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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.

Contents

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.