J. Great Lakes Res. 31:520–534
Internat. Assoc. Great Lakes Res., 2005

Evolution of Sea Level of the Big Aral Sea from Satellite Altimetry and Its Implications for Water Balance

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ABSTRACT. *The Aral Sea was one of the biggest lakes in the world before it started to shrink in the 1960s due to water withdrawal for land irrigation. Sea level decreases led to the separation of the Aral Sea into two basins—the Small Aral in the north and the Big Aral in the south. For several decades there were no continuous observations of Aral Sea level, and the few data that exist are fragmentary or unavailable. We present observations of the Big Aral Sea level estimated from the TOPEX/Poseidon (T/P) altimetry with high temporal resolution over the last decade (1993–2004). Since sea volume is one of the key parameters for the studies of water balance, we use the T/P-derived time series of sea level and a dedicated digital bathymetry model (DBM) to reconstruct temporal changes in the Aral Sea surface and volume. We introduce variations of the sea volume as the new constraint for the water budget of the Big Aral Sea. This is an important step toward estimating detailed seasonal and interannual changes of the water budget. We assess various existing components of the water budget of the Aral Sea and discuss the quality of the existing data and their applicability for establishing detailed water balance. In particular, large uncertainties in estimating the evaporation and underground water supply are addressed. Desiccation of the Aral Sea resulted in dramatic changes in the salinity regime and, consequently, affected its aquatic ecosystems. We also discuss changes in the aquatic fauna and their possible evolution under continuing desiccation of the Big Aral Sea. Combining satellite altimetry with other parameters of the water budget offers a promising potential for assessing temporal changes in the water budget of arid or semi-arid regions, even those with a poor ground monitoring network.*

INDEX WORDS: *Aral Sea, water balance, radar altimetry, underground water.*

INTRODUCTION

Until recently the Aral Sea was one of the biggest lakes in the world with a surface area of 57,000 km^2 and a volume of 950 km^3. The Aral Sea has two tributaries, the Amu Daria and the Syr Daria rivers (Fig. 1), and no outflow. Up to the 1960s, the river discharge provided an average of 56 km^3/yr (Bortnik 1999) of water to the Aral Sea, an amount sufficient to maintain the Aral Sea level at +53 m above sea level (Zenkevich 1963). At that time, the

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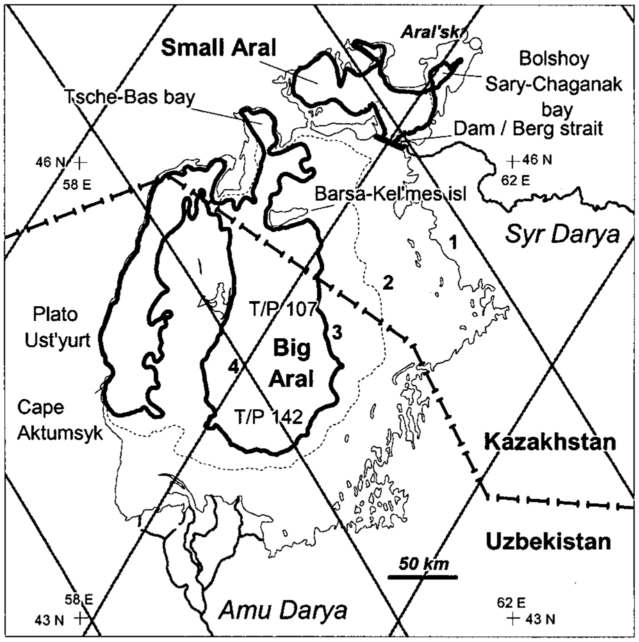

FIG. 1. The Aral Sea. The Aral Sea coastline in 1966 (1), 1992 (2), 2002 (3), and TOPEX/Poseidon ground tracks (4) with their reference numbers.

Aral Sea was a brackish lake with an average salinity of 8–10 ppt and characterized by low biodiversity and biological productivity.

In the early 1960s increased water intake for irrigation in Kazakstan and Uzbekistan led to a dramatic decrease of the Syr Darya and the Amu Darya discharge into the Aral Sea—from 16.7 km^3/year for 1971–1980 to 4.2 km^3/year for 1980–1989 (Bortnik 1999). Aral Sea level decreased to +40 m in 1989 and +30 m in 2004 (see Fig. 1); surface area and volume also decreased significantly—from 67,000 km^2 and 1,083 km^3 in 1960 (Bortnik 1999, Micklin 1988) to 16,000 km^2 and 100 km^3 in 2004 (data from the Digital Bathymetry Model, see section 1.4).

In 1989, when the sea level decreased to about +40 m (Aladin *et al.* 1995), Berg's Strait, the connecting channel between the northern and southern parts of the sea, dried out and the Aral Sea separated into two distinct water bodies—the Big Aral in the south, and the Small Aral in the north. Since separation, these two seas have changed in different ways. As the Small Aral continued to be fed by the Syr Darya, its level decreased in the 1990s at a slower rate than did the Big Aral (Aladin *et al.* 2005). For the Big Aral, the Amu Darya water discharge was too low to compensate for the high rate of evaporation. Precipitation is low (less than 200 mm/yr), particularly in comparison to evaporation which ranges from 1,000 to 1,200 mm/yr (Small *et al.* 1999, 2001). Evaporation minus precipitation is 25–30 km^3/yr while discharge from the Amu Darya River ranged from 0–15 km^3/yr in the 1990s. Therefore, during the 1990s, the water supply deficit to the Aral Sea reached 10–15 km^3/yr depending on the year.

When the two water bodies became separated, the salinity of the Aral Sea was about 28-30 ppt, and the fauna and flora of the Small and Big Aral were similar. The resulting differences in hydrological regimes rapidly led to biological differences between these two water bodies. While the salinity of the Small Aral was relatively stable, the Big Aral was quickly transformed from brackish water to mesohaline (Plotnikov *et al.* 1991) and then to hyperhaline conditions with salinity reaching 69–72 ppt in the western and 155–160 ppt in the eastern part (Mirabdullaev *et al.* 2004). At the time of the division into two lakes, only seven species of fish, ten common zooplankton species, and eleven common benthos species were present. Since then, typical hyperhaline species started to dominate, while most of the former inhabitants of the Big Aral Sea, including fishes, became extinct. According to our field observations none of fish species that were present in the Big Aral during the partition time remained in autumn 2002, when the salinity exceeded 70 ppt in the western coast. In autumn 2003, when the salinity exceeded 80 ppt, only few widely euryhaline rotifers zooplankton survived and only four species of zoobenthos remained.

In the early 1990s, after the separation from the Big Aral, the water level in the Small Aral began to rise due to a positive water balance, and as a result, water again began to flow southward toward the Big Aral. This outflow took place in the central part of Berg's Strait which was dredged earlier (in 1980) in order to facilitate navigation between the northern and the southern basins. This southward current was slow at first but then the flow sharply increased with the continuing decrease of the Big Aral level. When the Big Aral level fell to +37 meter the difference of level between the two water bodies reached 3 meters and this flow reached 100 m^3/s. In the summer of 1992 this canal was dammed and the flow has stopped. Over the next few years the dam in Berg's Strait was partly destroyed by floods and was restored several times (for details see Aladin *et al.* 2005). In April 1999 the dam was completely destroyed and the water of the Small Aral again flowed southward. However, because their surface areas had diminished the distance between the Big Aral and the Small Aral was much longer than before and the water did not reach the Big Aral Sea; it was lost in the sands and salt marshes north of the former Barsakelmes Island.

Several publications have been devoted to studies of the water balance of the Aral Sea. Small *et al.* (1999) quantified the water balance using a regional lake model and obtained values of evaporation minus precipitation (accounting for seasonal but not interannual variability) up to 1990. Small *et al.* (2001) next evaluated the effect of evaporation and precipitation on water level decreases up to 1990, separating anthropogenic and climatic factors. Next Benduhn and Renard (2003) developed a model of evaporation for the Big Aral including estimating the interannual groundwater inflow to the Big Aral until 1990. They showed that this contribution to the water mass balance was highly variable (from 1 to 15 km^3/yr) and averaged 8 km^3/yr. Jarsjö and Destouni (2004) also estimated the ground water discharge using the water mass balance equation and a different scenario for the evaporation and precipitation rates. They showed that ground water has become a major contributor to the hydrological budget of the Aral Sea, with annual values ranging from 5 to 30 km^3 depending on the scenario.

However, the problem with most of the water balance studies of the Aral Sea is that, for several decades, there were no continuous observations of sea level; the few data that exist are fragmentary or unavailable. This introduces large uncertainties into the water balance equations and seriously decreases the reliability of the results. With satellite altimetry, it is now possible to observe level variations of the large continental water bodies (Birkett 1995; Cazenave *et al.* 1997, 2002; Mercier 2001). In this article we present observations of the Big Aral Sea level from TOPEX/Poseidon (T/P) and Jason-1 altimetry with high temporal resolution over the last decade (1993–2004). As sea volume is one of the key parameters for the studies of water balance, we use the T/P-derived time series of sea level to reconstruct associated changes in the sea surface and volume, using a dedicated digital bathymetry model (DBM). We then introduce the variations of the sea volume as the new precise constraint for the water budget of the Big Aral Sea. We assess the various components of the water budget of the Aral Sea and discuss their quality and their usefulness for establishing detailed water balance. Desiccation of the Aral Sea resulted in dramatic changes in the salinity regime and, consequently, affected marine ecosystems. We consequently discuss the changes in the aquatic fauna and its possible evolution under continuing desiccation of the Big Aral Sea.

VARIATIONS OF LEVEL, SURFACE AND VOLUME OF THE BIG ARAL SEA

One of the fundamental parameters for the studies of inland water bodies and their water budget is variations in their level, surface, and volume. Traditionally, water level data are obtained from gauging stations installed along the coast, but for the Big Aral there have been no gauges for many years. A few scientific expeditions took place along the coast of the Aral Sea but either the level observations were not acquired or they were unavailable. A recent measurement of Big Aral level in November 2002 (+30.5 meters above Baltic Sea level) was published in Zavialov *et al.* (2003); however no *in situ* data were published for the 1993–2004 period. With more than a decade of satellite altimetry now available, it is possible to estimate the variability of the Aral Sea level.

Satellite Altimetry Data

The TOPEX/Poseidon (T/P) satellite was launched in August 1992. Its main objective was to measure the ocean surface topography with an accuracy of few centimeters. In 2002 T/P was followed by a second satellite altimeter (Jason-1) which operates in tandem with T/P. The T/P satellite carries a dual frequency radar altimeter operating in C and Ku bands (5.3 and 13.6 GHz respectively), which transmit a short pulse in the nadir direction reflected by the sea surface. The measurement of the time delay between emission and reflection provides a measurement of the distance between the satellite and the sea surface. Several corrections for atmospheric refraction, electromagnetic bias, tides, etc. are applied to estimate the sea surface height (Fu and Cazenave 2001, Birkett 1995).

Although designed to study the open ocean, satellite altimetry was used almost immediately over continental water bodies such as lakes, inland seas, flooding plains, or rivers (for exhaustive details on application of altimetry to lake study, see Birkett 1995). This study is an invaluable source of information for water level monitoring, with a time resolution of 10 days. The Big Aral surface was crossed over by two satellite tracks (see Fig. 1). The

TABLE 1. Monthly level of the Big Aral Sea (in meters above Geoid EGM96, (Lemoine **et al.** ***1998) from 1993 to 2004 deduced from altimetry data from TOPEX/Poseidon and Jason-1 satellites.***

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Jan	36.80	36.48	36.44	35.74	34.91	33.99	33.73	33.16	32.35	31.40	30.66	30.64
Feb	36.76	36.52	36.46	35.72	34.91	34.01	33.76	33.21	32.37	31.36	30.82	30.76
Mar	36.82	36.66	36.49	35.71	34.94	34.04	33.75	33.22	32.32	31.37	30.72	30.85
Apr	36.84	36.67	36.57	35.70	34.89	33.96	33.79	33.17	32.33	31.37	30.79	30.98
May	36.85	36.72	36.65	35.67	34.93	34.06	33.76	33.28	32.34	31.39	30.93	30.86
Jun	36.87	36.82	36.61	35.68	34.89	34.05	33.82	33.23	32.30	31.37	30.99	30.82
Jul	36.88	36.77	36.51	35.65	34.76	34.02	33.84	33.10	32.20	31.28	31.06	30.68
Aug	36.86	36.70	36.42	35.45	34.62	34.00	33.74	33.03	32.01	31.23	30.95	30.57
Sep	36.70	36.65	36.18	35.27	34.44	33.98	33.61	32.83	31.87	31.05	30.80	30.36
Oct	36.57	36.53	36.02	35.10	34.21	33.88	33.34	32.58	31.66	30.83	30.65	30.21
Nov	36.50	36.48	35.87	34.98	34.13	33.83	33.20	32.45	31.52	30.72	30.69	30.12
Dec	36.42	36.42	35.76	34.92	33.99	33.79	33.19	32.37	31.46	30.62	30.62	30.14
Mean	36.74	36.62	36.33	35.47	34.63	33.97	33.63	32.97	32.06	31.17	30.81	30.58

data analyzed consist of the merged T/P and Jason altimetric data (GDR-Ms) provided by the Centre for Ocean Topography and Hydrosphere (CTOH) at LEGOS, Toulouse, France for the orbital cycles 1 to 365 for T/P (September 1992 to August 2002) and 1 to 106 for Jason (January 2002 to November 2004). We use the 1Hz data which provide an along track ground resolution of about 6 km.

Data Correction and Selection

Due to the inhomogeneity in the mass distribution of the Earth, the altimetry measurements were corrected for the geoid height above the ellipsoid of reference (Fu and Cazenave 2001). For the ocean, the mean sea surface is usually used instead of the geoid, because both surfaces can be considered equal. For continental water bodies, however, the mean lake surface is not present in the GDR-Ms. We thus used first a low-resolution terrestrial geoid, deduced from geodetic data (Lemoine *et al.* 1998), and then averaged the data on the lake over the whole period of available measurements. This process removed all periodical and random fluctuations and produced a more precise mean lake surface estimate for 1993–2004. This mean lake level obtained for the Big Aral was then used to estimate the monthly averaged Aral Sea level.

Environmental and geophysical corrections of the altimeter range measurements relevant to the Aral Sea were applied. The corrections include ionospheric, wet and dry tropospheric, solid Earth tide corrections, and correction for the satellite's center of gravity. We neglected the corrections specific to the open ocean such as ocean and pole tides, ocean tide loading, inverted barometer effect, and sea state bias.

To ensure that the observations are not over land (that would otherwise contaminate the measurements), a geographical selection of data was done, taking into account the location of the instantaneous measurements with respect to the Big Aral coastline. For the Big Aral there was an additional difficulty related to the continuous displacement of the coastline due to the drying up of the sea. To solve this problem, we used two-step iterative processing: first computation of the instantaneous lake coastline using the lake level data in combination with a dedicated digital bathymetry model (see section on Surface and Volume from Digital Bathymetry Model), and then a geographical selection of the altimeter measurements to account for the variable coastline.

Precision of Altimetry Measurements over the Aral Sea

We produced a time series of Big Aral Sea level from 1993 to 2004 with 10-day temporal resolution. Mean monthly values of the sea level above the EGM96 geoid are presented in Table 1. In order to tie these values to the existing historical time series (referred to the Baltic Sea level) a constant value should be added. We compared the average annual level of the Big Aral relative to the Baltic Sea level from 1960 to 2002 that have been recently published (Ashirbekov and Zonn 2003) to our estimation through altimetry. We obtained a mean

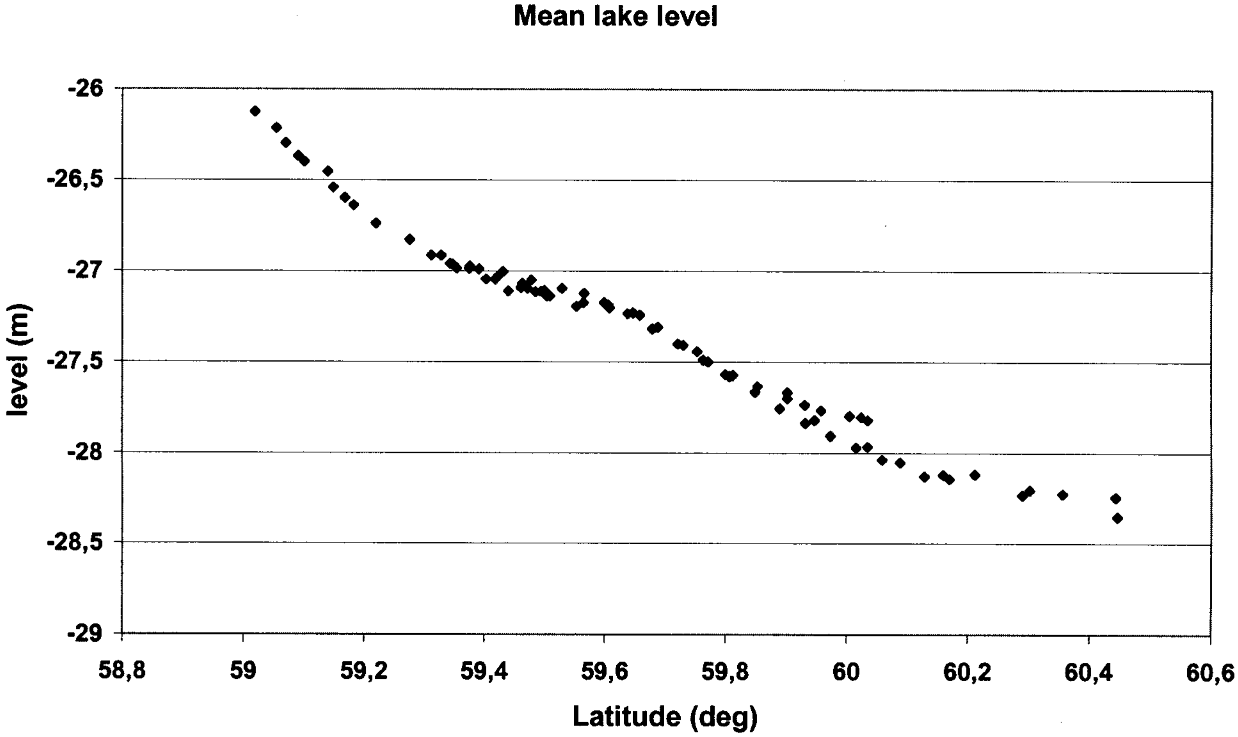

FIG. 2. Resulting mean lake surface as a function of latitude obtained from all Topex/Poseidon and Jason data over the 11 year (1993–2003) period.

difference (altimetry versus Baltic sea level) of 8 cm ± 17 cm (see Table 3).

An exhaustive error budget for altimetry technique over continental water bodies like lakes has been done by Birkett (1995). The author states that the mean lake level can be determined with an uncertainty of around 4 centimeters, depending on the availability of some corrections that must be applied to the range altimeter measurement. The RMS error estimated for our observations shows that for the Aral Sea the errors should be larger then 4 cm. One of the reasons is that the presence of snow and ice during winter in the Big Aral (Kouraev *et al.* 2003, 2004) generates additional errors in the height measurements since the reflection of the altimeter signal in the ice differs significantly from the reflection over open water. The existing T/P ocean retracking algorithm is not designed to process the return waveform from ice and this affects the precision of the determination of the altimetric height. Standard deviation for each set of sea level measurement (every 10 days in case of T/P) show that the error bar should be about 6 centimeters, which could represent an uncertainty of about 1.5 km^3 in the estimation of volume of the Big Aral at the present level.

Surface and Volume from Digital Bathymetry Model (DBM)

In order to obtain surface and volume for any given sea level mark and thus to construct time series of variations of surface and volume of the Big Aral, we developed a dedicated Digital Bathimetry Model (DBM) of the Aral Sea. The DBM was constructed using bathymetry data and isobaths contours from the map of the Aral Sea (scale 1: 500,000). Sounding positions were transformed from degrees into kilometers, assuming that the length of 1 degree in latitude is 111.15 km and 1 degree in longitude is 78.15 km (Geographical Atlas 1985). These data were interpolated onto a regular grid with a 250 m spatial resolution. Sea surface and volume were calculated for each level mark from 0 to 62 m with a 0.5 m time step (Table 2 and Figure 3).

We compared our results with existing assessments of surface and volume (see Fig. 2) for various parts of the Aral Sea (Nikolaeva 1969, cited

TABLE 2. Morphometric parameter of the Big Aral Sea according to the Digital Bathimetry Model. Sea surface (S, km^2) and volume (V, km3) for various depth marks (H, m). Depth mark 0 m corresponds to +53 m absolute Baltic Sea level (Kronstadt mark).

H	V	S	H	V	S	H	V	S	H	V	S
0	953.3	57342	**17**	205.9	29786	**34**	27.9	2088	**51**	4.1	660
0.5	925.1	55810	**17.5**	191.3	28579	**34.5**	26.8	2034	**51.5**	3.8	623
1	897.5	54695	**18**	177.3	27405	**35**	25.8	1986	**52**	3.5	587
1.5	870.4	53754	**18.5**	163.9	26172	**35.5**	24.9	1941	**52.5**	3.2	555
2	843.7	52986	**19**	151.1	24924	**36**	23.9	1900	**53**	2.9	524
2.5	817.4	52339	**19.5**	139.0	23581	**36.5**	23.0	1859	**53.5**	2.7	496
3	791.3	51818	**20**	127.6	21307	**37**	22.0	1819	**54**	2.5	469
3.5	765.5	51321	**20.5**	117.4	19682	**37.5**	21.1	1780	**54.5**	2.2	444
4	740.0	50845	**21**	107.9	18327	**38**	20.3	1740	**55**	2.0	421
4.5	714.7	50367	**21.5**	99.0	16962	**38.5**	19.4	1701	**55.5**	1.8	398
5	689.7	49321	**22**	90.9	15539	**39**	18.6	1662	**56**	1.6	377
5.5	665.2	48503	**22.5**	83.5	13992	**39.5**	17.7	1623	**56.5**	1.4	357
6	641.1	47853	**23**	76.9	12313	**40**	16.9	1585	**57**	1.3	336
6.5	617.4	47252	**23.5**	71.1	10851	**40.5**	16.2	1546	**57.5**	1.1	316
7	593.9	46645	**24**	66.0	9643	**41**	15.4	1507	**58**	0.9	296
7.5	570.7	45986	**24.5**	61.5	8558	**41.5**	14.6	1467	**58.5**	0.8	276
8	547.9	45352	**25**	57.5	7461	**42**	13.9	1425	**59**	0.7	257
8.5	525.4	44716	**25.5**	54.0	6469	**42.5**	13.2	1381	**59.5**	0.5	238
9	503.2	44060	**26**	51.0	5382	**43**	12.5	1334	**60**	0.4	219
9.5	481.3	43370	**26.5**	48.6	4343	**43.5**	11.9	1288	**60.5**	0.3	200
10	459.8	42119	**27**	46.6	3670	**44**	11.3	1245	**61**	0.2	181
10.5	439.0	41162	**27.5**	44.8	3432	**44.5**	10.6	1208	**61.5**	0.1	151
11	418.6	40358	**28**	43.2	3222	**45**	10.0	1179	**62**	0.1	116
11.5	398.7	39592	**28.5**	41.6	3043	**45.5**	9.5	1152	**62.5**	0.0	63
12	379.0	38852	**29**	40.1	2870	**46**	8.9	1125	**63**	0.0	16
12.5	359.8	38103	**29.5**	38.7	2771	**46.5**	8.3	1098	**63.5**	0.0	5
13	340.9	37345	**30**	37.3	2680	**47**	7.8	1071	**64**	0.0	1
13.5	322.5	36541	**30.5**	36.0	2597	**47.5**	7.3	1044	**64.5**	0.0	1
14	304.4	35685	**31**	34.7	2515	**48**	6.8	1017	**65**	0.0	1
14.5	286.8	34795	**31.5**	33.5	2435	**48.5**	6.3	990	**65.5**	0.0	0
15	269.6	33848	**32**	32.3	2356	**49**	5.8	963			
15.5	253.0	32849	**32.5**	31.1	2281	**49.5**	5.3	936			
16	236.8	31889	**33**	30.0	2212	**50**	4.8	746			
16.5	221.1	30917	**33.5**	28.9	2147	**50.5**	4.5	700			

from Bortnik and Chistyaeva 1990). These historical assessments were made for sea depths (with zero depth at +53 m mark) at 0, 2, 5 m and then from 10 m to 50 m with 10 m depth resolution. For the Big Aral Sea, our results compare well with these data. For depths from 0 to 20 m the differences in volume do not exceed 20–30 km^3 (less than 4% of absolute values), for deeper marks the difference ranges 3–4 km^3. From 0 to 20 m the difference in surface values rapidly decreases from 2,700 to 700 km^2 (from 5 to 2%), for 30–50 m depths the difference decreases to 9–200 km^2. These discrepancies may be related to the various initial data used, to the geographical selection of the region and to the calculation method. However, for the 15–25 m depth (that corresponds to the sea level for the period considered) these published estimations are given with a 10 m step that may lead to potential errors if linear interpolation is used between the given values. This is especially evident for the 10–30 m depth values for sea volume and for the 20–30 m depth values for sea surface. Thus, our estimations using digital bathymetry model provide, with significantly increased vertical resolu-

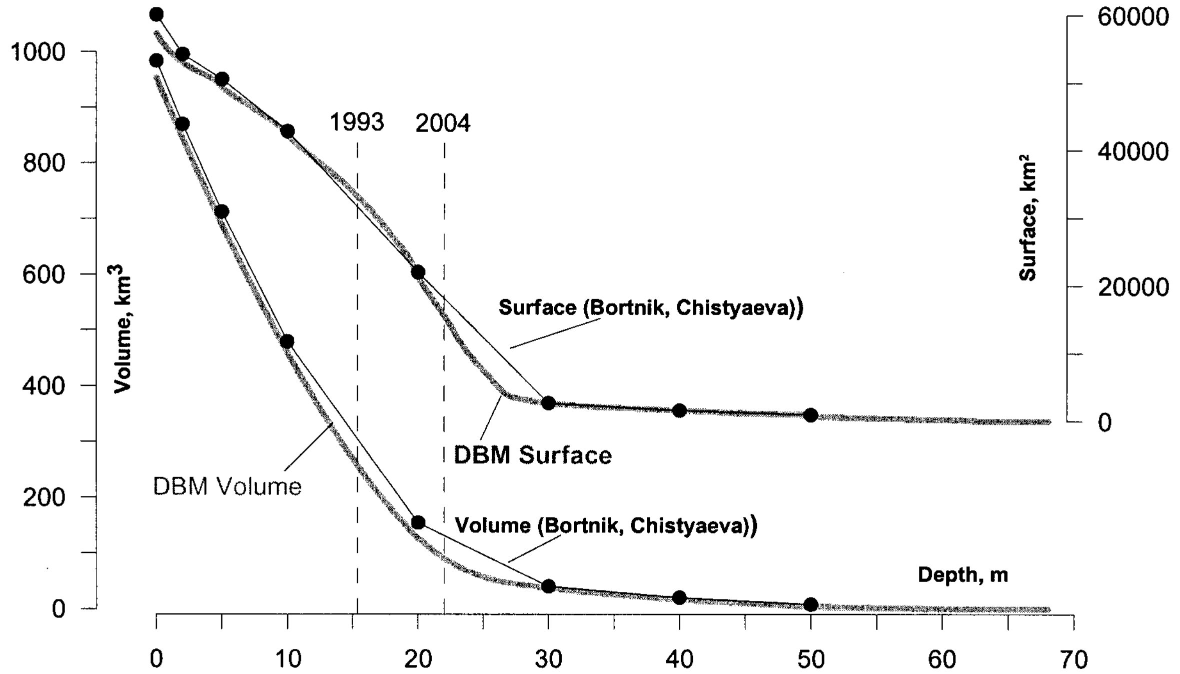

FIG. 3. Volume and surface of the Big Aral Sea according to Bortnik and Chistyaeva (1990) (thin black line with dots) and calculated using DBM (thick gray line). Dashed lines denote sea depth in 1993 and 2004. Depth mark 0 m corresponds to +53 m absolute Baltic Sea level (Kronstadt mark).

tion, more accurate and reliable values for the calculations of the contemporary water budget.

By combining satellite altimetry and DBM data we obtained time series of variations of the volume and surface of the Big Aral Sea over the last 11 years, with high precision and high temporal resolution. Mean annual values of these and other parameters are presented in Table 3. We used these time series to better constrain the equation of water balance and to assess the coherence with in-situ hydrological data currently available. In the next section we present an assessment of various parameters of the water budget of the Aral Sea.

BIG ARAL SEA WATER BALANCE

Water Balance Equation and Its Main Components

Usually the variation in volume for an enclosed water body results from differences between the volume of inflow and outflow water. For the Big Aral we can distinguish several components. Inflow

TABLE 3. Mean annual values of sea level (from satellite altimetry relative to the geoid and above the Baltic Sea level from Ashirbekov and Zonn 2003), morphometric parameters (obtained using DBM), and river discharge (from http://water.freenet.uz/post/amu/kizil.htm) for the Big Aral Sea.

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Sea level, m (geoid)	36.74	36.62	36.33	35.47	34.63	33.97	33.63	32.97	32.06	31.17	30.81
Sea level, m (Baltic)	36.95	36.60	36.11	35.48	34.80	34.24	33.80	33.30	32.16	30.90	—
Sea surface, km^2	32,100	31,800	31,600	29,200	27,200	25,700	24,700	22,500	19,500	17,300	—
Sea volume, km^3	240	236	232	201	179	162	153	138	120	104	—
Amu Darya runoff, km^3	16.14	21.19	2.32	4.7	0.84	20.45	3.89	1.77	—	—	—

is represented by (a) the surface river runoff (R), (b) the rate of precipitation (P) multiplied by the instantaneous surface of the lake (S(t)), (c) the underground water inflow (G_i), and (d) the inflow of water from the Small Aral. The outflow part consists of (a) the rate of evaporation (E) multiplied by the instantaneous surface of the lake (S(t)), and (b) the underground outflow (G_o).

While the construction of the dam in the Berg's strait had a significant influence on the water balance of the Small Aral (Aladin *et al.* 2005), its influence on the level of the Big Aral is not clearly assessed. In particular, no acceleration of desiccation of the Big Aral was observed when the dam was installed and no additional inflow was detected when dam was destroyed. Satellite images (Landsat) however indicate a seasonal stream flow southward, which is partly lost in the lowland south of Kokaral peninsula, while another part (about 2–3 km^3) flows to the east part of the Big Aral (Letolle *et al.* 2005). We consider that the inflow from the Small to the Big Aral for the period of satellite altimetry observations is very slight but should be included within the unknown contribution to the water balance equation which can thus be written as (Mason *et al.* 1994):

$$dV/dt = (R + Gi - Go) - (E - P)*S(t) + \varepsilon \qquad (1)$$

Next we consider the existing data for the components of the water budget of the Aral Sea, their quality and applicability for establishing a detailed contemporary water balance

Evaporation and Precipitation

Our analysis of published studies on the Aral Sea shows that evaporation (E) and precipitation (P) are the most uncertain components of the water budget. Thus obtaining accurate estimates of E-P is still a major concern even on an annual time scale. We have based our analysis on three recent articles (Bortnik 1999, Small *et al.* 1999, and Benduhn and Renard 2003). Bortnik (1999) provides a table with average values for E and P for every decade from 1960 to 1990, and also a figure of inter-annual evolution of these parameters. The average decadal rate of precipitation is between 110 and 143 cm/year, while for evaporation this value varies from 968 to 1,050 cm/yr. No specific secular trends were observed for these parameters in this article.

In Small *et al.* (1999) the authors computed E and P by inverting the simplified water balance equation. Their approach assumes a negligible underground budget (Gi-Go) and, since they did not have access to the variations of sea volume, considers instead only level variations. Using (a) sea level variations over the period 1988–1992, and (b) runoff for Syr Darya and Amu Darya, they computed a set of monthly data for the term E-P by inverting the water balance equation. Then they compared these data with the values they obtained from the evaporation model based on sea surface temperature (Small *et al.* 1999, 2001) and precipitation data from (Legates and Wilmott 1990). The values they obtained varied between 210 and 250 cm/yr for precipitation and 790 to 1,220 mm/yr for evaporation.

Benduhn and Renard (2003) proposed another kind of computation. For precipitation they used the data given by Bortnik (1999) but for evaporation they used the classical Penman formula which depends on various parameters including salinity, temperature, etc. It also takes into account the impact of variations in salinity on the evaporation rate which tends to decrease when salinity increases. The annual evaporation computed by these authors was around 1,180 mm/yr at the end of the 1980s (for salinity around 35 ppt) and 1,140 mm/yr at the end of the 1990s (for salinity close to 90 ppt).

However none of these published sources can provide a realistic amount of precipitation and evaporation in the frame of our study. Bortnik (1999) gave only average data without seasonal variations of P and E and did not take into account the evolution of both parameters related to climate change and high salinity change during the last decade. Small *et al.* (1999) gave an assessment of seasonal variation in precipitation and evaporation for 1988–1992. Later on, Small *et al.* (2001) also suggested that from 1960 to 1990, E-P had increased to approximately 150 mm/yr, mainly due to direct effect of global warming (around 100 mm/yr) and to positive feedback of the desiccation itself (for around 50 mm/yr which corresponds to almost 4 km^3/yr inflow to the Big Aral). The influence of these phenomena should have further increased during the last 10 years, largely due to the increase in temperature, but no assessment of this influence has been made so far.

Moreover, Small *et al.* (2001) based their analysis on the data prior to the separation of the Big and Small Aral (when salinity was around 30 ppt) and did not take into account the very high and non-homogeneous recent increases of salinity of the Big Aral. Even if salinity measurements in the Big Aral

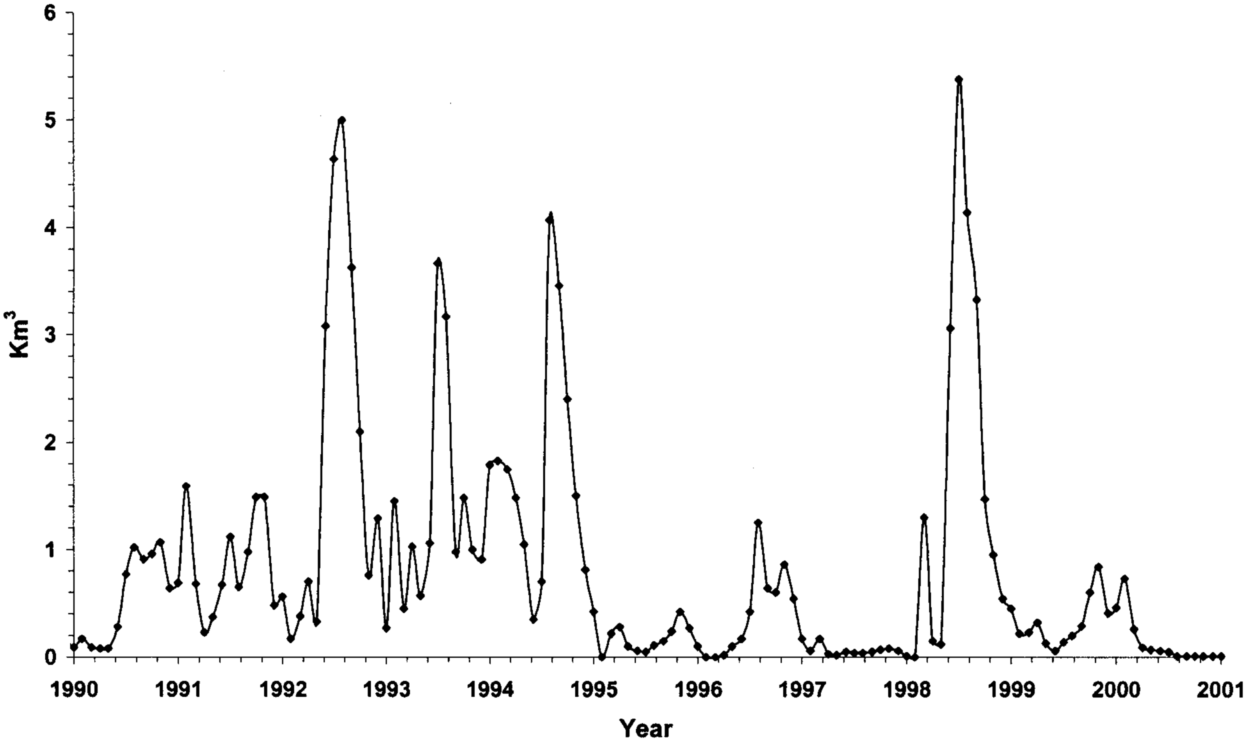

FIG. 4. Amu Darya river discharge (km^3/month) at Kizildgar (data from http://water.freenet.uz/post/amu/kizil.htm).

Sea are sparse and not well assessed, it is known that by 2002 salinity reached over 80 ppt (Zavialov *et al.* 2003) in the western part and around 100 ppt to 120 ppt in the eastern part in 2001 (Mirabdullayev *et al.* 2004). Because the Big Aral is still drying, the salinity should still be increasing. This extremely high salinity should result in a proportional decrease of evaporation (Benduhn and Renard 2003). Finally, Benduhn and Renard (2003), presented an analysis of the effect of salinity on evaporation but did not give the seasonal variability of these parameters. Nor did they take into account the effect of global warming over the last 10 years which tended to increase evaporation.

Another issue is that these authors used precipitation data precipitation collected before 1990. As a consequence, we do not have data describing interannual fluctuations of E-P for our 1993–2000 analytical periods. Moreover, none of these authors took into account the influence of ice cover on the evaporation. Every year the Aral Sea is covered by ice for several months and ice presence may strongly affect evaporation during winter time. In situ data on ice cover for the Aral Sea are not available since the mid-1980s. However, our recent research (Kouraev *et al.* 2003, 2004) shows that a combination of active and passive satellite microwave data provides the possibility of estimating ice cover extent and dates of ice formation and break-up in the Big Aral Sea. This, in turn, provides a basis for estimating the influence of ice cover on evaporation rate and is one of the points for our future research.

The accumulated errors in estimates of evaporation and precipitation rate for which direct measurements do not exist over the Aral Sea (at least for the most recent years) largely contributes to the budget error in the water balance equation: influence of regional climate change, increase of salinity, and presence of ice cover also adds large uncertainties in the E-P term used in the equation of the water balance.

Because various authors provide different values for precipitation, we considered different values of mean annual evaporation and precipitation (see Table 3) in our calculations. We took the maximum and minimum values provided in the literature for both evaporation and precipitation, and then performed a sensitivity study of the impact of this uncertainty on the water balance equation by varying E and P within the indicated range.

River Discharge

For the runoff of the Amu Darya (R) we used mean monthly values (Fig. 4) measured at Kizildgar (alternative versions of transcription—Kiziljar and Kyzljar), located several tens of kilometers upstream of the delta mouth. These data are available from January 1956 up to December 2000 at http://water.freenet.uz/post/amu/kizil.htm. The problem is that the measurements are made far upstream from the Big Aral; consequently it is very difficult to estimate the amount of water which actually reaches the Aral Sea as already noted by Small *et al.* (1999, 2001). An unknown fraction of the water runoff measured at the gauge point may be lost between the observation point and the sea (due to evaporation and infiltration). Or this infiltrated water may reach the sea as groundwater and with a significant time lag. This uncertainty finally contributes to errors in the water balance estimations.

Our results for the Small Aral Sea (Aladin *et al.* 2005) with the Syr Darya River runoff show that the loss of water within the Syr Darya delta before reaching the sea is around 20%. Although this is not directly transposable to the Big Aral, it gives an assessment of the order of magnitude of the possible error for this parameter in the water balance equation. If we consider that the average annual runoff of Amu Darya over the period 1993–2000 is around 9 km^3/yr (with high inter-annual variability of 0–20 km^3/yr) we can assume that, in the worst case, the error on this parameter is up to 1.8 km^3/yr.

We also compared these monthly data with the published mean annual runoff of Amu Darya at Kizildgar from 1959 to 1995 (Zholdasova 1999) for the time of overlap: 1974 to 1995. For these 22 years we obtained a mean difference of 0.6 km^3/yr between both sets of runoff data. By adding this uncertainty to the errors associated with the losses in the delta, and the uncertainty associated to the Syr Darya runoff (2–3 km^3) we have error budget of the Amu Darya runoff which amounts to 3 km^3/yr. In any case, in contrast to the E-P term, we have, at least, a reliable dataset for the inter-annual and monthly fluctuations of the Amu Darya River for almost the whole period of analysis.

Underground Discharge

The underground water discharge and outflow is an unknown parameter that is usually neglected in the water balance of the Big Aral, mainly because quality information is lacking. There are very few accurately assessed and/or published data on the hydrogeological features under and around the Big Aral that could be used to elaborate a realistic model of underground discharge into the Aral Sea. However, it should be noted that many *in situ* visual indications suggest that groundwater could be present in the region of the Aral (presence of reeds, or the remains of trees from ancient time). Based on the "negative correlation between fluvial and groundwater discharge," Benduhn and Renard (2003) assumed that the amount of underground water that follows the Amu Darya deltaic plain is probably not negligible. Moreover, in the Tsche-Bas Bay the biodiversity is higher than in the rest of the Big Aral. This could be associated with a freshening of the water in these areas by inflow of the underground fresh water from under cliffs of the Ustjurt plateau. This freshening provides favorable conditions for benthic organisms. For example, samples from Tsche-Bas Bay in autumn 2002 and 2003 contained a large variety of zoo-benthos—not only species of *Caspiohydrobia* (gastropod), various chironomids (Chironomidae), and the euryhaline ostracod *Cyprideis torosa* as in other places of the Big Aral, but also some recent (the bivalve *Abra ovata*) and ancient (*Cerastoderma isthmicum*) invaders. Also in the Tche-Bas Bay the presence of *Abra ovata* juveniles suggests continuing reproduction of this species. Evidence of freshwater inflow from the Ustjurt plateau has also been found at Aktumsyk cape (Radjabov, Tahirov, personal communication).

Nevertheless, the probable presence of significant underground water reserves does not necessarily imply a large supply of water into the Big Aral Sea. The assessment of the underground water transport through deltaic plains and/or bottom sediments, deep aquifers, as well as along the southwestern cliffs of the Ustyurt plateau needs to be complemented by *in situ* measurements which are out of the scope of this work. We consider the underground discharge as an unknown parameter and provide, through the inversion of equation (1) and an inverse least square adjustment, an assessment of the amount of underground discharge. We also estimate the order of magnitude of possible errors within the Big Aral water budget that could be as-

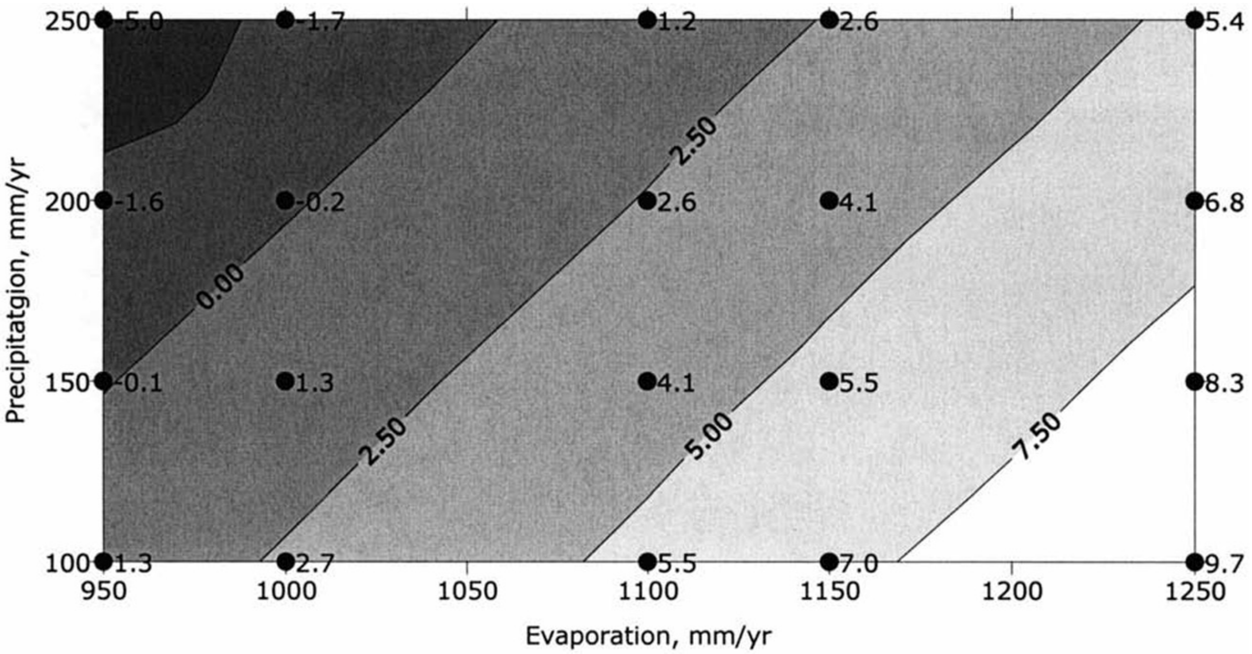

FIG. 5. Underground water balance and error term (left member of equation (2), in km^3 for different values of precipitation and evaporation.

sociated to uncertainties in the assessment of underground water inflow.

New Water Balance of the Big Aral Sea: Results and Comments

Satellite altimetry observations of the Big Aral Sea level and estimation of sea surface and volume from satellite and DBM data provide unique and very important information for water budget studies. Now it is possible to assess the water balance for the Big Aral with a much higher precision than was done in previous studies. We have performed a detailed analysis of the water balance in order to estimate the uncertainties associated with the main constituents of the water budget, estimate influence of errors, and analyze potential future development of the Big Aral.

We have rewritten equation (1) as:

$$U_w + \varepsilon = dV/dt - R + (E-P)*S(t) \tag{2}$$

where U_w is the underground balance (G_i–G_o) and ε is an additional contribution related to the uncertainty in the assessment of other parameters of the water balance equation (1).

The components dV/dt and R are known (on a 10 days temporal scale for V and monthly scale for R). To take into account the uncertainty on the E-P component of the water budget we choose 20 sets of values of E and P ranging from typical low to high values taken from (Bortnik 1999, Small *et al.* 1999, and Benduhn and Renard 2003). For each E and P value we then inverted equation 2 using data for the variation of volume and surface of the lake, and values for the Amu Darya surface runoff. The results of each inversion are given in Figure 5.

These values need to be interpreted in term of sum of errors on the river runoff, on the volume variation measurements, and on possible underground water fluxes. For the river runoff we have estimated that the errors may be in the range of 3 km^3/yr, while for the volume variation the error is around 1.5 km^3/yr (see sections on River Discharge and precision of Altimetry Measurements over the Aral Sea). According to the standard error theory this implies that the total error of our computation is around 3.3 km^3/yr. The resulting uncertainty is thus totally dependent on the errors in the evaporation and precipitation rate. If the actual evaporation is high (effect of global warming higher than the effect of high salinity on evaporation over the Big Aral Sea) then the underground water inflow should be not negligible—from 0 to about 6–7 km^3/yr depending on the value of annual precipitation. In the low evaporation scenario (preponderant effect of

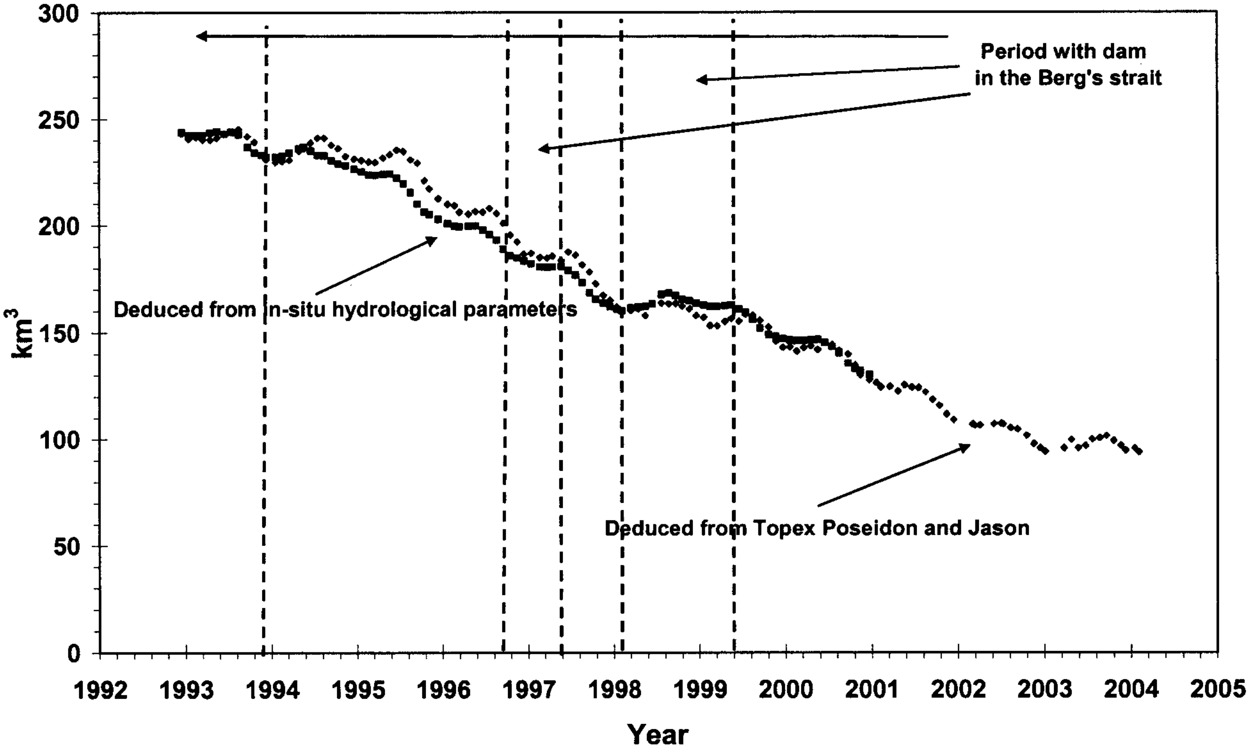

FIG. 6. Variations of volume of the Big Aral Sea (km3) both from Topex/Poseidon and bathymetry model and from* in situ *data, after estimation of residual errors depending on the value of (E-P) as given in Figure 5.

salinity over evaporation) underground water inflow is negligible, or does not even exist: in this case the left member of equation 2 can only be explained by errors on river runoff and measurements of volume.

If we consider a moderate evaporation rate, as suggested in the recent study by Bendhun and Renard (2003) where they estimate the evaporation rate over the Aral Sea for the 1990s at about 1,150–1,160 mm/yr, then we have an underground contribution of about 0 (for high precipitation rate) to around 3–4 km^3/yr (for low precipitation rate). This value of underground inflow seems to be reasonable, especially considering some external observations (presence of reeds and/or of unexpected large number of benthos species along the west coast of Big Aral).

We plotted the variations in volume deduced from hydrological in situ data and estimated the value of the underground discharge based on the results shown in Figure 5. Superimposed are the variations in volume deduced from altimetry measurements and bathymetry map. This figure shows that the annual oscillations of the Aral Sea deduced from hydrology are in good agreement with those deduced from altimetry measurements. It also shows a good agreement in the long-term variations after resolving equation (1) but a significant disagreement still remains for the years 1995–1996 for which we still do not have an explanation. This issue must be addressed further, but without better data on evaporation and precipitation, as well as more accurate runoff data, our results given in Figure 6 clearly show that it is still extremely risky to assume a significant effect of underground water.

FUTURE EVOLUTION OF THE BIG ARAL SEA

After establishing with as much precision as possible the water budget for the Big Aral Sea, we wanted to estimate the potential evolution of the Big Aral for various scenarios involving various data on evaporation, precipitation and underground inflow. We assumed that the discharge of the Amu Darya would be zero. We chose three typical scenarios based on values presented in Table 3. In the first ("dry") scenario we assumed high evaporation

(1,250 mm/yr) and low precipitation rates (100 mm/yr), thus high underground water (7 km3/yr); in the second ("medium") scenario we chose the medium values of evaporation (1,150 mm/yr) and precipitation (200 mm/yr) and underground water inflow of 2 km^3/yr; and for the third ("wet") scenario we took into account low evaporation (1,000 mm/yr) and high precipitation rates (200 mm/yr) and no underground water inflow.

Projecting these values into the future and using the relations between level, surface, and volume from DBM, we estimated that, for the "wet" scenario, in 15 years the level of the Big Aral Sea will decrease and stabilise at +27 meters and its surface will be around 6,000 km^2. For the "medium" scenario our computation shows that in 70 years the level will reach +19 meters and the surface only 2,000 km^3; and in the case of the "dry" scenario, in 30 to 40 years the Big Aral will fully desiccate. This shows that even if some underground water could supply the Big Aral, the level of the sea will inevitably continue to dry up to an equilibrium level. This level of equilibrium is hardly predictable, because it also depends on future surface runoff.

Continued desiccation of the Big Aral is thus almost assured. In a few years its water area will inevitably be divided into at least three parts: Tsche-Bas Bay will soon be separated in the north; a deep basin will be formed in the west, and a shallow water body in the eastern part. The shallow eastern part could dry up completely by 2010 or even earlier. The detached Tsche-Bas Bay will slowly become more saline, if underground freshwater inflow is significant. Nevertheless, sooner (2020) or later (2025), Tsche-Bas Bay will become more saline because low mineralized underground water in arid climate lakes cannot compensate evaporation for a long period of time. The deepwater basin of the west will exist for the longest time because it has the largest water volume and the lowest area/volume ratio, and, as the Tsche-Bas Bay, it has some subterranean inputs from the Ustjurt plateau. So, year after year this last part of the Large Aral will become smaller and more saline until stability will be reached.

What are possible paths for the evolution of the Big Aral Sea ecosystems? The rapid decline of the Big Aral Sea level has actually destroyed the delta of the Amu Darya. Unlike the delta of Syr Darya, where natural rehabilitation processes began after the dam was built, the rapid degradation of the Amu Darya delta continues. Moreover, while deltaic water bodies of the Syr Darya are regularly fed with fluvial waters, those of the Amu Darya do not receive regular flows. Thus the ecological situation in the south of the Big Aral is more complicated than in the northern Aral Sea.

In the future, before salinity increases to 200–300 ppt, there will be only euryhaline halophylic species, and their number will decrease as salinity will continue to increase even further. In the zooplankton only *Artemia salina* (*A. parthenogenetica*), which has invaded the Big Aral Sea and in some areas reaches high abundance, may survive in the future. There is no doubt that the Big Aral Sea may become an important center for harvesting brine shrimp cysts for use in aquaculture and thus provide some economic value (Letolle *et al.* 2005). As salinity will reach 300–350 ppt, only bacteria will survive.

CONCLUSIONS

Our result shows that a combination of satellite altimetry and digital bathymetry model provides a unique opportunity to estimate variability of sea level, surface, and volume, even for regions with poor *in situ* monitoring network. A combination of this information with data on other parameters of the water budget offers a promising potential for the assessment of the temporal evolution of the water budget for enclosed water bodies.

After the introduction of new and precise constraints—data from satellite altimetry and DBM—into the water balance equation, we see that there still remain uncertainties in the water balance of the Big Aral Sea, associated with the assessment of evaporation, precipitation, and underground inflow. One of the results is that the underground water inflow may not be negligible. This, however, needs to be assessed by hydrogeological modeling and more accurate data for evaporation and precipitation rates.

Even if accurately established in further studies, the probable amount of groundwater flow will only slow the desiccation of the Big Aral. To reverse the process or even to return to the situation of the mid 1990s, the amount of water necessary to stabilize the level of the sea is much higher than what underground flow could supply in the most optimistic scenario.

Restoration and rehabilitation of the Big Aral is practically impossible as it would require large amounts of both the Syr Darya and Amu Darya waters which are already diverted for irrigation. So the

Big Aral will continue to desiccate. The only issue left to predict is the time needed to reach an equilibrium sea surface, assuming that no political decision to try to restore the Big Aral by reducing irrigation will be made.

ACKNOWLEDGMENTS

The research was supported by the INTAS Project 00-1053. The authors gratefully acknowledge Rene Letolle from the University Pierre et Marie Curie of Paris, Philippe Renard from the Center for hydrogeology of University of Neuchatel, Nelly Mognard Campbell and Rosemary Morrow from Legos Laboratory, Toulouse, and Ivan Savitsky from the University of information and technology of Tashkent. We would like to thank the Centre for Ocean Topography and Hydrosphere (CTOH) at the LEGOS laboratory, Toulouse, France for providing altimetry data.

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Submitted: 15 March 2004
Accepted: 12 September 2005
Editorial handling: Barry M. Lesht