 (Cretaux et al., 2009). In this article, authors tried to calculate the water balance of both water bodies in order to deduce some unknown parameters like groundwater discharge.

3.2. Present-day water balance of the Aral Sea

The volume of stored water in a lake will vary with time according to changes in the hydrological budget. Under a constant climate scenario the volume will tend towards reaching an equilibrium level over a given time period, displaying a perfect balance between inflow and outflow (Mason et al., 1994). Lakes and reservoirs will thus exhibit seasonal changes in surface area and level due to proportional changes in precipitation and evaporation. The assessment of lake water balance could hence provide improved knowledge of regional and global climate change and a quantification of human stress on water resources across all continents.

The precipitation rate (P)[2] over the Aral Sea is rather low (less than 0.2 m/year) compared to evaporation (E) which ranges from 1 m to 1.2 m/year (Small et al., 1999, 2001). Evaporation minus precipitation for the Large Aral Sea represented an average loss of 25–30 km^3/year during the last decade, while river discharge from the Amu Darya varied from 0 to 15 km^3/year in the 1990s. Thus, in the last decade of the 20th century the water supply deficit reached 10–15 km^3/year depending on the year, and Large Aral has continued to shrink as the equilibrium level has not yet been reached. After the

[2] Both terms (E and P) considered here are valid only over the Aral Sea and differs from P and ET (evapotranspiration) over the whole Aral Sea Basin.

separation from the Large Aral, the water level in the Small Aral began to rise due to a positive water balance, and as a result, parts of its waters began to flow southward into the Large Aral. This outflow took place in the central part of the Berg's strait, which was dredged earlier (in 1980) to facilitate navigation between the northern and southern basins. This southward current was slow at first but increased as the level of the Large Aral continued to fall. When the Large Aral level fell to 37 m, the difference of level between the two water bodies reached 3 m and flow reached 100 m^3/s (Aladin et al., 1995). This canal was dammed in the summer of 1992 and the flow has stopped. Over the next few years the dam in the Berg's strait was partly destroyed by floods and was restored several times (Cretaux et al., 2005). In April 1999 the dam was completely destroyed and the water of the Small Aral again flowed southward. In 2005 a new dam was built with support of the World Bank and Kazakhstan's government. It is still operating and has allowed an increase of Small Aral's level to about 2 m with control of the level through seasonal release (in spring) to the Berg's strait.

Several publications have reported on studies of the water balance of the Aral Sea. Small et al. (1999) resolved the water balance equation by using a regional lake model and obtained values of E–P (accounting for seasonal but not interannual variability) up to 1990. Small et al. (2001) also evaluated the effect of E and P on the Aral Sea water level decrease up to 1990 and separated anthropogenic and climatic factors. Benduhn and Renard (2003) have developed a model of evaporation for the Large Aral based on the Penman equation and used the water mass balance equation to estimate the interannual groundwater inflow to the Large Aral until 1990. They showed that this contribution to the water mass balance has a high variability (from 1 km^3/year to 15 km^3/year) and an average value of 8 km^3/year. They also showed that the potential source of underground water can only originate from deltaic plains.[3] (Jarsjö and Destouni, 2004) have also estimated the groundwater discharge by using the water mass balance equation and different scenarios for the evaporation and precipitation rates. They concluded that groundwater has become a major contributor to the hydrological budget of the Aral Sea, with annual values varying from 5 to 30 km^3 depending on the scenario. More recently, Alexseeva et al. (2009) have estimated that underground water should range between 2 and 7 km^3/year, with an increase of the rate of underground discharge by about 0.013 km^3/year due to an increase of the hydraulic gradient with respect to the Aral Sea level drop. Their calculation was made for the period 1979–1994 under different assumptions related to the various components of the water balance equation of the Aral Sea. Those results also confirm the study made by Oberhänsli et al. (2009) who detected underground water inflow from oxygen and hydrogen isotopic analysis based on vertical lacustrine profiles collected in the Eastern and the Western basin of Aral Sea as well as in the Kulandy strait which connects both basins. However, their study did not provide quantification of this additional water to the Aral Sea, but conclude their article by saying, "*effluent flows of groundwater have reached a state where they are relevant for the groundwater reservoirs and water balance of the large Aral Sea*".

According to older studies (Sydykov and Dzhakelov, 1985; Glazovsky, 1990) the groundwater component of the Aral Sea water balance must be negligible and not exceed 1 km^3/year. But after the decline of Aral Sea water level, the fluxes from the deep aquifer to the shallow aquifer may have increased due to the lower water pressure on the bottom of the lake (Oberhänsli et al., 2009).

The problem with most of the water balance studies of the Aral Sea is that for several decades there were no continuous observations of water level, and the scarce data that does exist is fragmentary or unavailable. Because the historical Aral Sea volume cannot be determined accurately, there are large uncertainties in the water balance equations and reliability of the results has suffered. Using satellite altimetry, it is now possible to observe the level variations of the large continental water bodies (Birkett, 1995; Cazenave et al., 1997; Cretaux and Birkett, 2006) with high precision of 3–4 cm for a lake the size of the Aral Sea (Cretaux et al., 2011).

Using a combination of an accurate digital bathymetry map (DBM) of the basin with level variation deduced from altimetry, Cretaux et al. (2005) computed the resulting volume variation of the Large Aral Sea for the period 1993–2004. They showed that the reduction of lake volume as measured by T/P, GFO and Jason is smaller than that deduced from examination of the hydrological budget. There are errors within both methods but an additional positive water inflow to Large Aral of 5 km^3/year +/− 3 (through underground water inflow or due to errors in the water balance) has been assumed in order to make them coherent (Cretaux et al., 2005). It is in good agreement with the studies mentioned above regarding the possibility of significant underground water discharge to the Aral Sea.

3.3. New water balance of the Aral Sea from synergy of satellite and in situ data

Space technologies have been in wide operation over the last ten years for worldwide water surface monitoring and they have shown their capability of monitoring components of the water cycle and water balance at regional scales and on timescales ranging from months to decades. Radar altimetry was designed to study the ocean and has opened a new era in monitoring lakes, rivers and reservoirs. The recent missions of satellite altimetry (T/P, Jason-1/2, Envisat, ERS-1 and ERS-2) have made it possible to measure inland sea level variations with great precision which can be used to determine water mass balances.

Satellite imagery, from low to high resolution (1 km to a few metres), offers a useful tool to monitor surface water area for lakes and floodplains. MODIS data, for example, provides the surface water area from 2000 to 2012 every 8 days, with a spatial resolution of 500 m. It has been used to create a spatial time series for the Aral Sea, and lakes and wetlands in the deltas of Amu Darya and Syr Darya where the water area has been accurately measured.

The satellite altimetry technique was developed in the early 1970s with the launch of Seasat (1978). The measuring of water levels using satellite altimetry was designed and optimized for open ocean studies (Fu and Cazenave, 2001). Nevertheless, over the past 15 years, numerous studies have been published on continental hydrology utilising satellite altimetry for lakes (Birkett, 1995; Cretaux and Birkett, 2006; Swenson and Wahr, 2009; Abarca et al., 2012; Cretaux et al., 2011).

To understand the interest of using the radar altimetry technique for the contemporary Aral Sea survey we have plotted the water level variations of Small and Large Aral from all existing data: in situ and radar altimetry from 1950 to 2010. Note that in situ instruments were used to measure the Aral Sea level until the end of the 20th century. Therefore, from 1992 to 2000 we can compare the results obtained from radar altimetry with those measured in situ (Fig. 3). First, it proves the quality of altimeter measurements and warrants its use for monitoring water level variations of the Aral Sea, especially for the last 10 years when no in situ data was available. Other recent studies, using altimetry over lakes the same size as the Aral Sea, have shown a very good accuracy of about 3–4 cm (Cretaux et al., 2011; Ričko et al., 2012). For the Aral Sea surface ranging from 13,000 km^2 in mid-2005 to 6000 km^2 at the end of 2011, the associated error in water volume is between 0.3 and 0.65 km^3.

Very recent altimetry data has been analysed at LEGOS. We have benefited from the Envisat (European Space Agency mission) and Jason-2 (NASA/CNES mission) satellites over several water bodies in the Aral Sea basin: Small Aral, reservoirs in the Amu Darya and Syr Darya deltas, Tchebas Bay, west and east Large Aral (Fig. 1A). We have also used the in situ data available online from the Cawater project (www.cawater-info.net) mainly on river runoff at Kyzyldjar and

[3] In the following we do not make any assumptions on the origin of groundwater, which may come from different parts of the basin, including deep underground waters.

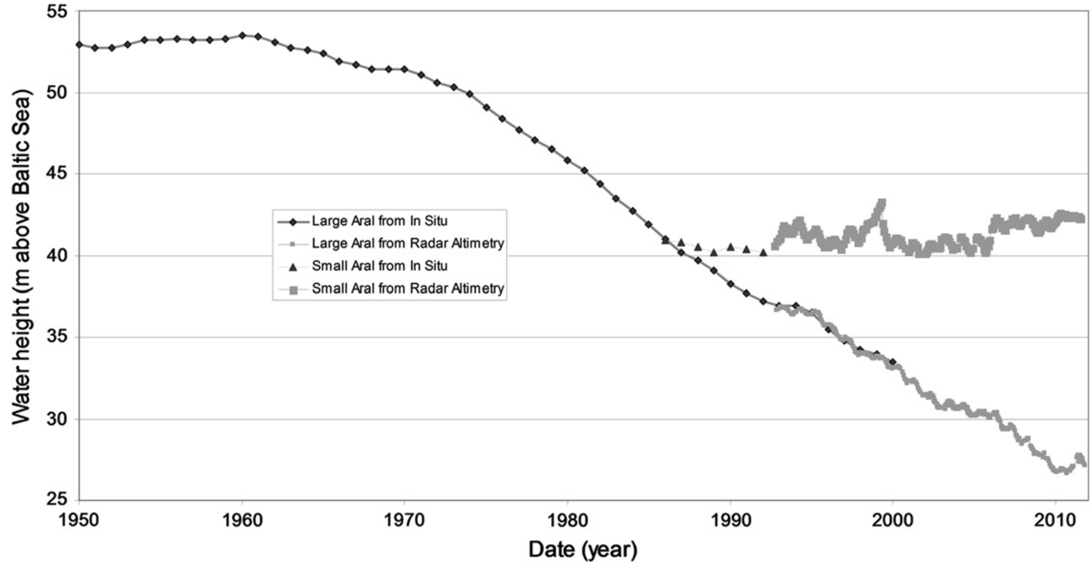


Fig. 3. Water level variations of the Aral Sea, from 1950 to 2010, inferred from in situ measurements until 2000 and from satellite altimetry from 1992 to 2010. After 1989, the water level of Large and Small Aral is given separately.

Kazalinsk (stations located at the entrance of the Amu Darya and Syr Darya deltas respectively), but also some precipitation data and surface extent of the reservoirs in the delta of Amu Darya. The monthly runoff of Syr Darya into the delta is given in Fig. 4. It shows the high interannual variability over the period 1992 to 2010. The same kind of data has been acquired for Amu Darya at the entrance of the delta (Fig. 5).

Further calculation of Aral Sea water balance is very sensitive to uncertainty on discharge data for these two rivers. Nevertheless, there are no standard errors provided on the Cawater database related to river discharge. We can assume that they have been estimated from historical calibrated relationships referred to as rating curves and also to water level measured at the hydrological stations.

However, rating curves are also subjected to various kinds of error. To summarize, in theory there is a unique relationship between water level and discharge but in natural river systems, many different effects can influence and alter this relationship. In practice it can be difficult to retrieve a single equation valid for a full range of water level and discharge. Leon et al. (2006) have established that errors on rating curves over the Rio Negro River (in the Amazon basin) can reach almost 20% of the absolute water discharge of the river. The Amazon basin is a critical case, due to a high complexity of the river system, and we assume that this represents a maximum of error. We have applied it to the value given in the Cawater web site for Amu Darya and Syr Darya.

To solve the question of the total amount of water entering the Small and Large Aral from rivers we calculated the water balance for each of them, as well as for the water bodies in the delta and Tchebas Bay. This was done for the period September 2005 (just after the construction of the Kokaral dam) to the end of 2010 (period of the last Envisat data). Fig. 6A and B give water level fluctuations of Small Aral and of Tchebas Bay. For Small Aral the water level variations were driven by variability of the river runoff and precipitation at seasonal timescale, and by succession of periods with a dam in the Berg's strait (for example, between 1997 and 1999 or since 2005) and periods when the dam was broken at interannual timescale. The Tchebas Bay has shrunk almost continuously since 2002 as shown in Fig. 6B. The same calculation has been made for the main reservoirs in the Amu Darya and Syr Darya deltas. To convert water level variations into volume, we used Modis instruments to monitor water surface area variations for each of these water bodies.

As a result, we calculated for each delta the water losses from the in situ stations to the Aral Sea (respectively Large and Small Aral). Losses comprised between 3 and 40% in the delta of Amu Darya (from one year to another, from 2005 to 2010). The yearly remaining discharge to the Large Aral comprised between 1 km^3 (2009) to 16 km^3 (2010) leading to high interannual water balance. However, water withdrawal inside the Amu Darya delta, based on our calculation is relatively constant from year to year, with an average value of

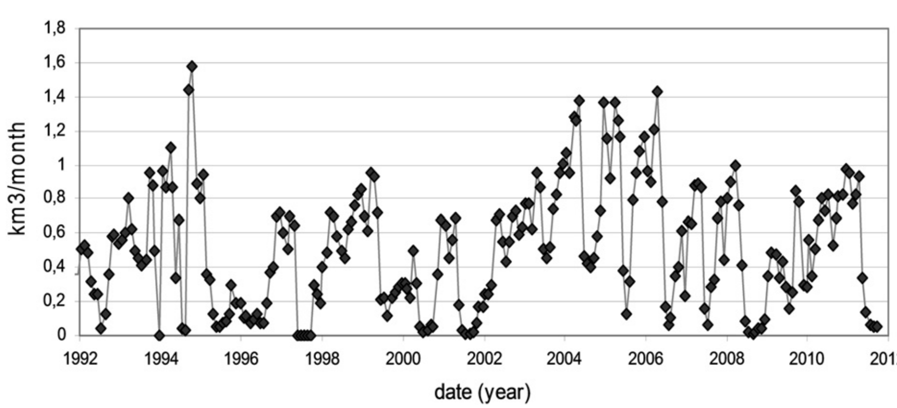


Fig. 4. Monthly runoff of the Syr Darya River (km^3) at Kazalinsk station. Kazalinsk is situated almost 50 km from the mouth of the river at the entrance of the delta. The data is provided by the CAWaterCawater project through their portal: www.cawater-info.net.

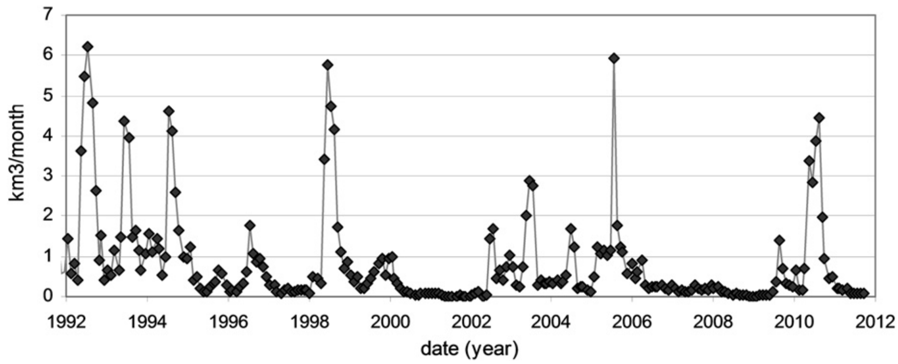


Fig. 5. Monthly runoff of the Amu Darya River (km^3) at Kyzyldjar station, near the entrance of the delta, at about 50 km from the mouth of the river. Same as Syr Darya, the data is provided by the Cawater project through their portal: www.cawater-info.net.

about 1 +/− 0.2 km^3/year. In the Syr Darya delta, water losses in reservoirs did not exceed 0.7 +/− 0.1 km^3/year. For the Small Aral, we calculated yearly discharge through the Berg's strait when the dam released excess water in the Small Aral and then we removed the water release to the Tchebas Bay and from the evaporation in the Berg's strait. The resulting discharge accounts for the Large Aral water balance: it ranges from 0 to 2.6 km^3/year from year to year.

We then calculated the water balance of the large Aral by resolving the equation:

$$dV/dt = (P(t) - E(t)) * S(t) + R_{ad} + R_b + G_w + \delta \quad (5)$$

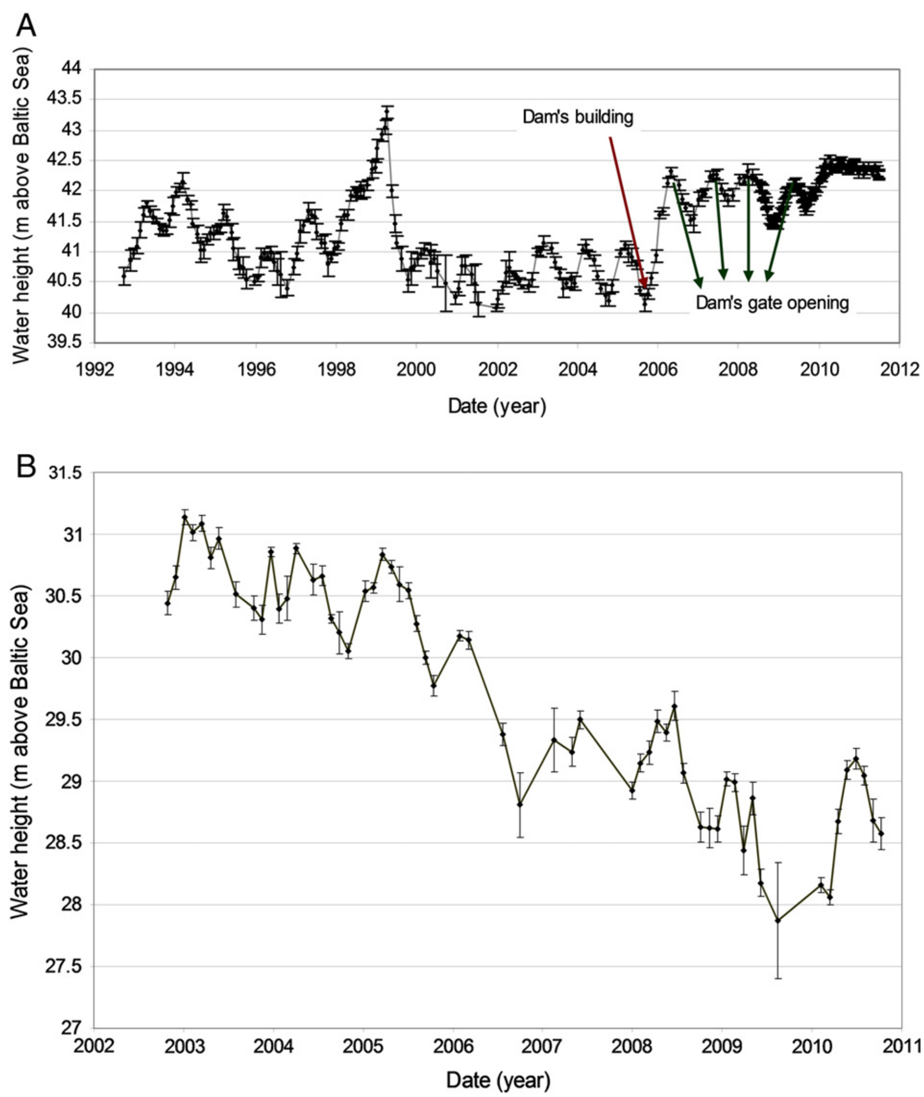


Fig. 6. (A) Water level variations of the Small Aral derived from multi satellite data processing (Envisat, T/P, Jason-1 and Jason-2). (B) Water level variations of the Tchebas Bay from Envisat satellite data. Error bars correspond to standard deviation of altimetry data calculated for each cycle over the water bodies.

where dV/dt is variation of volume with time, P(t) represents precipitation rates over the Aral Sea, E(t) is the evaporation rate, and S(t) is the total surface of water over the Aral Sea (including West and East basins) at time t. R_{ad} and R_b are the monthly runoff from Amu Darya delta and from the Berg's strait respectively calculated from the water balance of the delta of Amu Darya, Syr Darya and Small Aral as explained above. G_w is the underground water component, which will be estimated by solving the water balance equation and by considering all parameters known and δ the remaining uncertainty of the water balance equation.

Precipitation was taken from monthly averaged in situ data collected during the Cawater project, which was stopped in the beginning of the year 2000. On average, the precipitation over the region is 0.13 m/year. From other sources, such as GPCP products or satellite data (TRMM), precipitation is higher but general agreement between different studies (Cretaux et al., 2005) converges to within 0.13–0.14 m/year. We used the TRMM data to modulate the yearly average amount of precipitation in order to better account for the succession of wet and dry years over the period of observations (for example 30% of excess water was observed in 2010). For E we have used estimations given by Benduhn and Renard (2003) and Gascoin and Renard (2005), who took into account the increasing salinity of the Aral Sea, which tends to diminish E. S(t) is deduced from satellite altimetry and bathymetry of the Aral Sea bed.

From this study, we did not find any evidence of underground water inflow as shown in Fig. 7. It shows the volume variations of Large Aral in two cases: from radar altimetry and from the water balance equation with additional underground water of -0.5 km^3/year, which is the adjusted value for closing the water budget of Large Aral.

As the uncertainty regarding the evaporation and precipitation rate may be in the range of 10% we made several small changes in the E–P component of the water balance equation, but this did not radically change the conclusion. In fact, the Aral Sea surface has decreased so much over the last ten years that the effect of these components on the water balance has also diminished. Nowadays, the E–P term ranges between 6 and 6.5 km^3 if we consider that there is 10% uncertainty on E and P rates. Water balance in the two deltas has also been modified (taking different assumptions on E, water withdrawal from the rivers, and P) but this has had a very small impact on the water balance. We consider that uncertainties on river discharges of Amu Darya and Syr Darya are about 20% and are the major sources of error. A standard deviation of 0.6 km^3/year on water volume from radar altimetry was also considered. We obtained an underground water component of $0 +/- 3$ km^3/year that includes all sources of potential error.

Table 1 summarizes the underground water inflow obtained from different authors in the literature over the last 20 years. It shows that in contrast to many recent studies, here we can conclude on the very negligible contribution to the water balance of underground water with small uncertainty.

This conjecture needs to be further assessed by hydro-geological modelling and more accurate data on E and P.

Future satellite missions planned by space agencies will help the further monitoring of large basins like the Aral Sea (Jason-3, Altika, Sentinel-2, Sentinel-3, Jason-CS, SWOT, SMAP, GRACE-FO, Proba-V, etc.). All of these missions will also allow provision for long-term time series on different parameters essential to quantify water balance at the Aral Sea basin scale. Already we have shown here that questions like the potential underground water inflow to the Aral Sea can be addressed by satellite measurements. An assessment of regional water cycle at high spatial and temporal resolution over decades will be possible in the near future, with unexpected new results on the functioning of hydrological systems like the Aral Sea. It is probable that the remaining questions about the past history of water bodies could find new answers from the study of its present-day evolution. One condition to achieve this objective is the availability of accurate long term and multi-sensor data.

4. Conclusion

Establishing the history of Aral Sea level variability from geological times to the present-day is a challenging issue with several questions remaining under debate: what are the causes and the chronology of the past 5000-year succession of episodes of regression and transgression? What is the exact contribution of climate change with respect to irrigation during the modern Aral Sea crisis? How much have underground waters contributed to the Aral Sea balance over

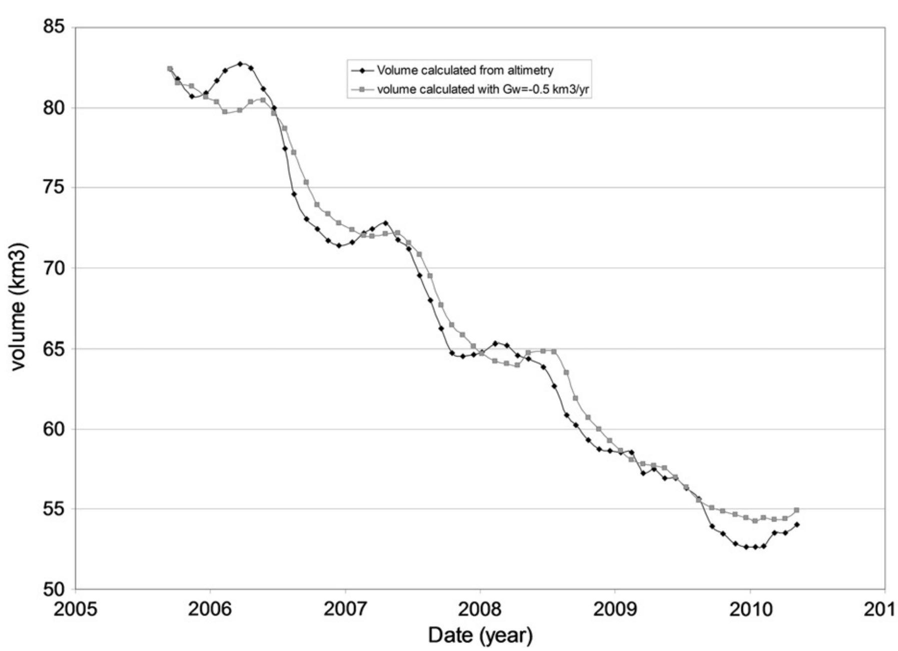


Fig. 7. Estimates of water balance for the Large Aral derived from altimetry and in situ data. Without any need of additional inflow of water both curves are correlated. This shows that there is likely no significant underground water inflow to the Aral Sea (with uncertainty of 3 km^3/yr), which is in contrast to previous publications over the last several years by other authors, including us in Cretaux et al. (2005).

Table 1
Underground water from different studies.

Author	G_w (km^3/yr)
Sydykov and Dzhakelov (1985) and Glazovsky (1990)	<1
Benduhn and Renard (2003)	1 to 15
Jarsjö and Destouni (2004)	5 to 30
Cretaux et al. (2005)	2 to 8
Alexseeva et al. (2009)	2 to 7
This study	0 +/− 3

the last few years? We have demonstrated in this article, through a review of large literature over the last 50 years, that the understanding of Aral Sea water level variability since the last deglaciation is possible only from comparative methodologies implying proxies and scientific disciplines of various natures (archaeological settlement position and dating, sediment core, palaeo-climatological indicators, historical archives, tectonic and geomorphological features of the Aral Sea basin, and space technologies).

Many authors surmise that apart from the last 50 years, the palaeolimnology of the Aral Sea is mostly governed by climate change with a small contribution coming from human action, while others are convinced to the contrary. A multidisciplinary approach including cross-validation of the results with a simple hydrological model of lakes allows better assessment of the relative role of climate change and human action. We used the results on the modern Aral Sea crisis to reveal that the role of climate change is not binary. It could be enhanced by irrigation (by more or less 15% depending on authors), and conversely, irrigation could be enhanced by climate change (a dry cold climate may promote irrigation).

We have highlighted the fact that technologies like satellite remote sensing are mature enough to complement in situ instrumentation or even replace them if missing, and feed models. It will become an invaluable source of information for the monitoring of continental water storage variability. Results regarding the current Aral Sea water balance are also good indicators to draw scenarios of past variability (Cretaux et al., 2009).

Quantification of possible underground components of the water balance has been performed thanks to satellite data and our results indicate a value close to 0 +/− 3 km^3/year (Fig. 7).

The situation regarding access of in situ data has improved these last few years on the Aral Sea watershed, thanks to the Cawater project providing data over the rivers, weather parameters or information on water uses for irrigation. Other parameters like precipitation, snow cover, or total water storage (Güntner, 2008) may be obtained from satellite measurements. Lake or land surface temperatures that are fundamental parameters for evaluating E and ET are also now accessible from satellite data (MODIS, ATSR, AVHRR). All together, this will allow better understanding of the hydrology of the current Aral Sea basin and its possible future in the frame of climate change and human stress. Therefore it will provide a new framework for scientists interested in the past hydrological history of the Aral Sea.

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