Chapter 11
Aral Sea Hydrology from Satellite Remote Sensing

Jean-François Crétaux and Muriel Bergé-Nguyen

Abstract Space technologies have been widely used over the last 10 years for water surface monitoring worldwide and they have shown their capability to monitor components of the water cycle and water balance at regional scales and on time scales ranging from months to decades. We present here the applications of space data from radar altimetry and satellite imagery (Terra/MODIS) over the Aral Sea Basin (ASB). Radar altimetry, which has been designed to study the ocean, has opened a new era in monitoring lakes, rivers and reservoirs. The recent missions of satellite altimetry (Topex-Poseidon, Jason-1/2, Envisat, ERS-1 and ERS-2) have made it possible to measure with great precision inland sea level variations that can be used to determine water mass balances. Radar altimetry, coupled with complementary in situ data, has allowed quantifying precisely the water balance of the Aral Sea since 1992 as well as balances for large reservoir systems along the Syr Darya, in particular Chardarya and Toktogul, and for Lake Aydarkul. This approach has also made it possible to ascertain the water balances of lakes and wetlands in the deltas of the Syr Darya and Amu Darya.

Satellite imagery, from low to high resolution (1 km to a few meters) offers a useful tool to monitor surface water area for lakes and floodplains. MODIS data for example provide every 8 days, the surface water area from 2000 to 2012, with a spatial resolution of 500 m. It has been used to create a spatial time series for the Aral Sea and the lakes and wetlands in the deltas of the Amu Darya and Syr Darya where water area has been precisely measured. Along with in situ observations and hydrological modelling, space observations have the potential to improve significantly our understanding of hydrological processes at work in large river basins, (including lakes, reservoirs and floodplains) and their influence on climate variability and socio-economic life. Unprecedented information can be expected coupling models and surface observations with data from space, which offer global geographical coverage, good spatial-temporal sampling, continuous monitoring

J.-F. Crétaux (✉) • M. Bergé-Nguyen
CNES/Legos, 14 avenue Edouard Belin, 31400 Toulouse, France
e-mail: Jean-francois.cretaux@legos.obs-mip.fr

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over time, and the capability of measuring water mass change occurring at or below the surface. Based on these different techniques we have determined the surface area of water features within the Aral Sea Basin, as well as volume variations, which are the key parameters to the understanding of the hydrological regime in ungauged basins. A focus on the Aral Sea and the water bodies in the deltas of the Syr Darya and the Amu Darya rivers over the last 20 years from satellite data is presented in this chapter, with some implications for the water balance. We will also describe the specific behaviour of the Western and Eastern basins of the Large (South) Aral Sea over the last 5–6 years

Keywords Radar altimetry • Satellite imagery • Water balance

11.1 Introduction

The satellite altimetry technique was developed in the early 1970s with the launch of Seasat (1978). The measuring of water levels using satellite altimetry has been designed and optimized for open oceans' studies (Fu and Cazenave 2001). Nevertheless, over the past 15 years, numerous studies have been published on continental hydrology utilizing satellite altimetry for global analysis (Birkett 1995; Crétaux and Birkett 2006; Calmant et al. 2008; Crétaux et al. 2011a, b) or in more specific lake or river basin case studies (Cazenave et al. 1997; Mercier et al. 2002; Frappart et al. 2005a; Birkett 2000; Coe and Birkett 2005; Aladin et al. 2005; Crétaux et al. 2005a, b; Swenson and Wahr 2009; Kouraev et al. 2009; Ginzburg et al. 2009; Kouraev et al. 2009, 2011; Lee et al. 2011; Zhang et al. 2011a; Abarca et al. 2012). When focusing on lakes, these studies have shown that radar altimetry is a very useful technique for different applications: hydrological water balance (Cazenave et al. 1997; Crétaux et al. 2005a; Swenson and Wahr 2009), prediction of lake level variations (Coe and Birkett 2005), studies of anthropogenic impact on lakes water storage (Aladin et al. 2005), correlation of inter annual fluctuations of lake levels on a regional scale with ocean–atmosphere interaction (Mercier et al. 2002; Becker et al. 2010). Thanks to these many studies, the altimetry technique has clearly shown its capability to monitor components of the water balance of lakes on time scales ranging from months to decades.

Radar altimetry has been used to monitor water level variations over the Central Asian lakes and reservoirs (Aral Sea, Sarykamysh, Chardarya, Aydarkul, Toktogul, Balkhash, and Issyk-Kul) (Peneva et al. 2004; Aladin et al. 2005; Crétaux et al. 2005a, b, 2009a, 2011a, b; Crétaux and Birkett 2006; Kouraev et al. 2009; Ginzburg et al. 2010). This is particularly valuable when in-situ data are not available (Aral Sea since the beginning of the twenty-first century, Lake Sarykamysh and some reservoirs along the Syr Darya and Amu Darya, and lakes and wetlands in the deltas). When in situ ground measurements are available this also allows assessing the quality of the altimetry measurements as done with Lake

Issyk-Kul, with observational accuracy observed of about 3–4 cm (Crétaux et al. 2009b, 2011a). It is therefore evident that altimetry provides a source of important independent information complementary to that produced by the ground-based networks and perhaps more critically, can provide hydrological information where gauges are lacking. In this respect it provides an additional tool for decision-makers in the field of water management of the ASB.

Satellite imagery is another remote sensing tool, which can be very useful for survey of continental water bodies. For example Liu et al. (2009) have studied Lake Namco (Tibetan Plateau) surface area variations from 1970 to 2005 from analysis of Landsat imagery to understand the long-term response of the lake system to climate change. Ye et al. (2007) have studied some lake basins in southern Tibet and have investigated the linkage between lake surface variations and glacier retreat in the Himalayas. Many other studies have been conducted in recent years over the Tibetan plateau using satellite images to quantify the linkage between lakes and climate (Huang et al. 2011; Zhang et al. 2011b).

Satellite images from the Moderate Resolution Imaging Spectral radiometer (MODIS) instrument is also well suited for monitoring the surface area of large lakes with high spatial variations at medium resolution of 250–500 m. It has been used, for example, in Abarca del Rio et al. (2012) to study the hydrological linkage between Lake Titicaca and Lake Poopo in the South American Altiplano. Peng et al. (2005) have used the MODIS data to develop a method of surface area extent and level monitoring, which, however, depends on knowledge of topographic maps of the area under study or on a relation between surface area and water level. They applied their method to Lake Dongting, which regulates flooding along the Yangtze River in China. The Meris instrument onboard the Envisat satellite has also been widely used to monitor lake surface changes as done in Yesou et al. (2011). Synthetic Aperture Radar (SAR) Interferometry (Alsdorf and Lettenmaier 2003; Alsdorf et al. 2007) and passive and active microwave observations (e.g., Prigent et al. 2001) also offer important information on land surface waters, such as the changing area of large wetlands.

In synergy with radar altimetry, satellite imagery is therefore a pertinent system to estimate water storage variability for different lakes (Crétaux et al. 2011a). In Crétaux et al. (2009a), MODIS images have also been used to estimate water surface variations of the Aral Sea. Section 11.2 describes the basics of the remote sensing techniques (radar altimetry and satellite imagery) while in Sect. 11.3 the main results obtained over the Aral Sea Basin from Remote Sensing data are presented. It focuses mainly on the Aral Sea (Large and Small) but also deals with artificial reservoirs in the deltas of the Syr Darya and Amu Darya (see Fig. 11.1), that could indeed, be monitored from the combination of radar altimetry and satellite imagery, allowing the calculation of their water volume variations. Section 11.4 is dedicated to the description of the water balance of the Aral Sea and the new information inferred from current satellite data.

Indeed, together with a precise digital bathymetry map (DBM) of the Aral Sea Basin, and some hydrometeorological information, the Remote Sensing data can be used to calculate the water balance of the Aral Sea (Crétaux et al. 2005a, 2009a).

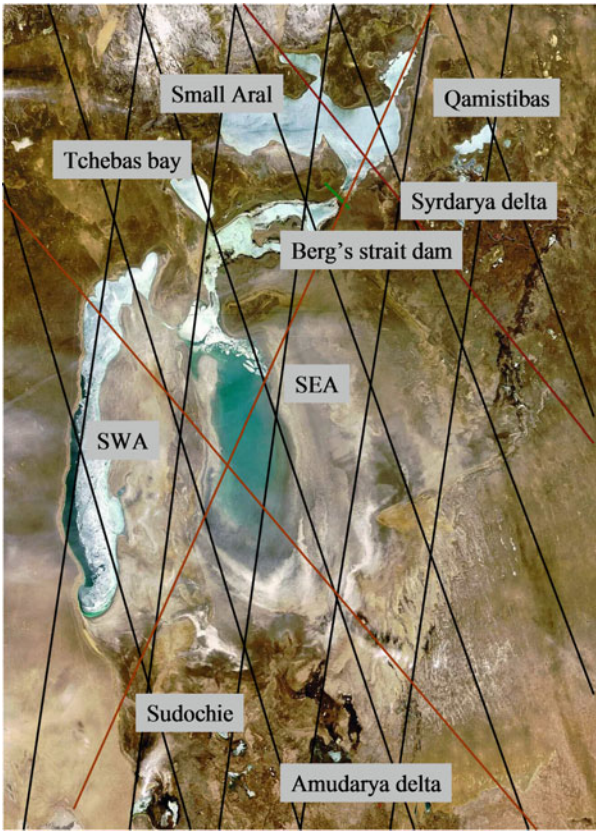

Fig. 11.1 Map of the Aral Sea with satellite altimetry mission tracks shown: T/P, Jason-1, Jason-2 (*red line*) and Envisat (*black lines*). The water bodies in the deltas of the Syr Darya and Amu Darya are shown

It could, for example, give answers to the questions of the existence and quantity of underground water inflow to the Aral Sea, which has been under debate among several researchers for the last 30 years (Sydykov and Dzhakelov 1985; Glazovsky 1990; Benduhn and Renard 2003; Jarsjö and Destouni 2004; Crétaux et al. 2005; Alexseeva et al. 2009; Oberhänsli et al. 2009). In this chapter an attempt to compute again the Aral Sea water balance from the data over the last 10 years [2002–2012] has been done.

For the next decade the space agencies around the world have programmed several new missions that would improve our knowledge of global hydrology, and at least will allow continuing the existing mission. We make a short review of those new missions and their potential implication for Central Asia, with a focus on the SWOT (NASA-CNES) mission based on a new concept of interferometry for hydrology.

Section 11.5 will describe some new missions that will allow continuing the survey of the Aral Sea in particular and continental water bodies worldwide in general.

11.2 Remote Sensing Techniques

11.2.1 Radar Altimetry

The classical radar altimetry measurements that mainly consist of waveform (e.g., raw radar altimetry echoes reflected from the land surface) are much more complex over land surfaces than over the oceans, and multi-peaked due to interfering reflections from water, the vegetation canopy, sand and or inhibited by rapidly varying topography (Frappart et al. 2006). These effects result in data having decreased validity, compared to those collected over oceans.

Radar altimetry is a profiling technique, which does not allow a global view of the Earth surface, hence limits worldwide surveying as well as spatial resolution in the cross-track satellite direction. Current altimetry satellites thus do not see large numbers of lakes. Stage accuracies are also dependant on targets size. However, radar altimetry is a good alternative for systematic monitoring of lakes where gauge data are absent. Typically altimetry measurements can range in accuracy from a few centimetres (e.g. Great Lakes, USA) to tens of centimetres depending on size and wind conditions (Crétaux et al. 2011a). It primarily measures the surface water level of water bodies in a terrestrial reference frame with a return time varying from 10 to 35 days depending on the orbit cycle of the satellite, with fairly good accuracy (a few centimeters over large bodies such as Lakes to tens of centimeters over rivers Calmant et al. (2008)).

The concept of satellite altimetry measurement is rather straightforward. The onboard radar altimeter transmits a short pulse of microwave radiation towards the nadir. Part of the incident radiation is bounced back to the altimeter, providing distance between the water surface and the satellite position, which is then transformed to the instantaneous water height above a reference fixed surface, a geoid model for instance. The accuracy of a single lake height measurement will vary depending on the knowledge of the range, the orbit and the various corrections (Cretaux et al. 2011c). The precision of the measurement will then strongly depend on the capability to retrieve the time that corresponds to the actual height at the nadir of the antenna. The major difficulty in retrieving ranges over continental waters results from the variability in shape of the return waveforms when onboard trackers are designed for a typical ocean waveform. Some algorithms have been developed to analyze waveform on a non- oceanic surface, (see Calmant et al. 2008 for details). Experts agree that among the existing algorithms, the so-called “Ice-1 retracker” is the most suitable to extract range over continental water bodies (Frappart et al. 2006). Kouraev et al. (2009) have also demonstrated that over water surfaces with winter ice cover, like the Aral Sea, this algorithm (Ice-1) better fits the water surface.

Several satellite altimetry missions have been launched since the early 1990s: ERS-1 (1991–1996), T/P (1992–2005), ERS-2 (1995–2002), GFO (2000–2008), JASON-1 (2001-), JASON-2 (2008-) and ENVISAT (2002–2012). ERS-1, ERS-2 and ENVISAT have a 35-day temporal resolution and 80 km inter-track spacing at the Equator. T/P, JASON-1 and JASON-2 have a 10-day temporal resolution and

350 km inter-track spacing at the equator. GFO has a 17-day temporal resolution and 170 km inter-track spacing at the Equator. The derivation of time series of surface height variations involves the use of the repeat track method. This methodology employs the use of a mean (reference) lake height profile. This is derived from averaging all height profiles across the lake within a given time interval, effectively smoothing out the varying effects of tide and wind set-up. The height differences between the reference pass and each repeat pass enable the time series of lake height variation to be created. The combined global altimetry historical data set now spans over two decades and is intended to be continuously updated in the coming decade (AltiKa, Jason-3, Sentinel-3, Jason-CS). Combining altimetry data from several in-orbit altimetry missions also increases the spatial-temporal resolution of the remotely sensed hydrological variables.

For the Aral Sea (Small and Large), Tchebas Bay, and the different water bodies in the deltas of the Amu and Syr Darya, we present in the following section, water elevation time series deduced from radar altimetry and multi-satellite data, from T/P, Jason-1, Jason-2 and Envisat. This has allowed us, for example, for the Small and Large Aral to derive water level variations from 1992 to 2012, which constitutes 20 years of continuous measurements with a time interval between measurements of 10 days.

11.2.2 Satellite Imagery: MODIS

In order to measure the surface area of water over the Aral Sea Basin, which is a key parameter for determining the water balance of the Aral Sea, we have used the data of the MODIS instrument. It was launched in December 1999 on the sun-synchronous polar orbiting Terra spacecraft (at an altitude of 705 km) and since Feb 2000 has been acquiring daily global data in 36 spectral bands with spatial resolution of 250 and 500 m. The MODIS instrument is a multi-spectral imaging system that observes the whole Earth every day. The basic measurements used to classify the earth's surface are surface reflectance measured over seven spectral bands from the visible to the middle Infrared. The surface reflectance product, which we have used, is defined as the reflectance that would be measured at the land surface if there were no atmosphere. It provides information on the type of surface, which reflects the incident solar energy. A classification method based on the fact that water does not reflect incident solar energy in the infrared part of the spectrum has been developed (Crétaux et al. 2011d) and has enabled monitoring the water surface area of the Aral Sea (see Sect. 11.4 for results).

The surface reflectance product we used (MOD09GHK) is corrected for atmospheric effects. These data are distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the U.S. Geological Survey, Earth Resources Observation and Science (EROS) (http://lpdaac.usgs.gov). The MODIS images are very useful because they offer high temporal and spectral

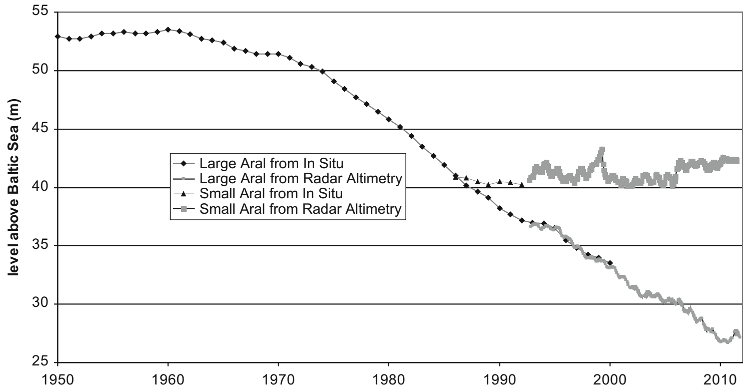

Fig. 11.2 Levels of the Small and Large Aral from 1950 to 2012 from in situ measurements and radar altimetry data

resolution while covering broad areas measured in the several tens of thousands square kilometres and are free of charge. Spatial resolution is 500 m for the images used in our study. Here, we used MODIS images to detect open water area changes over time, principally for the water bodies in the delta of the Amu Darya. MODIS images over the Aral Sea have also been processed.

11.2.3 Aral Sea Monitoring Products from Remote Sensing and Insight on the Water Balance

To understand the use of remote sensing techniques for the contemporary Aral Sea survey, let us first provide a summary of the historical water balance since 1960. At that time, after a few decades of stable water level for the entire Aral Sea, a decision made by political leaders led to a rapid drop of the sea's level and shrinkage of the sea's area (Bortnik 1999). It is not the object of this chapter to report on the historical Aral Sea water level variability, but we nevertheless can note that from the period starting at the beginning of the twentieth century until the latter part of the twentieth century, the Aral Sea level was measured by in situ instruments (staff gauges). From 1992 to 2000 we are therefore able to compare the results obtained from radar altimetry with those measured in situ (See Fig. 11.2). It first of all shows the quite good quality of radar altimetry measurements and allows considering this technique as a good tool for measuring water level variations of the Aral Sea, especially for the last 10 years when no in situ data are available.

11.3 Monitoring of the Aral Sea Basin from Remote Sensing Techniques: Radar Altimetry and MODIS Imagery

11.3.1 Small Aral

From Fig. 11.2, we see that in 1989, the Aral Sea separated into two progressively disconnected water bodies, the Small Aral in the North, and the Large Aral in the South. And as we will see further, 2009 was the first year when the Large Aral has been also separated into two water bodies (SEA for South East Aral, and SWA for South West Aral). On the northern part of the former Large Aral, a smaller saline lake, named Tchebas Bay also formed (see Fig. 11.1). All of these water bodies (Small Aral, SEA, SWA and Tchebas) are crossed by altimetry tracks, which allow measuring their respective levels.

After 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, water began to flow southward into the Large Aral (Fig. 11.3). This outflow took place in the central part of the Berg Strait, which was dredged earlier (in 1980) in order to maintain navigation between the northern and the southern basins. This southward current was slow at first but increased as the level of the Large Aral continued to fall. When the Big 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 stopped. Over the next few years the dam in the Berg Strait (also called Kok-Aral Dam) was partly destroyed by accumulated water pressure and was restored several times (for details see Cretaux et al. 2005).

In April 1999 the dam was completely destroyed and the water of the Small Aral again flowed southward. The water level in the Small Aral dropped about 3 m after this dam's destruction (Fig. 11.3). In 2005 a new dam was built with support of the World Bank and Kazakhstan's government. It has made possible, again, to regulate the water level of the Small Aral: After a sudden increase in level of about 2 m in a few weeks, the dam gates were opened to release the surplus spring-melt water carried by the Syr Darya River, thus maintaining the mean level of the North Aral Sea at 42 m through seasonal releases (in spring) via the Berg Strait dam. These releases of water have sent a few cubic kilometres of water per year to the south via the Berg Strait. Some of this water has reached the former Tchebas Bay maintaining it as a very saline, small lake (Fig. 11.1).

A small amount of water also reached the Large Aral Sea, without, however, being able to stop the level dropping (Fig. 11.4b). During 2010, the level of the North Aral Sea rose more than in previous years (during which there was a systematic surplus due to the spring floods of the Syr Darya River being drained by opening the dike gates), to an average of 42.5 m instead of its normal 42 m. The opening of the gates in 2010 also made it possible to supply a greater volume of water via the Berg Strait towards the south, which also no doubt helped raise the level of Tchebas Lake and the basins of the southeast and southwest Aral.

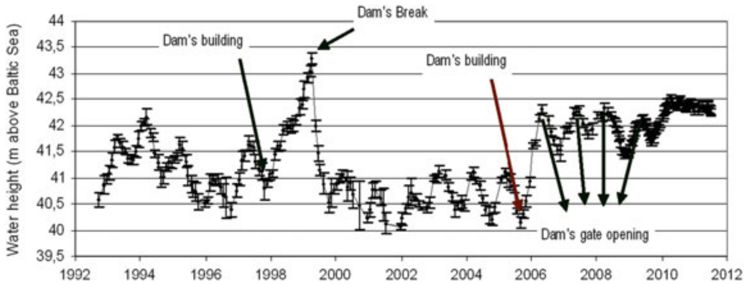

Fig. 11.3 Levels of the Small Aral from radar altimetry measurements (T/P, Jason-1, Jason-2, and Envisat satellites)

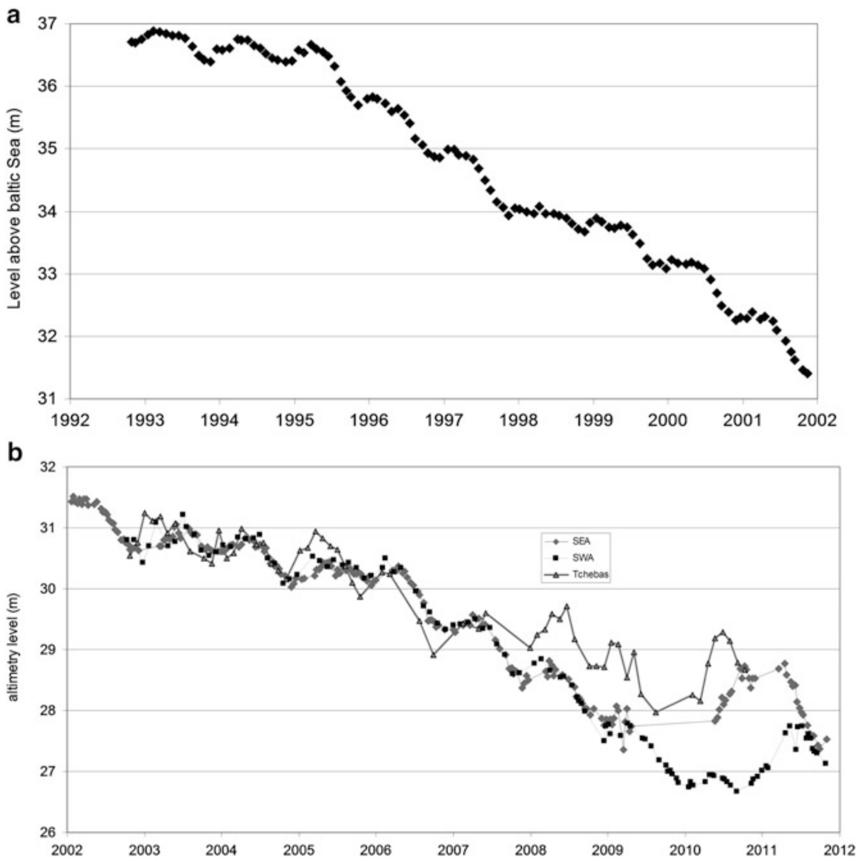

Fig. 11.4 (**a**) Level of the Large Aral 1992–2002 from radar altimetry measurements (T/P, Jason-1 and Envisat); (**b**) of Large Aral (West and East Basin) and Tchebas bay 2002–2011 from radar altimetry measurements (T/P, Jason-1 Envisat and Jason-2)

Furthermore, an article was published on 20 August 2011 in a Kazakhstan daily newspaper about the decision of the Kazakh government to finance the construction of a new dike for the North Aral basin. In an appendix we investigate the impact of this new dike and we provide an estimate of the time needed to fully fill the Small Aral.

11.3.2 Large Aral

Figure 11.4a shows the water level fluctuations of the Large Aral from 1992 to 2005 deduced from T/P, Jason-1 and Envisat. It clearly shows the significant and continuous shrinkage of the Large Aral. The rate of water level decrease was 20 cm/year for wet years (e.g., 1998) to about 1 m/year for very dry year (e.g., 2001). Figure 11.4b shows the water level variations of the Large Aral west (SWA) and east basins (SEA) and of the Tchebas bay, from 2002 to 2012 deduced from radar altimetry of Jason-1, Jason-2 and Envisat only. For the years 2002–2009, the level of both basins dropped at the same rate and their levels were essentially the same.

For 2009, since the level of the SEA had previously dropped so much and its area grown so small, the ground tracks of the *Jason*-1 and *Jason*-2 satellites no longer covered the flooded area; consequently the altimetry measurements were not as capable of showing the level. At the beginning of 2010, the measurements were again able to show the level, following the renewed inflow to the SWA from the Amu Darya, which greatly increased its area. For the SWA, this rise in level occurred later. It probably took some time for the flood arriving from the south east of the basin via the Amu Darya Delta, and which was recorded by altimeters fairly early in this flood episode, to propagate gradually to the North and thus supply the south-west Aral basin whose level also increased strongly during the summer of 2010.

At the beginning of 2011, the southeast Aral was entirely frozen (personal communication from Dr. Peter Zavialov, a Russian researcher at the Shirshov Oceanographic Institute in Moscow), which was not the case for the SWA and which might explain the "gap" in the altimetry measurements at the beginning of 2011 for the SEA. During the spring of 2011, the SEA began to again dry out but, for the first time since this basin had been observed by satellite altimetry, this was not the case for the SWA, or at least it has occurred much later (in June). It is possible that the drop in the level of the SEA was due to an adjustment between the two basins via the Kulandy strait separating SEA and SWA in the north (Fig. 11.1). Altimetry measurements showed that the levels of the two basins were fairly similar during early summer 2011 and then followed again the same behaviour. A time lapse was also observed for the conveying of water between the Amu Darya Delta and part of the southeast Aral basin, which are now about 100 km apart.

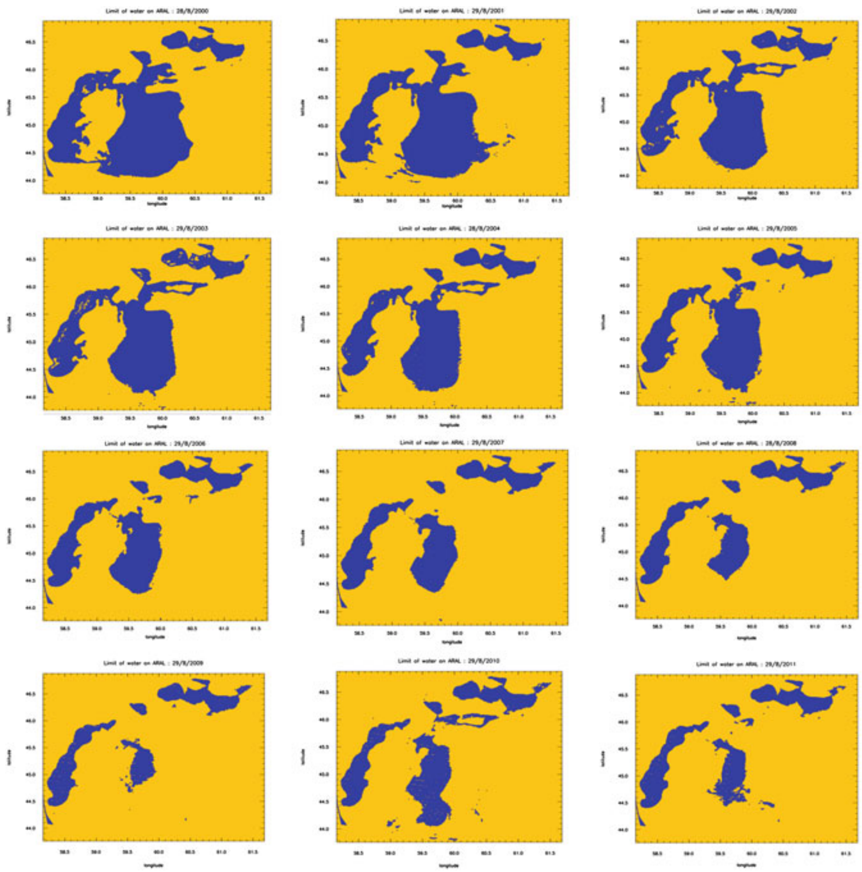

Fig. 11.5 Surface area of Aral Sea 2000–2011 derived from Modis images. Each image was acquired at the end of August of each year

The filling or draining of the SEA and SWA sub basins is no longer instantaneous: we are witnessing the gradual separation of the Large Aral into two basins, which, if the level continues to drop, will become independent of each other as was the case more than 20 years ago for the Small and Large Aral. The MODIS data analysis confirms quite well this scenario. Figure 11.5 shows the water surface decline of the Aral Sea from 2000 to 2011 (each image on this figure corresponds to the end of August of each year). The continuous shrinking of the Large Aral is highlighted by the significant dry year of 2009, and the following year of 2010 when there was a new increase of water surface area of the Large Aral. Between the end of August 2005 and 2006 the effect of the Kok-Aral Dam is also evident on the Small Aral. Figure 11.6 shows, using four MODIS images from March and July 2009 and March and December 2010, that the level drop that occurred in spring 2009 was so large that no altimetry tracks were still crossing the SEA, while in 2010

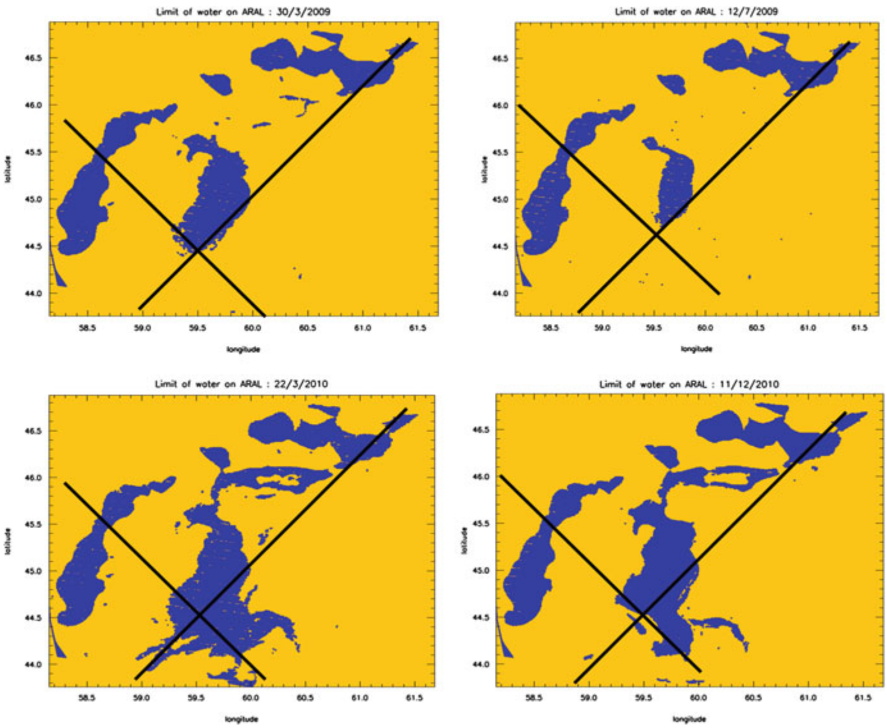

Fig. 11.6 Surface area of Aral Sea in March and July 2009, and March and December 2010 calculated from Modis images. *Black lines* represents the Jason-1, and Jason-2 satellites tracks

the total surface area of the Large Aral increased sufficiently that its surface was rather well covered by radar altimetry. It also shows that during the whole year 2010, overflow from the Berg Strait Dam reached the Eastern Basin of the Large Aral. The Kulandy strait separating SEA and SWA does not appear on this image because of the coarse resolution of the MODIS images (500 m) which resulted in retention of only pixels of 500 m fully covered by water in the classification results. As the Kulandy strait is currently rather narrow it does not appear as inundated although it was. Note that using a high resolution Satellite Image, P. Zavialov observed that a very narrow channel remains open in the Kulandy Strait in 2009 but, not wider than 200 m, smaller than the resolution of the MODIS images we used (P. Zavialov, personal communication). A Recent Landsat 7 band 5 panchromatic image with 15 m resolution acquired on July 14, 2012, shows the Kulandy channel is almost closed at its eastern end, with a width not more than 30 m. (scene ID LE16102820196PFS00, available at http://glovis.usgs.gov/).

11.3.3 Tshchebas Bay and the Water Bodies in the Deltas of Amu and Syr Darya

Tchebas bay (Fig. 11.1) located in the North West of the former Large Aral was at the same level as the Large Aral until 2007. In recent years its decline was less than the Large Aral with an average difference about 1 m higher (Fig. 11.4b). Water level variations of Tchebas Bay have been obtained from radar altimetry measurements from the Envisat satellite. From the DBM (digital bathymetric map) it could be explained by the fact that below a level of around 29.5 m (±50 cm) the Large Aral is not connected anymore to the Tchebas bay, therefore the evaporation volume from Tchebas Bay is smaller (the surface is on average 370 km^2) than from the Large Aral. When water is released from the Kok-Aral Dam, some part still reaches the Large Aral (as seen on the MODIS images in 2008 or 2010 for example, see Fig. 11.5), some part is filling Tchebas Bay (which explains the spring increase in its surface area as seen on Fig. 11.4b). But most of the year we see from MODIS (Fig. 11.5) that the Large Aral and Tchebas Bay are disconnected after 2007. The water level variation of the Tchebas Bay, coupled with DBM data, has allowed calculating the total amount of water entering annually in this bay and therefore not reaching the Large Aral. This has been used to better constrain the water balance of the Large Aral (see Sects. 11.3.2 and 11.4).

The deltas of the Amu Darya and Syr Darya are both regions of ecological importance. The desiccation of the Aral Sea has enhanced the need to maintain sustainable water bodies in the deltas by the construction of artificial reservoirs and wetlands in the deltas. Currently, lakes in the delta of the Amu Darya are either fed by drainage water like the biggest one (Sudochye: Fig. 11.1) or by direct diversion of the Amu Darya River (Mezdurechye). In recent years, with the cooperation of Germany, a plan of rehabilitation of the so-called Priaralye reservoirs in the delta of the Amu Darya has been underway (see CAWATER web site: http://cawater-info.net). In situ monitoring of the water quantity in the Amu Darya Delta, with collection of in situ measurements every 3 months has been performed since 2009.

Thanks to satellite altimetry, with the Evisat satellite, it is also possible to estimate the water level of some reservoirs in this delta. In Fig. 11.7a for example we can see the water level variations of the Sudochye reservoir. From 2003 to 2008, its level has been around 52.5 m, but in 2009 the water balance of this reservoir was mainly negative, hence a significant decrease of 2 m has been observed. This is confirmed by in situ data downloaded from the CAWATER web site. The same observations from satellite altimetry have been made on other reservoirs of the delta. These altimetry measurements, coupled with CAWATER observation data on lake surface areas (confirmed by MODIS data) have allowed computation of the volume of water, which was retained every year in the delta and, therefore, did not reach the Large Aral. This has been used for the water balance computation of the Large Aral (see Sects. 11.3.2 and 11.4).

In the delta of the Syr Darya, a large lake (Kamyshlybas) with an area of about 400 km^2 is also by chance crossed by altimetry tracks (Envisat: Fig. 11.1). Water

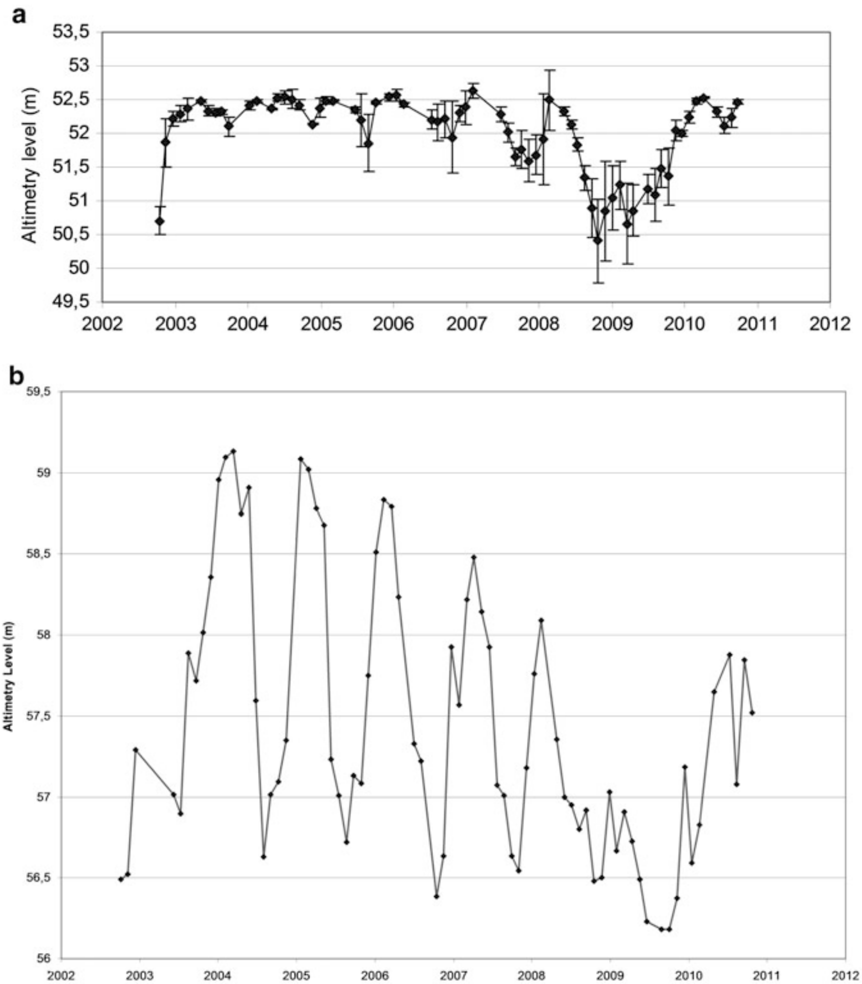

Fig. 11.7 Levels of Lake Sudochie in the delta of the Amu Darya (**a**) and Lake Kamyshlybas in the Syr Darya Delta (**b**) from 2002 to 2010 calculated from altimetry measurement of the Envisat satellite

level variations have hence been calculated from 2002 to 2010. It is shown in Fig. 11.7b. A significant annual oscillation of about 1.5–3 m has been observed from 2002 to 2008 with an inter-annual decrease trend, followed in the very dry year of 2009 by stagnation of the reservoir, and in 2010, due to higher inflow and atmospheric precipitation, it rose again. Using MODIS images to estimate the surface variations of this reservoir in time, and the altimetry data for water level variations, the water balance of the Kamyshlybas reservoir has allowed calculation of the amount of water entering the delta at the post of Kazalinsk and which was retained annually in the reservoir. From 2005 (after the construction of the Kok-Aral dam) to 2010 it has reached between 0.1 and 0.7 km^3/year, which represented 4–10 % of total runoff measured at the entrance of the delta at Kazalinsk. This has also allowed to better estimate total surface water inflow to the Small Aral.

11.4 Water Balance of Aral Sea: Generalities

The volume of stored water in an inland sea like the Aral will vary with time according to changes in the hydrological budget. Lakes and reservoirs will thus exhibit seasonal changes in surface area and level due to proportional changes in precipitation and evaporation (Mason et al. 1994). 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. In an arid region, marked by low precipitation and high evaporation, the sensitivity of an inland sea to water use and climate change is therefore enhanced and the assessment of the lake water balance could provide improved knowledge of regional and global climate change and a quantification of the human stress on water resources across all continents.

The water balance is simply given by the difference of the water inflow and the water outflow, and for a closed (terminal) lake it can be represented by the following equation.

$$dV/dt = (R + Gw) - (E - P) * S(t) + \varepsilon \tag{11.1}$$

Where dV/dt is the volume's variations with time, R is the river runoff, Gw is the underground net inflow, E the evaporation rate, P the precipitation rate, S(t) the surface at the time t, and ε the sum of the remaining uncertainties.

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 have obtained values of evaporation minus precipitation (accounting for seasonal but not interannual variability) up to 1990. Small et al. (2001) have also evaluated the effect of evaporation and precipitation on the Aral Sea level decrease up to 1990 and have separated anthropogenic and climatic factors.

As far as the water balance is concerned in a very arid region like Aral Sea, the contribution of rainfall is slight (of the order of 10–15 cm per year) whereas evaporation is much higher (of the order of 1–1.2 m). Evaporation minus precipitation for the Large Aral Sea has 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 (Fig. 11.8a). Thus, in the last decade of the twentieth century the water supply deficit reached 10–15 km^3/year depending on the year, and the Large Aral has continued to shrink as the equilibrium level was not reached. The only contributor

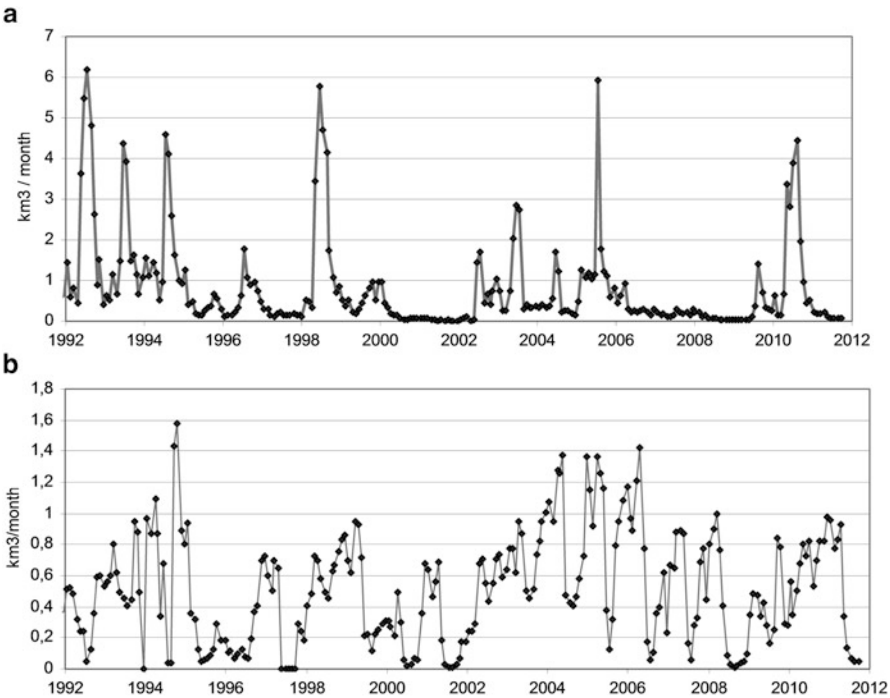

Fig. 11.8 Runoff of Amu Darya (**a**) and Syr Darya (**b**) from 1992 to 2011 from in situ measurements

which could stop the Large Aral basin from drying up would be surface run-off from the Amu Darya whose delta is located in the south-east part of this basin, but this is not possible since too much water is tapped for irrigation in Uzbekistan.

Only excess rainfall would enable a very temporary respite. This is what happened in 2010 with a level which had not been reached for at least 20 years, since, as can be seen in the time series of the level of the Southeast Aral (SEA), the level rose by about 1.4 m in 2010 (Fig. 11.4b). The flooded surface area doubled (from 2,400 to 4,900 km^2 as measured by MODIS data) and the volume was increased fourfold (from 1.75 to about 7 km^3). In situ measurements of the flow of the Amu Darya from the Kyzldjar station (Fig. 11.8a), have confirmed this phenomenon, which occurred in 2010 and explain it very well. The same phenomenon was revealed by altimeter measurements for several other major lakes in central Asia (Balkhash, Zaysan, Sassykol, Issykul, Kapchagayskoye (see Hydroweb: http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/).

Other years with as much rainfall (1998 for instance) did not reproduce this phenomenon since at that time, evaporation predominated. The surface area of the Large Aral Sea was then about three times larger (25,000 km^2 as compared with 8,500 km^2 in 2010) and consequently the evaporation was three times as great. In 2005, since the surface area of the Large Aral had again decreased, the particularly strong floods in that year were also able to prevent the Large Aral basins from drying out but without however reversing the trend.

Benduhn and Renard (2003) 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 to 15 km^3/year) and has an average value of 8 km^3/year. Jarsjö and Destouni (2004) have also estimated the ground water discharge by using the water mass balance equation and different scenarios for the evaporation and precipitation rates. They concluded that ground water 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. Alexseeva et al. (2009), have estimated that the underground water should range between 2 and 7 km^3/year, with increases of the rate of underground discharge of 0.013 km^3/year related to increases of hydraulic gradient correlated to the Aral Sea level drop. Those results also confirm the study made in Oberhänsli et al. (2009) who have 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. Their study however did not provide quantification of this additional water to the Aral Sea, but they concluded their article 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" (quoted in Obershänli et al. 2009). Other studies drew opposite conclusions about underground inflow to the Aral Sea: indeed according to older studies Sydykov and Dzhakelov (1985) and Glazovsky (1990) the groundwater component of the Aral Sea water balance must be negligible and not exceeding 2–3 % of water volume variations. During Soviet times, experts estimated net groundwater inflow from −1.3 to + 3.4 km^3/year (Bortnik and Chistyayev 1990, p. 38)

Another component of the water balance equation, which is hard to accurately measure, is the runoff of the rivers, Amu Darya to the Large Aral and Syr Darya to the Small Aral. Runoffs for these two rivers are measured only at the entrance of their respective deltas, at Kazalinsk for Small Aral and for the Large Aral at Kyzyljar. In such arid regions, and also due to diversion of river water to small reservoirs in both deltas, it is therefore very uncertain to determine the exact water entering into the Aral Sea at the mouths of the deltas (Crétaux et al. 2005; Small et al. 1999, 2001). In Aladin et al. (2005) an attempt to adjust for water lost in the delta of the Syr Darya (based on the water balance of the Small Aral and radar altimetry measurements) have shown that about 10–20 % of water that reached Kazalinsk was lost in the delta. For the Large Aral no real measurements exist for this component although a monthly measurement of river runoff is made at Kyzykjar, which is available on the web site of the CAWATER project (http://cawater-info.net). From 2000 to 2012 we have noted from data extracted from the CAWATER web site the very high inter-annual variability of river runoffs especially of the Amu Darya (see Fig. 11.8a).

11.5 Aral Sea Current Water Balance: What Do We Learn from Modern Satellite Techniques?

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 few data that do exist are fragmentary or unavailable. Because the historical Aral Sea volume cannot be determined accurately, there are large uncertainties in the water balance equations and the reliability of the results has suffered.

By using a combination of satellite altimetry measurements and a dedicated DBM with a 250 m spatial resolution, it is now possible to observe the volume variations of the Aral Sea (See Crétaux et al. 2005) for more details).

A verification of the validity of this DBM has been performed by comparison of surface water area of Large and Small Aral inferred from the combination of radar altimetry and DBM with surface area of the Aral Sea measured by MODIS over the last 10 years. Figure 11.9 shows that the agreement between both methods of calculation of surface area has a correlation coefficient of more than 0.99. It is therefore possible to estimate water volume variations of Small and Large Aral with high precision and use them to solve the water balance equation. Here we determine a water balance for the Large Aral utilizing satellite techniques in conjunction with terms for the equation for evaporation, precipitation and river runoffs taken from different sources. The purpose is to determine if right and left members of Eq. 11.1 can be equalized and if underground water inflow to Aral Sea can be estimated.

As far as evaporation is concerned, we used the model given in (Bendhun and Renard 2003) and (Gascoin and Renard 2005), who have taken into account the salinity of the Large Aral, which tends to diminish the evaporation rate. From their estimation this component of the water balance has an absolute value of 1,160 mm/year.

For precipitation input, monthly averaged in situ data are available on the CAWATER project website but end at the beginning of 2000. On average the precipitation over the region is 1.3 cm/year. From other sources like the GPCP products or the satellite data (TRMM) the precipitation is higher but there is general agreement among different studies (Crétaux et al. 2005) that converge to 1.3–1.4 cm/year. We simply used the TRMM data to modulate yearly the average amount of precipitation in order to better take into account the succession of wet and dry years over the period of observation (for example a 30 % water excess was observed in 2010). From the CAWATER web site the precipitation measured near the Aral Sea until the end of the 1990s was between 40 and 170 mm/year depending on the year. Due to uncertainties on these two components of the water balance we consider that the error is about 100 mm/year.

To solve the question of the "real" amount of water entering the Small and Large Aral from rivers we have calculated the water balance of each as well as for the water bodies in the delta and for Tchebas Bay from September 2005 (just after the construction of the Kokaral dam) to the end of 2010 (period of the last Envisat data). Figure 11.7a, b gives water level fluctuations of Tchebas Bay and reservoirs in both

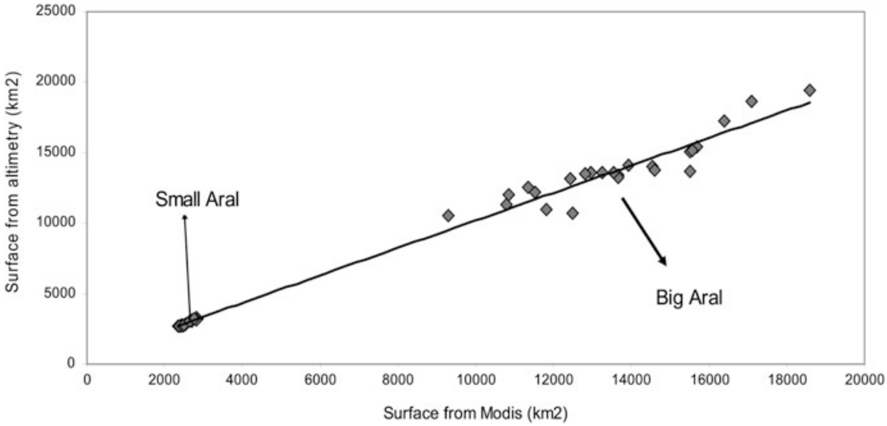

Fig. 11.9 Scatter plot of surface area of Small and Large Aral comparing measurements from Modis images, and Altimetry combined to DBM

deltas. To convert into volume, we have used MODIS water surface area variations for each of these water bodies.

We have calculated for each delta the water losses from the measurement station to the Aral Sea (respectively Small and Large Aral). Yearly losses from 2005 to 2010 varied from 3 % to 40 % in the Amu Darya Delta. The remaining discharge to the Large Aral ranged from 1 km^3 (2009) to 16 km^3 (2010) leading to a highly variable inter-annual water balance. From the Small Aral, we have calculated yearly discharge across the Berg Strait Dam of excess water in the Small Aral and then we have subtracted water that enters Tchebas Bay and estimated evaporation from the water bodies formed south of the Berg Strait Dam. The residual added to Large Aral water balance: it has ranged from 0 to 2.6 km^3/year.

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

$$dV/dt = (P(t) - E(t)) * S(t) + R_{ad} + R_b \qquad (11.2)$$

$R_{ad} + R_b$ are the monthly inflow from the Amu Darya and from the Berg Strait, and S(t) is the inundated area of the Large Aral (including West and East basins) 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 on Fig. 11.10. As the uncertainty on evaporation and precipitation rate may be in the range of 10 % we have made several small changes in the E-P component of the water balance, but this did not change the conclusion. Water balance in the two deltas has also been modified (using different assumptions on evaporation, water withdrawal from the rivers and precipitation) but this had also a small impact on the water budget. In all cases, we simulated realistic changes of the different

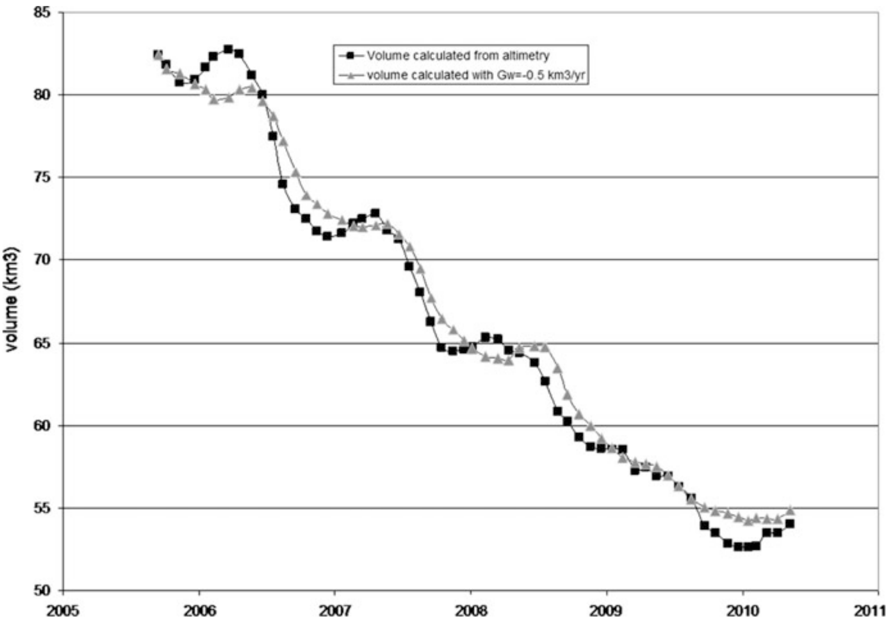

Fig. 11.10 Volume of Large Aral from combination of altimetry and DBM versus volume deduced from water balance with an adjusted ground water input of -0.5 km^3/year

parameters. The underground water component from our analysis comprises between -0.5 and $+0.5$ km^3/year, numbers that are within the global uncertainty of the calculation.

The Fig. 11.8a. b gives the monthly river runoff at Kyzyldjar and Kazalinsk. Figure 11.10 shows the volume variation of the Large Aral in two cases: from radar altimetry and from the water balance equation with underground water of -0.5 km^3/year which is the adjusted value for closing the water budget of the Large Aral. However this conjecture needs to be further assessed by hydrogeological modelling and more accurate data on the evaporation and precipitation rates that are, for all studies made until now, the main limiting parameters of the water balance.

11.6 Future of Remote Sensing for Hydrology and Conclusions

What does the next decade hold for Aral Sea Basin monitoring from Space? Multispectral imagery from MODIS is still (in 2012) operating and is well suited to monitor the water surface area of water bodies over large regions with continuous data at relatively high temporal resolution. It is particularly well adapted for the Arid Zone as the cloud cover is often rather low. In the framework of the establishment of the new Global Monitoring for Environment and Security (GMES) capacities by the European Union, several new missions have been planned for the next decade, with dedicated missions in land monitoring from multispectral sensors (Sentinel-2), and radar altimetry in dual Ku-C bands (Sentinel-3). Sentinel-2 will provide multispectral imagery at high resolution (4 spectral bands at 10 m, 6 at 20 m and 3 at 60 m), with full coverage of the Earth every 5 days. It will consist of a pair of satellites, with initial launch in 2013. This will be more suitable to monitor the areas of small water bodies in the deltas of the Amu Darya and Syr Darya. The Sentinel-3, mission is designed to measure sea surface topography but classical radar altimetry will also be used for water level estimation on lakes and reservoirs. Sentinel-3 will also consist of a pair of satellites with expected first launch in 2013. In 2013, the Centre National d'Etudes Spatiales (CNES) and Indian Space Research Organisation (ISRO) will launch the Saral/Altika mission, which will be the first altimeter operating in Ka band which will have the main advantage of a better spatial resolution due to the smaller footprint of the radar signal (150 m instead of several km), allowing a better discrimination of surface water area for small water bodies. This mission will be placed in the same orbit as Envisat and will hence allow continuing the monitoring of water bodies irs in the delta. It should be noted that Envisat ceased at the end of 2010 to provide data on repeat orbit, and was totally switched off at the beginning of 2012. In 2013, the CNES, EUMETSAT, and NASA will continue the Jason program, with the launch of Jason-3 radar altimeter in Ku and C bands and in 2017 with the launch of the Jason-CS mission for operational oceanic purposes.

However, none of those missions is dedicated exclusively to continental hydrology. The future SWOT (Surface Water and Ocean Topography) mission is the first satellite mission dedicated to the measurement of continental surface water. SWOT will provide a global inventory of all terrestrial water bodies whose surface area exceeds 250 m by 250 m and rivers whose width exceeds 100 m, at sub-monthly, seasonal and annual time scales (Biancamaria et al. 2010). The principal instrument of SWOT will be a Ka-band Radar Interferometer (KaRIN), which will provide heights and co-registered all weather imagery of water over two swaths, each 60 km wide, with an expected precision of 1 cm/km for water gradients and absolute height level precision of 10 cm/km^2. SWOT will also provide an estimate of river discharge, and map floodplain topography and channel reaches.

For the Aral Sea Basin, the monitoring improvement will be enormous. River runoff will be estimated every 10 km along the Syr Darya and Amu Darya rivers. The whole delta's wetlands (with a resolution of 250 m by 250 m) will also be monitored. Volume fluctuations of small water bodies will also be estimated from SWOT missions, which is a key parameter for water balance computation. The potential of SWOT measurements will be enhanced if coupled with other remote sensing data (radar altimetry, imagery, gravimetry and meteorological satellite data sets). It will considerably improve our understanding of the Aral Sea Basin, not only just the terminal Aral Sea water body, but in fact, all water bodies in Central Asia (including small reservoirs and lakes, rivers and floodplains).

The combined radar and multispectral approach described in this chapter demonstrates the current capabilities for operational space monitoring of the areas and levels of the Aral Sea and water bodies in the deltas. It also shows the serious limitations of current technologies, which could be overcome by future missions. By complementing in situ observations and hydrological modelling, space observations have the potential to improve significantly our understanding of hydrological processes at work in the entire Aral Sea Basin (ASB) and their influence on climate variability, and socio-economic life. It offers a comprehensive view of the ASB, continuous and accurate spatial-temporal sampling, and the capability to determine with reasonable accuracy the water balance of the Aral Sea. It also helps to understand in "real time" how the Aral Sea is evolving.

Appendix: Scenarios of Evolution of Small Aral

On August 20, 2011 an article was published in a Kazakhstan daily newspaper about the Kazakh Government's plan to refill the Small Aral to the level of 50 m above the Baltic Sea as measured at the Kronstadt gauge on the Gulf of Finland near St. Petersburg. The purpose is to fully renew the Small Aral as it was before and that the city of Aralsk becomes again a major fishing center on the North coast of the Aral Sea. To accomplish this, two scenarios are under consideration.

The first one is to raise the existing dike in the Berg Strait, which today does not allow reaching this objective. The second one consists in the construction of a new dike at the mouth of the bay southwest of Aralsk's harbor, hence leading to the separation of the Small Aral into two separate water bodies (upper and lower, see Fig. 11.11). The height of this new dike would allow the level in the upper reservoir to reach 50 m. The reservoir formed would have a maximum depth of about 10 m, and a volume of 5 km^3. A canal coming from the Syr Darya would supply it. This project costing millions of dollars would be partly financed by the Kazakh government and partly by the World Bank, as was the case in 2005 for the Kok-Aral Dam.

From DBM (digital bathymetry map) of Aral Sea and the water balance equation we are able to compare both scenarios in terms of the time necessary for achieving the final objective. With the current average water inflow into the Small Aral from river runoff (R) of the Syr Darya river (~5/6 km^3/year) and with annual water release through the berg's strait of about 2–3 km^3 the total annual average area of the Small Aral (A_0) is about 3,200 km^2 and the current annual average volume of the Small Aral (V_0) is 26.8 km^3.

Scenario 1

If the Kokaral dam is raised to 50 m at least and if water release is stopped during the filling of the Small Aral, the new equilibrium surface of this basin is given by

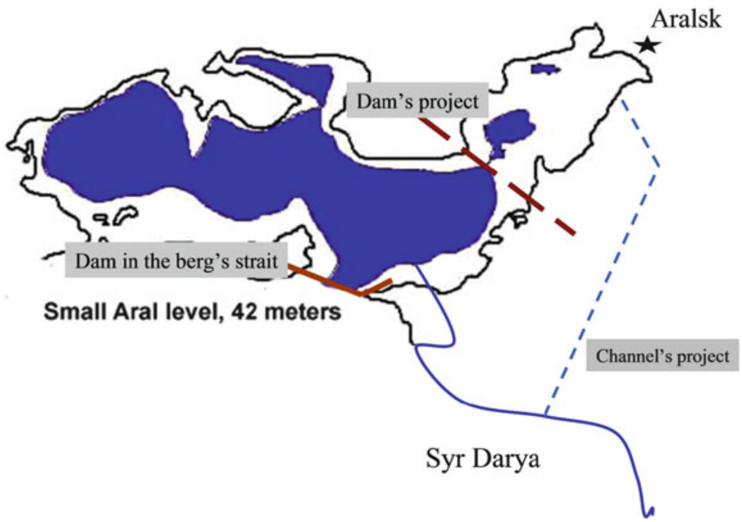

Fig. 11.11 Map of Small Aral with the project for construction of a new dike at the entrance to the Gulf of Saryshaganak southwest of the city of Aralsk

$$A_{LE} = \frac{R}{(E - P)} \tag{11.3}$$

From the DBM, at water height of 50 m, the surface of the Small Aral is 5,066 km^2. It corresponds well to equilibrium water surface of this basin with R = 5 km^3/year and average net evaporation of 1 m/year. 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. That current equilibrium is broken by the additional water supply from the Syr Darya River (3 km^3/year of net supply after subtracting the water discharged from the Berg Strait Dam).

τ_ε is given by the following equation:

$$\tau_e = \frac{1}{dA/dV(E_l - P_l)} \tag{11.4}$$

Where dA/dV corresponds to the average slope of the bottom topography and is given by $(A_{LE} - A_0)/(V_{LE} - V_0)$

From Mason et al. 1994, we also may calculate the Area of the Small Aral at each time span (yearly in our case) given by the following equation:

$$A_l(t) = A_0 + [A_{LE} - A_0]\left(1 - e^{\frac{-t}{\tau_e}}\right) \tag{11.5}$$

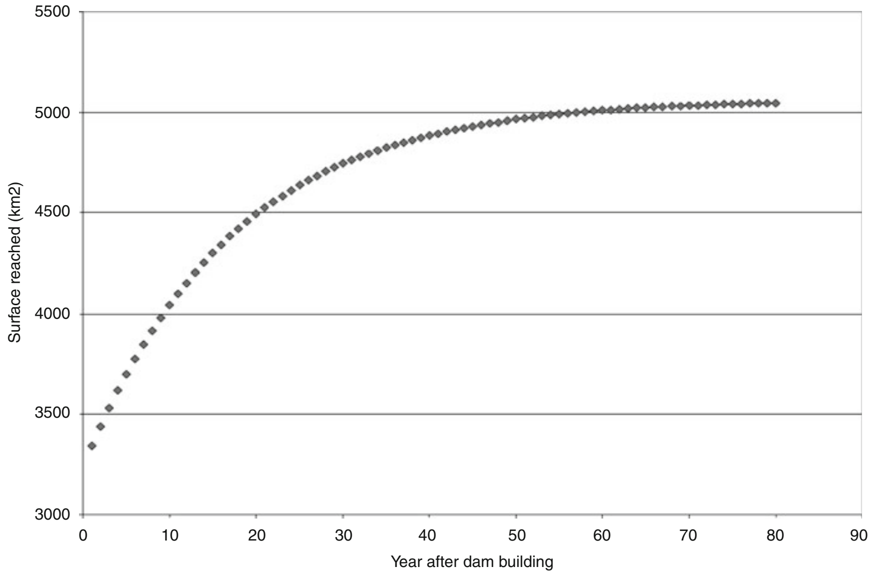

Fig. 11.12 Evolution of surface area of the Small Aral for the next 80 years if the existing dam is raised to 50 m

We have obtained for τ_ε, a value of 17.3 years, and from Eq. 11.5 (Fig. 11.12) the total time to reach the water level of 50 m, therefore an equilibrium surface of 5,066 km^2, is about 70–80 years.

Scenario 2

Let us see now about the time to fill both reservoirs if a second dam is built as explained above. From DBM we have calculated that the surface of the upper reservoir would be 800 km^2. From Eq. 11.3 we calculate that the runoff necessary to insure equilibrium at this surface area is 0.8 km^3/year. From Eq. 11.4, considering that a canal would divert this amount of fresh water into this reservoir yearly, the equilibrium response time τ_ε, would be 6.25 years, and from Eq. 11.5 the time for fully filling the reservoir would be about 25–30 years. For the lower reservoir, which would receive the residual runoff from the Syr Darya of about 4–5 km^3/year, and have a surface of about 3,000 km^2, this would limit annual releases from the Berg Strait Dam southward toward the Large Aral to about 1–2 km^3.

Let us now assume that for a short period of time, the flow of water into the upper reservoir would be more than the runoff of 0.8 km^3/year necessary to maintain a surface area of 800 km^2. This would obviously accelerate the filling of this water body. Assuming that 3 km^3/year is necessary to maintain the lower reservoir at equilibrium, about 2–3 km^3/year would remain that could be used to fill the upper reservoir. Employing the same computation that has been done above indicates that only 2–3 years would be required to fill this reservoir.

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