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Global surveys of reservoirs and lakes from satellites and regional application to the Syrdarya river basin

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Abstract

Large reservoirs along rivers regulate downstream flows to generate hydropower but may also store water for irrigation and urban sectors. Reservoir management therefore becomes critical, particularly for transboundary basins, where coordination between riparian countries is needed. Reservoir management is even more important in semiarid regions where downstream water users may be totally reliant on upstream reservoir releases. If the water resources are shared between upstream and downstream countries, potentially opposite interests arise as is the case in the Syrdarya river in Central Asia. In this case study, remote sensing data (radar altimetry and optical imagery) are used to highlight the potential of satellite data to monitor water resources: water height, areal extent and storage variations. New results from 20 years of monitoring using satellites over the Syrdarya basin are presented. The accuracy of satellite data is 0.6 km^3 using a combination of MODIS data and satellite altimetry, and only 0.2 km^3 with Landsat images representing 2–4% of average annual reservoir volume variations in the reservoirs in the Syrdarya basin. With future missions such as Sentinel-3A (S3A), Sentinel-3B (S3B) and surface water and ocean topography (SWOT), significant improvement is expected. The SWOT mission's main payload (a radar interferometer in Ka band) will furthermore provide 2D maps of water height, reservoirs, lakes, rivers and floodplains, with a temporal resolution of 21 days. At the global scale, the SWOT mission will cover reservoirs with areal extents greater than 250×250 m with 20 cm accuracy.

1. Introduction

During the 20th century, the number of reservoirs has been relatively stable (until the 1950s), then increased continuously, with a peak in new reservoirs built at the beginning of the 1980s (Chao *et al* 2008). At a regional scale, reservoirs are an important component of water resources management and, due to the international nature of many river basins, can play a role in regional politics. The main role of reservoirs is to control water resources in river basins. They allow mitigation of negative impact of inter-annual flooding, produce electricity, or supply water for irrigation and cities.

Currently, more than 260 rivers worldwide are considered as transboundary and drain a total of 145 countries (Wolf *et al* 1999, Sood and Mathukumalli 2011). In other words, a large number of countries depend on water originating from one or several upstream countries. Therefore, any new construction of dams, or development of irrigation systems can potentially create a conflict. Climate change and population growth are projected to increase freshwater demand in the future. Gleditsch and Hegre (2000) show that the potential for conflict over transboundary river basins due to water sharing will increase over time.

In order to coordinate international use of transboundary river water resources, in many parts of the world, riparian countries have created international committees for water management and sharing. Although, in general, such committees are a political tribune for countries to debate and decide on water quotas and legal dispositions, often the basic data on total water stored in reservoirs, operational modes (release or retention of water), or river discharges are

Table 1. List of past, current and future satellite radar altimetry missions. The period of operation corresponds to the period when the altimeters were functioning, not necessarily the entire life time of the satellite. CNES: Centre National d'Etudes Spatiales, NASA: National Aeronautics and Space Administration, ESA: European Space Agency, NOAA: National Oceanic and Atmospheric Administration, EUMETSAT: European organisation for the exploitation of METeorological SATellites, ISRO: Indian Space Research Organisation, CAST: China Academy of Space Technology. L-band: 1.275 Ghz, Ku-band: 13.6 Ghz, Ka-Band: 35.75 Ghz.

Mission	Agency	Period of operation	Orbital cycle (days)
	PAST		
SEASAT (L)	NASA	1978 (June–October)	17
GEOSAT	US-Navy	1985–1990	17
TOPEX/POSEIDON (Ku)	NASA/CNES	1992–2005	10
JASON-1 (Ku)	NASA/CNES	2001–2012	10
GFO (Ku)	US-Navy	1998–2008	17
ERS-1 (Ku)	ESA	1991–2000	35
ERS-2 (Ku)	ESA	1995–2003	35
ENVISAT (Ku)	ESA	2001–2011	35
	PRESENT		
JASON-2 (Ku)	NASA/CNES/NOAA/EUMETSAT	2008-	10
SARAL/AltiKa (Ka)	CNES/ISRO	2013-	35
HY-2A (Ku)	CAST	2011-	14
CRYOSAT-2 (Ku)	ESA	2010-	369
	FUTURE		
JASON-3 (Ku)	NASA/CNES/NOAA/EUMETSAT	2015-	10
SENTINEL-3A (ku)	ESA	2015-	27
SENTINEL-3B (Ku)	ESA	2016-	27
JASON-CS (Ku)	ESA/NASA/CNES/NOAA/EUMETSAT	2017-	10
SWOT (Ka)	NASA/CNES	2020-	21

considered sensitive information or monitoring of such parameters is limited for economic reasons.

Based on modeling analysis Biemans *et al* (2011) show that water supply by reservoirs worldwide for irrigation has increased from 18 to 460 km³ yr⁻¹ throughout the century with large disparities among different regions globally, particularly in Asia, Europe and Africa. Data on irrigation water needs are difficult to collect in many parts of the world (Biemans *et al* 2011), and reservoir impacts on downstream river discharges has mainly been most accurately quantified over North America (Gao *et al* 2012).

Since the early 1990s, radar altimetry has provided valuable information on water levels over rivers, lakes and reservoirs (Birkett 1995, Cretaux and Birkett 2006, Calmant *et al* 2008). Additionally, satellite imagery can be used to develop water contours, and if used in combination with radar altimetry data, allow estimation of inter-annual and seasonal water storage variations of lakes and reservoirs (Gao *et al* 2012, Song *et al* 2013, Arsen *et al* 2014). In Gao *et al* (2012) for example, radar altimetry combined with MODIS imagery have been used to compute storage variations in 34 large reservoirs globally. Data on water levels of 63 large reservoirs globally (and volume variations of 15 of them) are also available in the Hydroweb database: http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/ (Cretaux *et al* 2011a).

From the beginning of the satellite radar altimetry era (i.e. 1978, with the launch of Seasat) until now, several missions have been used to calculate water level variations over lakes and rivers: Geosat, T/P, JASON-1, JASON-2, GFO, ENVISAT, ERS-1, ERS-2, HY-2A,

and SARAL/AltiKa. From now to the launch of the surface water and ocean topography (SWOT) mission in 2020, time series obtained from historical data will be extended as a result of new missions (table 1): S3A (2015) and S3B (2017), JASON-3 (2015), and JASON-CS (2017). Then, the wide swath interferometer onboard the SWOT satellite will allow coverage of the entire Earth with a hectometer resolution.

The objective of this paper is to illustrate the use of satellite remote sensing data for surveying reservoirs at the regional scale using results along the transboundary Syrdarya river basin as a case study. We will show that when *in situ* data are lacking, then satellites can be a useful tool for water management purposes.

This paper is organized as follows: section 2 provides a description of remote sensing techniques generally used to survey lakes and reservoirs for water height and volume variations. This is the methodology used for the Hydroweb database. In section 3 we present and discuss the main results obtained from satellite data in the case study of the reservoirs along the Syrdarya river basin in Central Asia. Perspectives together with conclusions are drawn in section 4.

2. Remote sensing for reservoir monitoring

In this section we present the methodologies used to calculate reservoirs water height and surface from remote sensing techniques. This is the approach used to compute the Hydroweb products. Reservoirs volume variations are then easily computed using the following equation assuming that the bathymetries of lakes have a pyramidal shape (Abileah *et al* 2011):

$$\Delta V = \frac{(L1 - L0).\left(A1 + A0 + \sqrt{A1 \times A0}\right)}{3}, \quad (1)$$

where ΔV is the volume variation between two consecutive measurements, $L1$, $L0$ and $A1$, $A0$ are levels and areal extents at date $T1/T0$ respectively.

2.1. Satellite radar altimetry

A radar altimetry measurement is the distance between a satellite and Earth surface deduced from the time for a radio signal to be reflected back to the emitter onboard (Birkett 1995). All of the basics for the use of radar altimetry over continental water can be found in Birkett (1995), Cretaux and Birkett (2006), Calmant *et al* (2008) and Gao *et al* (2012). In the present paper, the methodology used for altimetry data processing is exactly the same as described in Cretaux and Birkett (2006). Several factors result in the increased use of radar altimetry in hydrology:

Due to the extremely large number of lakes and reservoirs on the Earth, it is impossible to measure them globally from the ground. Moreover the number of *in situ* gauges has declined over the past years, or their data are not available.

- Satellite radar altimetry has moved from experimental to operational under the support of agencies from many parts of the world (Europe, USA, China, India) assuring continuity of services.

- Accuracy of satellite altimetry products for lakes, rivers and reservoirs is high enough to be exploitable for different purposes, from science to operational (Biancamaria *et al* 2011, Ričko *et al* 2012, Hossain *et al* 2014).

In Cretaux *et al* (2009) and Ričko *et al* (2012), it has been shown that for large lakes (with an area >100 km^2), the accuracy of satellite altimetry products may be as low as 2 cm. However, accuracies for narrow reservoirs range from 10 s of cm to 1 m (Duan and Bastiaanssen 2013).

However for most reservoirs, altimetry can be used to measure long-term variations in water levels because the order of magnitude of variations ranges from meters to decameters. Improvements in these results are expected from the SARAL/AltiKa mission (Arsen *et al* 2015)

The future of nadir altimetry moves towards the synthetic aperture radar (SAR) mode which is expected to improve the ability of altimeters to measure water heights over small or narrow water bodies such as rivers and reservoirs. In SAR mode, the along track resolution (300 m) is much higher than in low resolution mode (LRM) diminishing the footprint's areal extent by a factor of 100. Moreover, the signal to noise ratio is expected to increase with respect to LRM. SAR will have the ability to refocus the measurement target point along track, allowing better selection of the water body, thus lowering the pollution of the signal from surrounding terrain. Moreover, the S3A/S3B tandem orbit configuration will increase the coverage of the Earth. Altogether, this new configuration, orbit and system of measurement, will significantly improve, quantitatively and qualitatively the survey of narrow reservoirs. It will therefore be possible to conduct global surveys of reservoirs by the years 2015–2016.

2.2. Satellite imagery

We have used satellite imagery from Landsat 7 ETM+ and Landsat 5 TM, available on the US Geological Survey GLOVIS images archive (http://glovisusgs.gov/), and from the TERRA/MODIS instrument available through the Land Processes Distributed Active Archive Center, Earth Resources Observation and Science https://wist.echo.nasa.gov/api/. There are many methods for the extracting water surfaces from satellite imagery, which, according to the number of bands used, are generally divided into single-band and multi-band methods. With Landsat images the water masked is based on a supervised combination of multi band ratio characterized by the normalized difference waterIndex (NDWI) (McFeeters 1996) and the modified normalized difference water index (MNDWI) (Xu 2006). Selecting an adequate threshold value to establish a water mask can be very tricky because the threshold value of the NDWI for delineating open water features is known to vary in multi-temporal studies (McFeeters 1996, Liu *et al* 2012). These indexes are expressed by the following equations:

$$\text{NDWI} = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \quad (2)$$

$$\text{MNDWI} = \frac{\text{Green} - \text{MIR}}{\text{Green} + \text{MIR}} \quad (3)$$

(MIR and NIR represent mid and near infra red parts of the spectrum, respectively.) Starting from an initial value of 0.4, we then apply manual adjustment of the threshold (all pixels above are assigned to be inundated) on a satellite by satellite basis in order to achieve a more accurate result in the water delineation (McFeeters 1996, Ji *et al* 2009, Clemens *et al* 2012, Arsen *et al* 2014). Water class is maintained constant during the study, guarantee stability of the classification.

In the simplest approach a single band can be selected from a multispectral image and used to extract water surface information. In the method described in Cretaux *et al* (2011b) and Arsen *et al* (2014) it was assumed that the strong water absorption at wavelength >1 μm allows delineation of open water over lakes, without any consideration of normalized index. The method has been used and validated in several studies in arid zones (Abarca-Del-Rio *et al* 2012, Pedinotti *et al* 2012, Aires *et al* 2013) and will be illustrated in section 3 using the Syrdarya basin case study.

Figure 1. Water mask (black color) calculated with Landsat 5 images (9 June, 2004) over the Lake Powell in USA derived from the approach based on the NDWI and MNDWI index.

More information about the Hydroweb MODIS data processing can be found in Cretaux *et al* (2011a) and (2011b). We also recommend processing guidelines proposed by Ji *et al* 2009. Figure 1 provides an example based on the classification done over the Lake Powell with a Landsat-5 image collected on 9June, 2004, based on the NDWI test.

2.3. Computation of water surface and volume in Hydroweb

To compute reservoir area variations with time in Hydroweb, we use a method based on the relationship between level and surface. We determine when water levels in a reservoir were at the maximum, minimum and at some intermediate level from radar altimetry time series in order to select corresponding satellite images. We preferentially use Landsat 7 ETM+ and Landsat 5 TM images but also MODIS when the spatial resolution is not an issue. We process 10–15 images collected at different dates to compute the area versus water level function (called hypsometry). The areal extent of the reservoir is then recalculated using the hypsometry and the radar altimetry time series. The function selected is either a linear relationship or a quadratic polynomial to fit as closely as possible to the shape of the hypsometry curve.

The areal extent time series in the Hydroweb database may vary slightly from that of others studies. These differences are perfectly understandable. As there is no clear definition on where a lake or reservoir starts or ends, each author performs its own delineation. Discrepancies among results may be greater due to low-resolution bias which is the inaccuracy
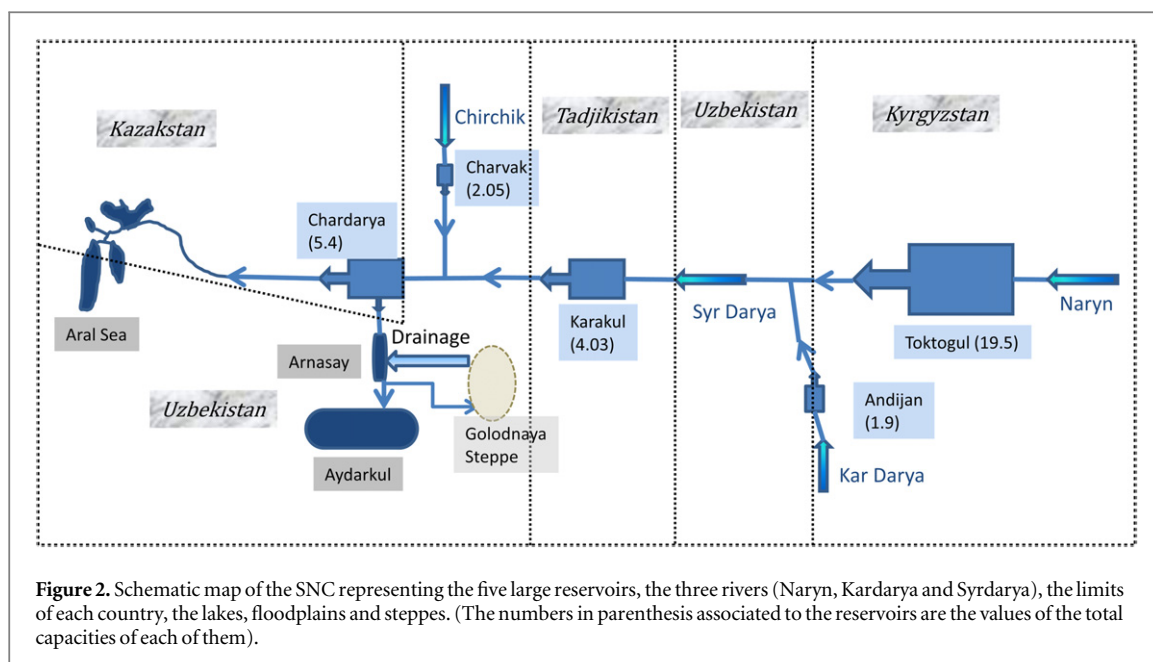
introduced by the differences in spatial resolution between high and low-resolution data (Boschetti *et al* 2004).

3. Reservoirs along the Syrdarya river

This section presents an application case of satellite data to derive potentially useful information for water management purposes, in the context of a transboundary river basin where reservoirs play a crucial role.

An internet database (named Cawater: www.cawater-info.net) of *in situ* quantitative information on reservoirs including water volume, inflow and outflow, and reports with metadata and maps was freely accessible during the years 2010–2011. It is now only accessible to authorized users, and we could not download *in situ* data for the past few years. We have used this database in order to:

- compare the water volume with products inferred from remote sensing data

- combine *in situ* and satellite data to lengthen time series of water storage variations of reservoirs

- show that in cases where no *in situ* data are available, then the satellite data can be used although the accuracy may be lower.

Figure 2. Schematic map of the SNC representing the five large reservoirs, the three rivers (Naryn, Kardarya and Syrdarya), the limits of each country, the lakes, floodplains and steppes. (The numbers in parenthesis associated to the reservoirs are the values of the total capacities of each of them).
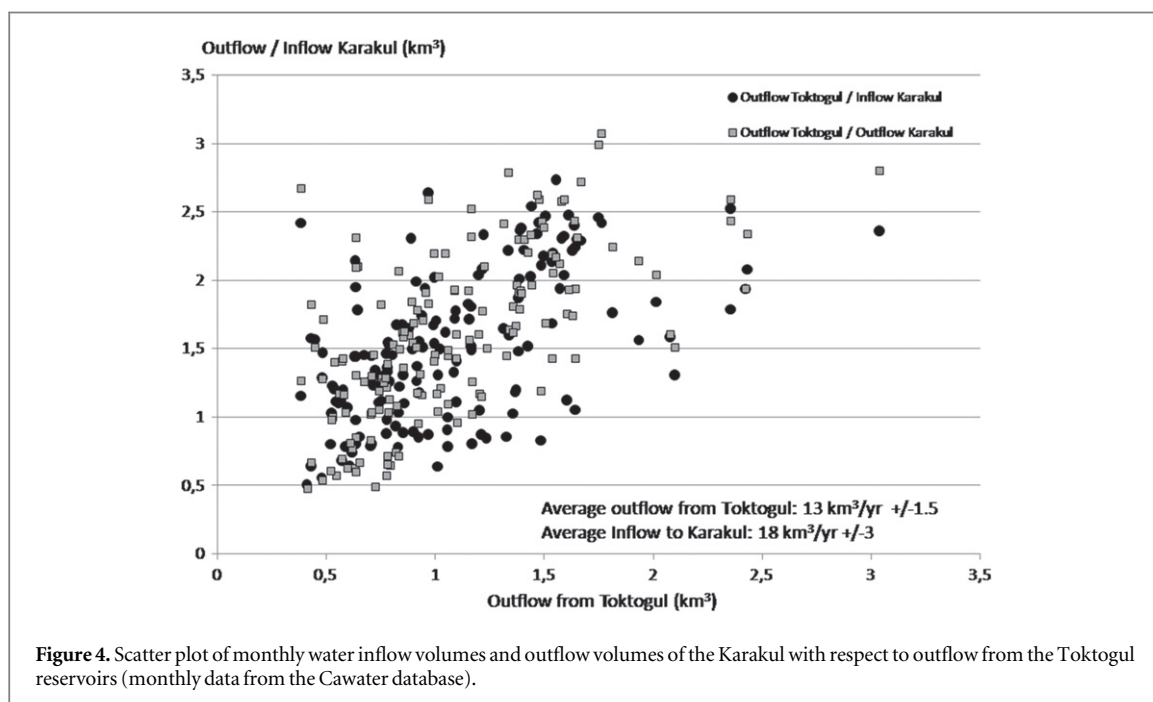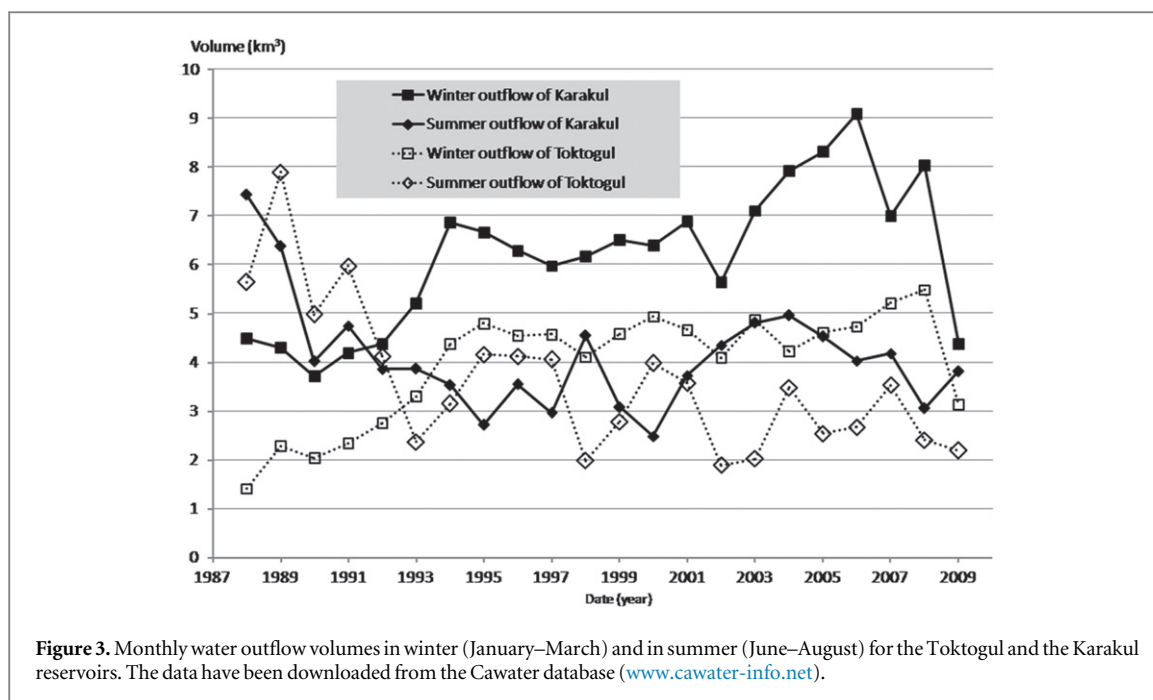
3.1. General context

The Syrdarya river is located in Central Asia, and belongs to the Aral Sea Basin (figure 2). It is sourced from two locations, in the Tian Shan and Pamir Mountains in Kyrgyzstan (Naryn and Kardarya rivers). Both rivers join together to form the Syrdarya in Uzbekistan between the Toktogul and the Karakul reservoirs. The total drainage area of this river is 485 000 km^2 and it has a length of 2337 km from the confluence of the Naryn–Kardarya rivers to the Aral Sea. The middle reach of the river crosses a steppe region and it terminates in the Aral Sea. The Syrdarya River, which until 1991 was located in the territory of the Soviet Union, is now shared by four independent countries, Kyrgyzstan, Uzbekistan, Tadjikistan and Kazakstan.

Surface runoff of the Syrdaria river, totals ~41 km^3 yr^{-1} with an average of 38 km^3 yr^{-1} between the sources and the Chardarya reservoir (figure 2). Its flow is almost fully regulated by a series of reservoirs, from the Toktogul in Kyrgyzstan to the Chardarya in Kazakstan and along its tributaries, such as the Chirchik and the Kardarya rivers (figure 2). Over the 20th century, irrigated land increased by a factor of two due to the Soviet Union's policy for economical development of remote areas in Central Asian steppes lowlands (Micklin 1988, Cretaux *et al* 2013). Along the 1000 km river's length between the Toktogul and the Chardarya reservoirs, three other main reservoirs (Karakul, Andijan and Charvak) are included to the Naryn–Syrdarya-cascade (NSC) (figure 2). The Toktogul is the main regulator of the NSC for two reasons: it has the largest water storage capacity, and it is located in the upstream part of the NSC.

When the reservoirs were built, (between 1930 and 1970), their role was to release most of the water during the so called 'vegetation season' for irrigation purposes, between April and September, and to accumulate water in the reservoir during the autumn and winter months. However, due to climate conditions of the regions crossed by the river (cold and rainy in winter in the upstream part and warm and arid in the low lands), major water consumers located in the downstream republics had to be supplied in summer time, while upstream republics need water release to generate energy in winter. Therefore, to compensate for the fact that upstream republics (Kyrgyzstan and Tadjikistan) could not use the water stored in the Toktogul and Karakul reservoirs to produce hydro-electricity, energy supplies were provided by delivery of gas and oil (abundant in downstream republics). When the Soviet Union collapsed in 1991, the Syrdarya river became transboundary with new water management issues. In 1992 countries agreed to not change the quota of water use but no strict resolution of compensation for energy losses in winter by the upstream countries had been signed (Weinthal 2006). These quotas have then been challenged by Kyrgyzstan, which could not afford to store water in the Toktogul reservoir in winter. Consequently, in the winter of 1992–1993 water release from the Toktogul reservoir started to increase. From 1987 to 1995 winter releases increased from 1–2 to 4–5 km^3, while summer releases decreased from 6–8 to 2–4 km^3 (figure 3). A similar decision was taken by Tadjikistan for the Karakul reservoir which could not store the large amount of water resulting from the Toktogul winter release. Outflow from the Toktogul reservoir and inflow to the Karakul are highly correlated (figure 4) and highlights the fact that the Karakul reservoir acts more like a transit zone for the water coming from the upstream basin than a water storage infrastructure. The operation of the Chardarya also had to adapt to the significant increase in winter inflow during the nineties.

Figure 3. Monthly water outflow volumes in winter (January–March) and in summer (June–August) for the Toktogul and the Karakul reservoirs. The data have been downloaded from the Cawater database (www.cawater-info.net).

Figure 4. Scatter plot of monthly water inflow volumes and outflow volumes of the Karakul with respect to outflow from the Toktogul reservoirs (monthly data from the Cawater database).
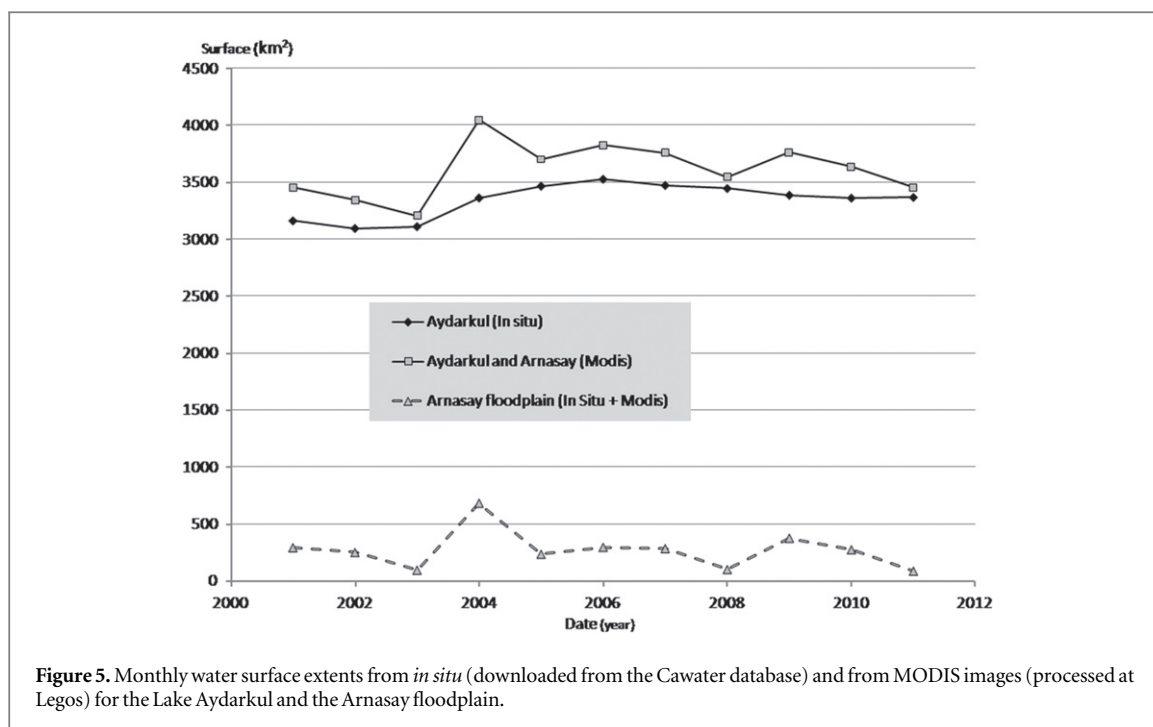
The impacts on the downstream countries were: (1) insufficient available water for irrigation and (2) winter flooding in the Arnasay depression in the territory of Uzbekistan and in the lower reach of the Syrdarya due to unusual releases from the Chardarya.

A short focus on the Chardarya–Arnsay–Aydarkul system may help to better understand how the regulation over the entire basin is affected by the use of the Toktogul for hydropower generation in conflict with its former role of water flow regulation for irrigation purposes.

In 1964, the Chardarya reservoir has started to sustain irrigation in Kazakhstan with additional release into the Arnasay depression (figure 2 and Rodina 2010). In the early 90s, increasing release from the Chardarya to the Arnasay depression took place. *In situ* monthly amounts of water release into Arnasay have been obtained from the *in situ* information (www.cawater-info.net). These data showed that in 1994, more than 9 km^3 was diverted in this way, and again 5 km^3 in 2003. We have used data on Chardarya releases to Arnasay in combination with water level and surface measurements of the Aydarkul lake from *in situ* information (www.cawater-info.net) and satellite altimetry and imagery (section 3.2) to calculate this additional contribution as follows:

Figure 5. Monthly water surface extents from *in situ* (downloaded from the Cawater database) and from MODIS images (processed at Legos) for the Lake Aydarkul and the Arnasay floodplain.

$$C = R - \Delta V, \tag{4}$$

where C is the sum of the additional contribution ($E - P$—drainage into the Arnasay floodplain), R the release of the Chardarya into the Arnasay floodplain, and ΔV, the water volume variation given by equation (1).

Currently, Lake Aydarkul covers between 3000 and 4000 km^2 (figure 5), which makes it the second most extensive water body in Central Asia, after the Aral Sea. It is worth noting that opposite priorities of each of all Syrdarya riparian countries led them to negotiate new agreements (in 1998) for more efficient transboundary water operation. However, water release from the Toktogul reservoir in winter constantly increased until 2008 (figure 3). Mean water volume in Lake Aydarkul dropped by $\sim$4 km^3 compared to the previous winter which was the highest observed over the period of measurements (figure 10). Moreover, Toktogul reached the lowest level of the period of measurements in 2008. Consequently, the winter release of both Toktogul and Karakul reservoirs in 2009 were much lower than previous years (figure 3). However, the water release in 2008 from Toktogul and Karakul did not reach Kazakhstan because it was captured by Uzbekistan to meet their own needs (Libert *et al* 2008). At its maximum in 2008, the water volume of the Toktogul reservoir was almost the same as the lowest level reached in summer time over the preceding ten years (figure 10).

It is clear that different and constant negotiations among the four countries have not smoothed the disagreement about the priorities concerning the use of the water resources of the Syrdarya. One source of dispute comes from the reticence about sharing accurate information on the exact operational status of the

reservoirs on the one hand, and needs and use for irrigation on the other hand. In the following section we will show how independent datasets based on satellite remote sensing data could be used as a tool for building trust among countries and ensuring mutual compliance of the commitment signed by all countries.
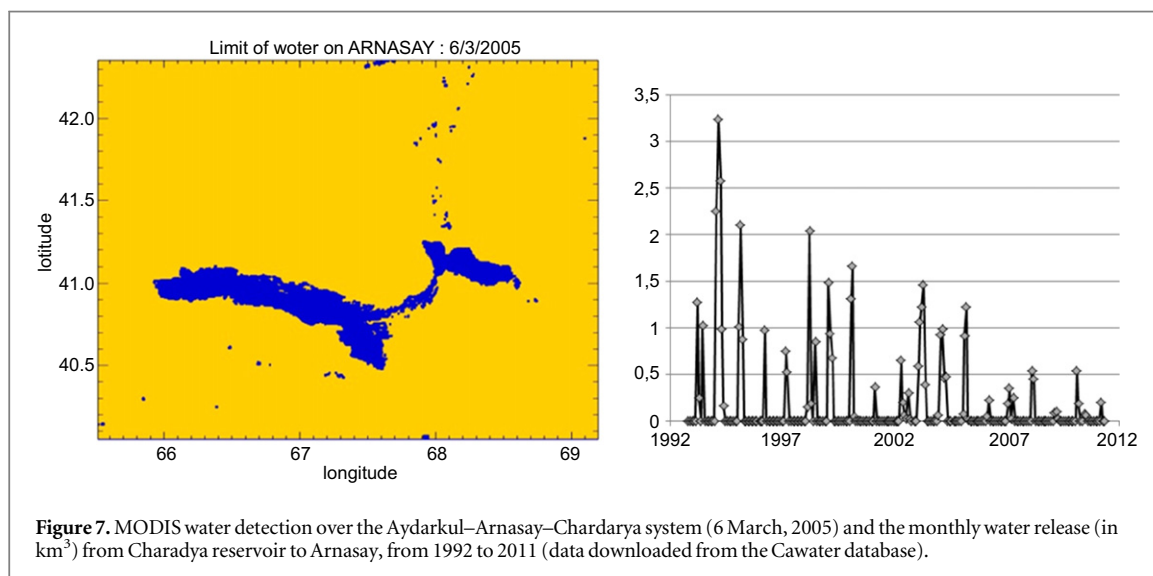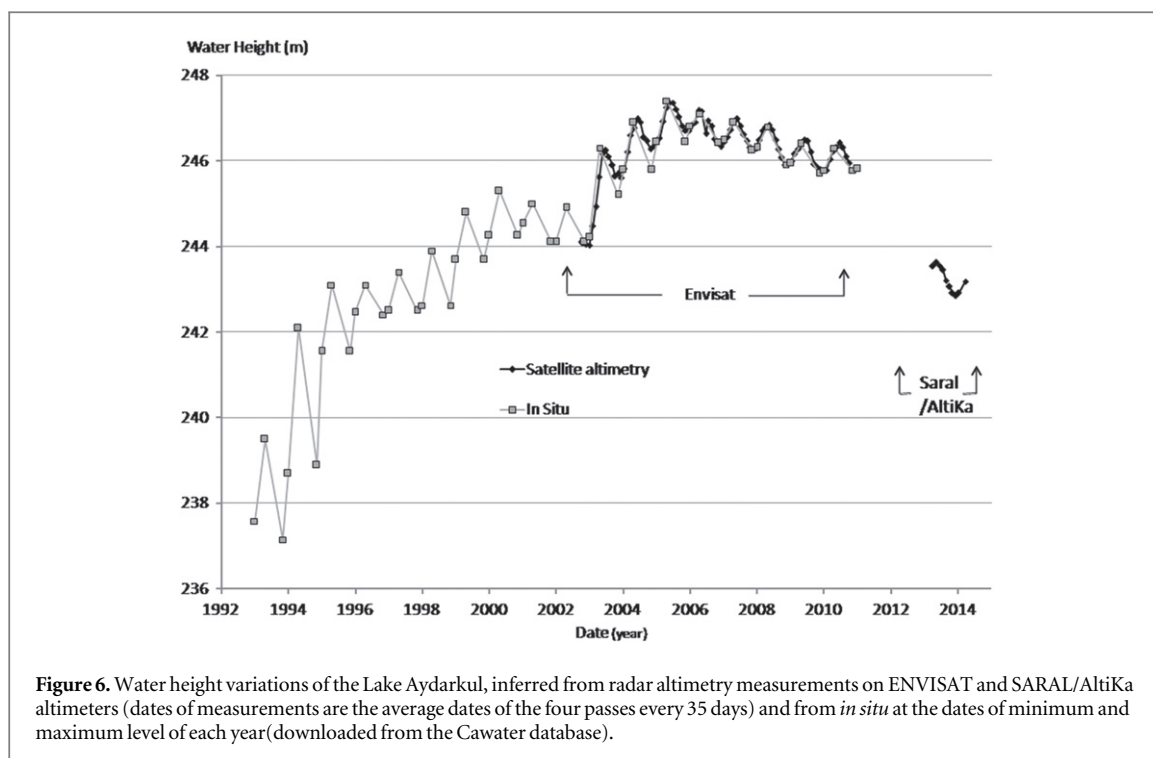
3.2. What can we learn from satellite remote sensing about the Syrdarya water management?

We have used the data from the Cawater database to calculate the hypsometry relationship between water height and water volume for each reservoir. Cawater provides only water volume while water heights were obtained from satellite altimetry.

The Cawater database has also allowed us to perform water budget for some reservoirs and to compare water surface variations observed by MODIS over the Arnasay floodplains with *in situ* data provided in Cawater database. A second objective was to use the hypsometry to reconstruct time series of parameters that are not available anymore using satellite data.

These comparisons allow evaluation of the order of magnitude of accuracy of the satellite products. Figure 6 shows for example that over the Aydarkul Lake (Cawater also provided the height for this lake) accuracy of altimetry is 12 cm. In addition to the Aydarkul Lake, there are altimetry data (sometimes on a multi-mission context) on four among the five main reservoirs along the NSC: Charvak (not presented here), Karakul, Toktogul and Chardarya.

For example, the Chardarya water level is calculated over more than 20 years from a combination of T/P, ENVISAT, JASON-2 and now SARAL. *In situ* data of storage changes over this reservoir from 1993 to 2000 allow calculation of the hypsometry $V(L)$,

Figure 6. Water height variations of the Lake Aydarkul, inferred from radar altimetry measurements on ENVISAT and SARAL/AltiKa altimeters (dates of measurements are the average dates of the four passes every 35 days) and from *in situ* at the dates of minimum and maximum level of each year(downloaded from the Cawater database).

Figure 7. MODIS water detection over the Aydarkul–Arnasay–Chardarya system (6 March, 2005) and the monthly water release (in km^3) from Charadya reservoir to Arnasay, from 1992 to 2011 (data downloaded from the Cawater database).

therefore storage changes can be computed up to 2014 (figure 8).

We have also calculated water storage variations of the Chardarya and the Toktogul reservoirs using only satellite data: altimetry and Modis and Landsat images. Using water heights and water areal extents we calculated hypsometry $A(L)$ and then using equation (1) we calculated the volume variations. The estimations (altimetry + *in situ*, and altimetry + imagery) were compared to *in situ* data and we obtained a root mean square differences of 0.6 km^3 for Chardarya and 0.2 km^3 for Toktogul for both estimations which is small (2–4%) compared to the average annual volume variations.

Figure 7 shows results of analysis of MODIS images over an image of the whole system Aydarkul–Arnasay–Chardarya taken in March 2005. Water release from the Chardarya to the Arnasay in 2005 was about 2 km^3, mainly in winter time (February–March). We see that the release water fills all the Arnasay floodplain and then the Aydarkul terminal lake. Using surface variations of the Lake Aydarkul (from Cawater *in situ* data at each date of the radar altimetry measurement time series: figure 6) allows calculation of the surface of the Arnasay floodplain, year by year, before the start of the release from the Chardarya reservoir.

For Lake Aydarkul, *in situ* data of surface extent and radar altimetry measurements of water height, allow calculation the hypsometry for this lake:
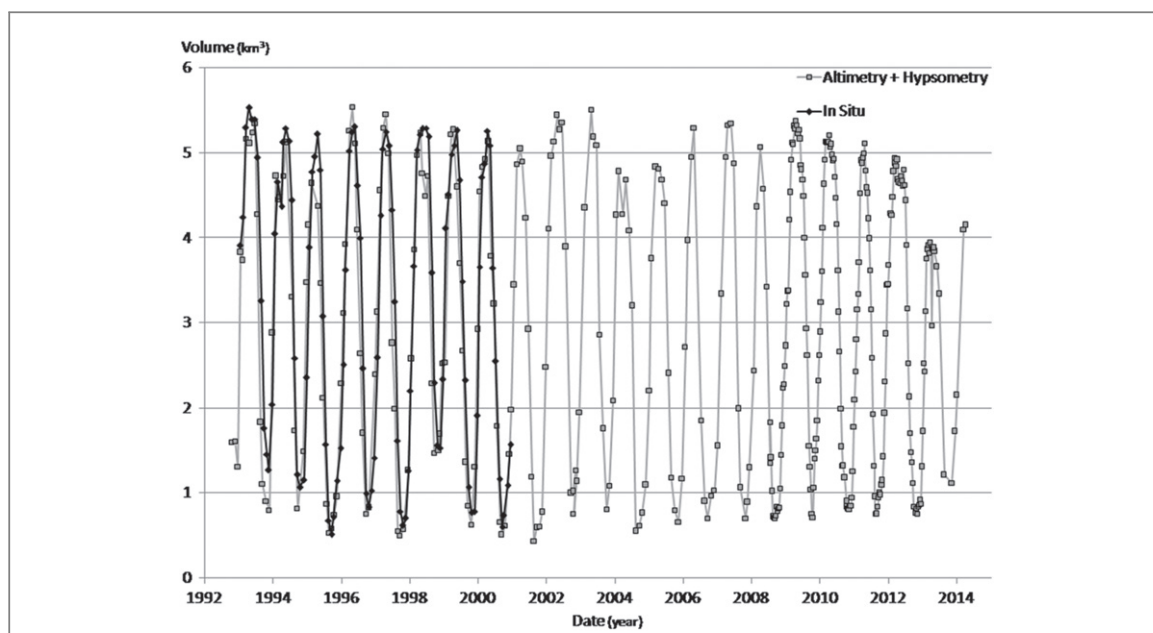
Figure 8. Chardarya: monthly volume from *in situ* (downloaded from the Cawater database), from radar altimetry data using the adjusted relationship by classical inverse method: $V = 0.03\,404L^2 - 163\,324L + 1959.21$, and equivalent volume variations from MODIS and from the radar altimetry data using the hypsometry: $A = 74.853L - 181\,010$ and equation (1).
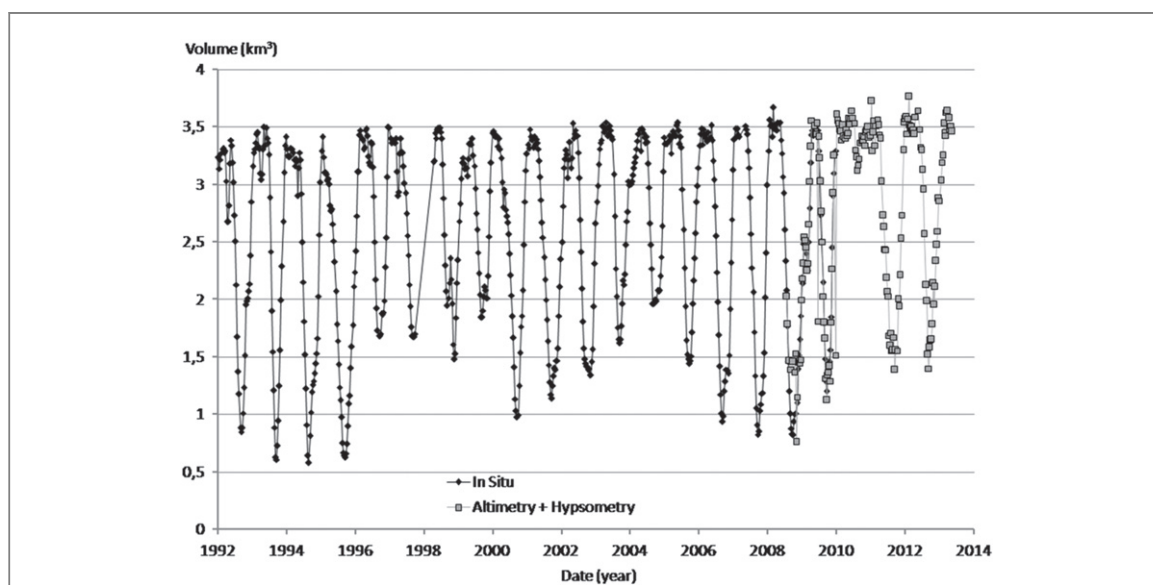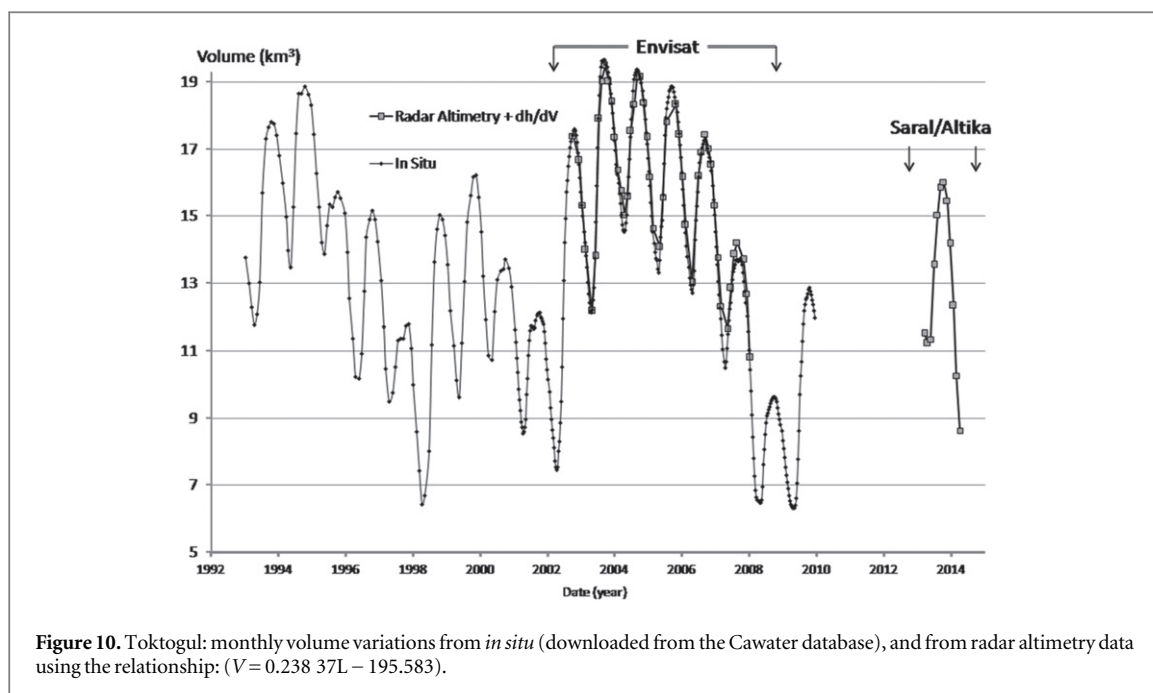

Figure 9. Karakul: monthly volume variations from *in situ* (downloaded from the Cawater database), and from radar altimetry data using the relationship: ($V = 0.014\,73\,L^2 - 9.73L + 1606.1$).

$$A(L) = 160.2698*L - 36031.9. \qquad (5)$$

Using satellite altimetry and (equations (1) and (5)) to estimate water storage within the Lake Aydarkul (figure 6) we estimated that between 2011 and 2013, this lake lost 7.8 km^3 and then again 1.9 km^3 in 2013. Without any *in situ* data available on the whole region it is however now possible to monitor these parameters (*L*, *A* and *V*) over the Lake Aydakul as a result for the SARAL/AltiKa altimeter as seen on figure 6, and the water extent of the Arnasay floodplain.

Going up to the Karakul (with JASON-2) and the Toktogul (with ENVISAT and SARAL/AltiKa)

reservoirs (figures 9 and 10) water storage variations can also be computed. Unfortunately we don't have any *in situ* or radar altimetry measurements valid over the Toktogul reservoir from 2010 to 2012, but in March 2013 (first SARAL/AltiKa measurements) the minimum storage of the reservoir after winter release is already much higher than the maximum reached in 2008 and only slightly lower than the maximum of 2009. This shows that the release of the Toktogul in 2010 was too small to refill the Karakul reservoir and explain why the release of water from the Karakul reservoir was likely lower than when it receives high amounts of water from the Toktogul (figures 3 and 4).

Figure 10. Toktogul: monthly volume variations from *in situ* (downloaded from the Cawater database), and from radar altimetry data using the relationship: ($V = 0.238\ 37L - 195.583$).

4. Perspectives and conclusions

At a global scale, estimating total water storage changes of all lakes and reservoirs remains a challenge and could only be estimated with huge uncertainty (Biancamaria *et al* 2010).

At a regional scale, satellite measurements from satellite nadir altimeters provide complementary additions and alternatives to *in situ* measurements as shown over the Syrdarya river basin. In 2015, four nadir altimeters (S3A, S3B, JASON-3 and SARAL/AltiKa) will fly at the same time. The instruments onboard these satellites have different characteristics in term of footprint: JASON-3 altimeter is the same than those on JASON-2 with a footprint of about $300\ \mathrm{km}^2$, while for SARAL/AltiKa it is reduced by a factor of 2–3 allowing the finest selection of measurements over narrow water bodies like rivers and reservoirs. The altimeters onboard S3A and S3B are planned to operate in SAR mode in Ku band of frequency. This will also allow gain of a factor ranging from 10 to 50 in term of footprint with respect to classical LRM altimetry mode.

In 2018–2019, another mission, JASON Continuity of Service (JASON-CS), will be launched on the same orbit asJASON-3. If JASON-3 will still be operational, it would be put on a new orbit, called interleaved orbit, (ground track shifted in longitude by half of its initial orbit equatorial ground track distance) doubling the coverage of both satellites. The footprint will be the same as that for JASON-3 ($300\ \mathrm{km}^2$).

This satellite constellation will provide a dense monitoring network along the SNC (figure 12) with an increased sampling time of reservoirs surveyed. Knowing the exact orbital parameters of each of these missions it has been possible to predict the spatio-temporal coverage of the SNC (table 2 which show how many tracks and days between two consecutive passes over each reservoir) when the constellation of the five nadir altimeters will be in orbit and then when SWOT will be launched. Having different satellites will also preclude erroneous measurements from one of them.

To improve the spatial sampling and overcome the intrinsic limitation of nadir measurements, a 2D map of water elevations (water extent and elevation at the same time) would be needed. That is why National Aeronautics and Space Administration (NASA), Centre National d'Études Spatiales (CNES), Canadian Space Agency and UK Space Agency are collaborating to develop the future SWOT mission (Rodríguez 2012). It is specifically designed to observe, at a global scale, surface water storage changes and river discharges for a nominal life time of 3 years with a launch in 2020.

SWOT's main payload will be the Ka-band radar interferometer, providing images of water elevations on two 50 km swaths, on each side of the satellite. These two swaths will be separated by a 20 km band with no observations except along the track with an additional Nadir altimeter. SWOT will observe rivers wider than 100 m (with a goal of 50 m) and lakes and reservoirs with an extent greater than 250 m × 250 m (with a goal of 100 m × 100 m). The SWOT orbit is at an altitude of 891 km and has 20.86 day repeat period and 77.6° inclination. Figure 11 shows the number of SWOT observations per orbital repeat period over the upper and mid part of the Syrdarya watershed. Because of the 20 km nadir gaps, few locations will never be observed but in fact most of the basin will be monitored (small reservoirs, floodplains, rivers) between 1 and 4 times per 21 day repeat period.
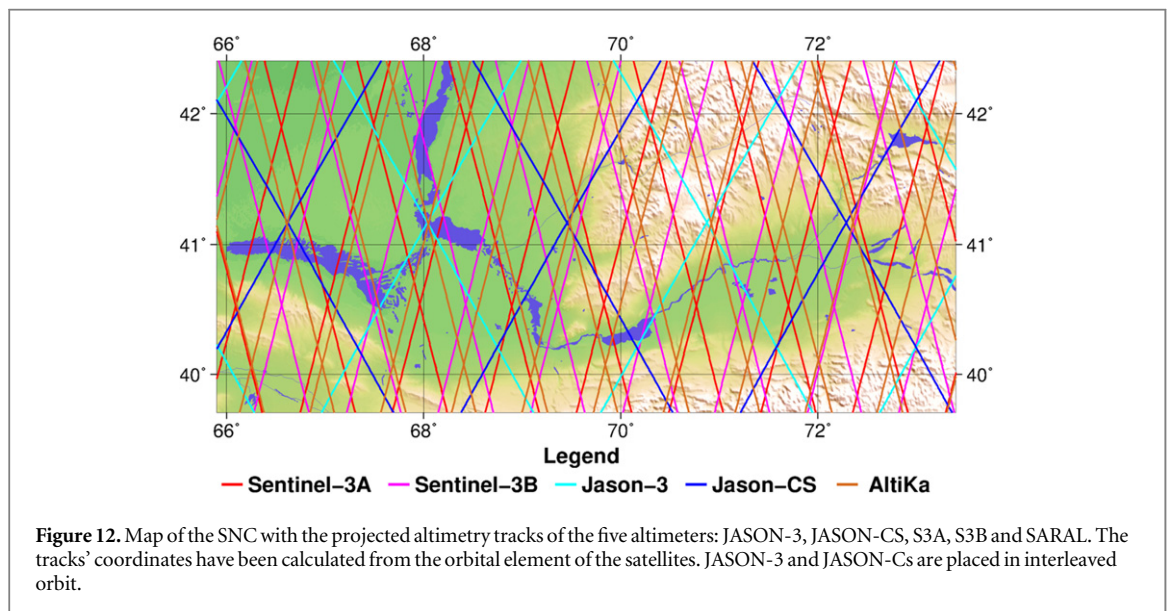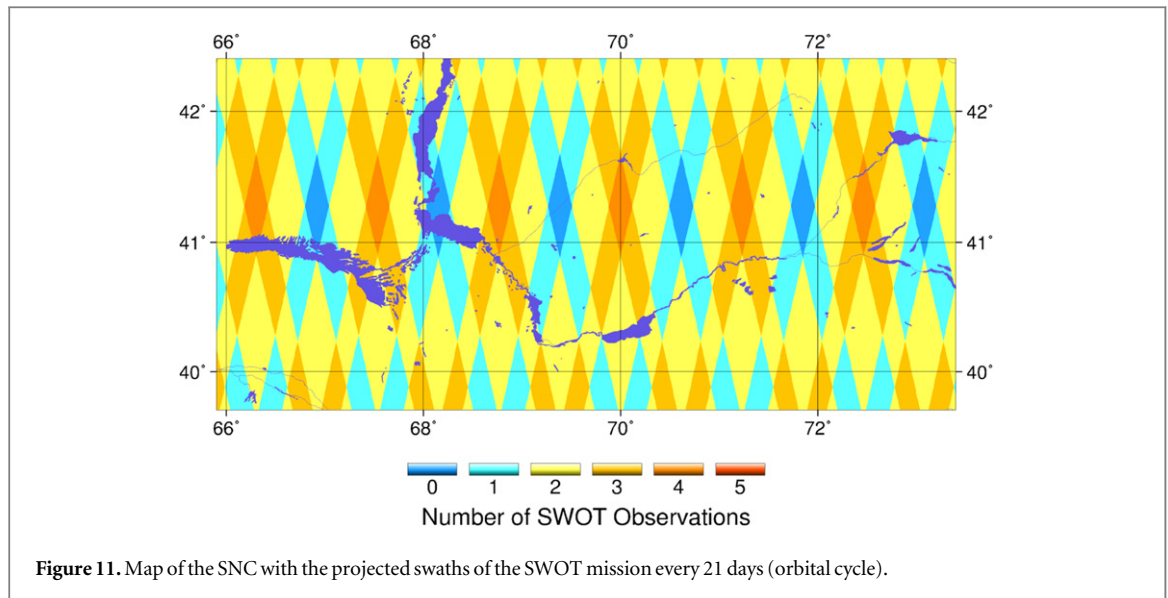
Figure 11. Map of the SNC with the projected swaths of the SWOT mission every 21 days (orbital cycle).

Figure 12. Map of the SNC with the projected altimetry tracks of the five altimeters: JASON-3, JASON-CS, S3A, S3B and SARAL. The tracks' coordinates have been calculated from the orbital element of the satellites. JASON-3 and JASON-Cs are placed in interleaved orbit.

Table 2. Number of tracks and period of revisit (days between two consecutive passes) per reservoir in different scenarios of satellites constellation. (1) Current situation with SARAL/AltiKa and JASON-2, (2) situation in 2017 with JASON-CS, JASON-3, S3A, S3B and SARAL/AltiKa, and (3) constellation of scenario 2 and SWOT.

Reservoir	Scenario 1	Scenario 2	Scenario 3
Toktogul	1/35	3/8	4/7
Chardarya	4/5	6/4	11/2
Karakul	1/10	5/4	11/2
Charvak	1/35	1/35	4/7
Andijan	0/none	0/none	3/7
Aydarkul	4/8	12/2	29/<1

Expected precision of the SWOT mission (Rodríguez 2012) is that river slope will be measured over each 10 km length of rivers larger than 100 meters with 1 cm km^{-1} of accuracy allowing monitoring of river discharge. Water heights of Lake, reservoirs and floodplains will be measured with 10 cm accuracy for 1000×1000 m areas (1 km^2 area), 20 cm accuracy for 250×250 m area (0.0625 km^2) and 45 cm for 100×100 m area (0.01 km^2). This accuracy within the entire SNC is expected to be sufficient to calculate hypsometry of all reservoirs ($V(L)$ and $A(L)$).

From now to the launch of SWOT the potential for reservoir monitoring from satellite radar altimetry will also be improved (higher temporal revisit (table 2), whole coverage and improved accuracy: 10 cm). Measurement of Karin over the river will also allow provide river discharge every 10 km, and contours of each water body. It will allow controlling the inflow and outflow discharge for each of the reservoirs of the SNC. With a unique mission, it will be possible to propose to water managers and scientists of these countries, an independent, reliable, and accurate system of measurements of the different parameters controlling

the flow and the water storage availability and uses over the entire basin.

Dams and reservoirs play a key role in water management of river basins (for irrigation and hydropower generation) that are transboundary by nature. Efficient water management of transboundary rivers usually relies on decision making through basin committees that need survey systems of water resources and their spatio-temporal variability. These surveys can be achieved using well-designed networks of ground-based gauges, however economic difficulties or political reasons may lead to mistrust among riparian countries and data are not always shared.

Over the Syrdarya river basin, three countries (Kazakstan, Uzbekistan and Tadjikistan) depend on water resources decisions within Kyrgyzstan with respect to the upper basin and the Toktogul reservoir. Lack of clear agreement among the countries, and opposite objectives regarding the use of the water resources led to inefficient water management. The decision taken in 1993 by Kyrgyzstan to use the Toktogul reservoir as a source of electricity generation in winter led to poor consequences for downstream countries. The release of the Toktogul reservoir is supposed to occur in summer time for irrigation purposes. The downstream countries have to mitigate decision of Kyrgyzstan to release water from the Toktogul in winter. Shared information system is therefore a crucial tool for water resources managers.

In this context, remote sensing satellites may provide independent assessment of water resources uses and their consequences over the Syrdarya basin. Combined with water extent variations of reservoirs or floodplains from imagery, water level variations of the reservoirs of the SNC inferred from radar altimetry allowed calculation of water storage variations. It has been possible to reconstruct more than 20 years of water storage variations on the main reservoirs along the SNC from multisatellite datasets although *in situ* data are currently not available. We have shown that satellite data can be used to complement *in situ* data, but, if necessary to fully replace them. We have indeed calculated that the accuracy of water storage variations from satellites data is low compared to *in situ* data in the case of Syrdarya basin.

Acknowledgments

References

Abarca-del-Rio R, Crétaux J-F, Bergé-Nguyen M and Maisongrande P 2012 Does the Titicaca Lake still control the Poopo lake water levels? An investigation using satellite altimetry, and MODIS data (2000–2009) *Remote Sens. Lett.* **3** 707–14

Abileah R, Vignudelli S and Scozzari A 2011 A completely remote sensing approach to monitoring reservoirs water volume *Int. Water Technol. J.* **1** 63–77

Aires F, Papa F, Prigent C, Crétaux J-F and Bergé-Nguyen M 2014 Characterization and space/time downscaling 1 of the inundation extent over the Inner Niger Delta using GIEMS and MODIS data in preparation to the SWOT mission *J. Hydrometeorol.* **15** 171–92

Arsen A, Crétaux J-F, Berge-Nguyen M and Abarca-Del-Rio R 2014 Remote sensing-derived bathymetry of lake Poopó *Remote Sens.* **6** 407–20

Arsen A, Crétaux J-F and Abarca-Del-Rio R 2015 Use of SARAL/AltiKa over mountainous lakes, intercomparison with Envisat mission *J. Adv. Space Res.* Special issue on SARAL/AltiKa minor revision

Biancamaria S, Andreadis K M, Durand M, Clark E A, Rodríguez E, Mognard N M, Alsdorf D E, Lettenmaier D P and Oudin Y 2010 Preliminary characterization of SWOT hydrology error budget and global capabilities *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **3** 6–19

Biancamaria S, Hossein F and Lettenmeir D P 2011 Forecasting transboundary river elevation from space *Geophys. Res. Lett.* **38** L11401

Biemans H, Haddeland I, Kabat P, Ludwig F, Hutjes R W A, Heinke J, von Bloh W and Gerten D 2011 Impact of reservoirs on river discharge and irrigation water supply during the 20th century *Water Resour. Res.* **47** W03509

Birkett C M 1995 Contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes *J. Geophys. Res.* **100** 25179–204

Boschetti L, Flasse S P and Brivio P A 2004 Analysis of the conflict between omission and commission in low spatial resolution dichotomic thematic products: the Pareto boundary *Remote Sens. Environ.* **91** 280–92

Calmant S, Seyler F and Crétaux J-F 2008 Monitoring continental surface waters by satellite altimetry *Surv. Geophys.* special issue on 'Hydrology from Space' **29** 247–69

Chao B F, Wu Y H and Li Y S 2008 Impact of artificial reservoir water impoundment on global sea level *Science* **320** 212–4

Clemens R S, Phinn S R, Murray N J, Roelfsema C M and Fuller R A 2012 Continental scale mapping of tidal flats across East Asia using the Landsat archive *Remote Sens.* **4** 3417–26

Crétaux J-F and Birkett C 2006 Lake studies from satellite radar altimetry *C. R. Geosci.* **338** 1098–112

Crétaux J F, Calmant S, Romanovski V, Shabunin A, Lyard F, Bergé-Nguyen M, Cazenave A, Hernandez F and Perosanz F 2009 An absolute calibration site for radar altimeters in the continental domain: lake Issykkul in Central Asia *J. Geod.* **83** 723–35

Crétaux J-F, Letolle R and Bergé-Nguyen M 2013 History of Aral sea level variability and current scientific debates *Glob. Planet. Changes* **11** Special issue SI 99–113

Crétaux J-F *et al* 2011a SOLS: a lake database to monitor in near real time water level and storage variations from remote sensing data *J. Adv. Space Res.* **47** 1497–507

Crétaux J-F *et al* 2011b Flood mapping inferred from remote sensing data *Int. Water Technol. J.* **1** 48–62

Duan Z and Bastiaanssen W G M 2013 Estimating water volume variations in lakes and reservoirs from four operational satellite altimetry databases and satellite imagery data *Remote Sens. Environ.* **134** 403–16

Gao H, Birkett C and Lettenmeir D P 2012 Global monitoring of large reservoir storage from satellite remote sensing *Water Resour. Res.* **48** W09504

Gleditsch N P and Hegre H 2000 Shared rivers and interstate conflict *Political Geography* **19** 971–96

Hossain F, Siddique-E-Akbor A H, Mazumder L C, ShahNewaz S M, Biancamaria S, Lee H and Shum C K 2014 Proof of concept of an altimeter-based river forecasting system for transboundary flow inside Bangladesh *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **7** 587–601

Ji L, Zhang L and Wylie B 2009 Analysis of dynamic thresholds for the normalized difference waterindex *Photogramm. Eng. Remote Sens.* **75** 1307–17

Libert B, Orolbaev E and Steklov Y 2008 Water and energy crisis in Central Asia *China Eurasia Forum Q* **6** 9–20

Liu Y, Song P, Peng J and Ye C 2012 A physical explanation of the variation in threshold for delineating terrestrial water surfaces from multi-temporal images: effects of radiometric correction *Int. J. Remote Sens.* **33** 5862–75

McFeeters S K 1996 The use of the normalized difference water index (NDWI) in the delineation of open waterfeatures *Int. J. Remote Sens.* **17** 1425–32

Micklin P P 1988 Desiccation of the aral sea, a water management disaster in the Soviet Union *Science* **241** 1170–6

Pedinotti V, Boone A, Decharme B, Crétaux J-F, Mognard N, Panthou G, Papa F and Tanimoun B A 2012 Evaluation of the ISBA-TRIP continental hydrologic system over the Niger Basin using *in situ* and satellite derived datasets *Hydrol. Earth Syst. Sci.* **16** 1745–73

Ričko M, Birkett C M, Carton J A and Crétaux J-F 2012 Intercomparison and validation of continental water level products derived from satellite radar altimetry *J. Appl. Remote Sens.* **6** 061710

Rodina K 2010 They Aydar–Arnasay lakes system: formation, functions and future water management scenarios, *Master of Science Thesis* Central European University, Budapest

Rodríguez E 2012 Surface water and ocean topography mission (SWOT), science requirements document *JPL document.* (http://swot.jpl.nasa.gov/files/swot/SWOT_science_reqs_release2_v1.14.pdf)

Song C, Huang B and Ke L 2013 Modeling and analysis of lake water storage changes on the Tibetan Plateau using multi-mission satellite data *Remote Sens. Environ.* **135** 25–35

Sood A and Mathukumalli B K P 2011 Managing international river basins: review in gIndia–Bangladesh transboundary water issues *Int. J. River Basin Manage.* **9** 43–52

Weinthal E 2006 Water conflict and cooperation in Central Asia *Human Development Report* 2006 UNDP

Wolf A, Nathrius J, Danielson J, Ward B and Pender J 1999 International river basins of the world *Int. J. Water Resour. Dev.* **15** 387–427

Xu H 2006 Modification of normalized difference water index (NDWI) to enhance open water features in remotely sensed imagery *Int. J. Remote Sens.* **27** 3025–33