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ORIGINAL ARTICLE

Changes in water volume of the Aral Sea after 1960

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Abstract The Aral Sea is the biggest saline lake in Central Asia. This brackish water body was the world's fourth largest lake before it started to shrink in the 1960's due to water withdrawal for land irrigation. The runoff decreased from 20.6 km^3 in 2003 to 4.5 km^3 in 2010 and precipitation reduced from 9.4 km^3 in 1960 to 3 km^3 in 2010. Based on comparative hydrological data between 1960 and 2005, water volume of the Aral Sea reduced significantly. The observed values of runoff, evaporation, precipitation, and water volume were used to estimate water volume from 1957 to 2010, and the coefficient of determination for predicted water volume is 0.7647. We have obtained regression parameters using previously observed data to further estimate corresponding magnitudes of precipitation, runoff, and evaporation from 2011 to 2031, and as a result are then applied in the estimation of the water volume. Our prediction proposes that water volume of the Aral Sea will be decrease approximately to 75.4 km^3 in 2031.

Keywords Aral Sea · Water balance · Evaporation · Irrigation

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Introduction

The Aral Sea is a terminal lake, has no outlet, and is located in Central Asia (Fig. 1). The Aral Sea was the world's fourth largest lake with surface area of 68,000 km^2, water level of 53.4 m, and salinity of 10 g/L in 1960 (Micklin 2007; Glantz 1999; Aralgenefund 2011). It has existed in that form during the past 8,000–10,000 years (Boomer et al. 2000). The Aral Sea surface area has declined from 68,000 km^2 in 1960 to 14,280 km^2 in 2010, water volume reduced from 1,093.0 km^3 in 1960 to 98.1 km^3 in 2010, and salinity increased from 10 g/L in 1960 to 130 g/L in 2010 (Alikhanov 2010; Aralgenefund 2011). The Aral Sea water level declined by more than 29 m (Large Sea) in 2007 (Aralgenefund 2011).

The initial reason for the Aral's decline was the fact that Soviet planners' diverted water from Aral Sea's two big feeding rivers (the Amu Darya and the Syr Darya) into cotton fields in the territory of Uzbekistan. The Amu Darya and Syr Darya are major rivers in the Central Asia. This rivers' water flows from the Tien Shan and Pamir mountains (it is chiefly fed by glaciers and snowmelt) across Kara-Kum and Kyzyl-Kum deserts into the Aral Sea. This is intensively used for irrigated agriculture, especially 85 % of water used for irrigation areas. The average annual flow from the drainage basin is around 79 km^3 of Amu Darya and 37 km^3 of Syr Darya river (Micklin 2000). The irrigation areas in this rivers' basin have rapidly increased, which had grown to 30,000 km^2 in 1913, 45,000 km^2 in 1960, and then to 70,000 km^2 in 2000 (Bortnik 1999; UNDP 2007).

The Aral Sea crisis was one of the world's largest environmental disasters (Glazovsky 1990; Kostianoy 2006). The Aral Sea-exposed dry seabed has reached from

Fig. 1 Aral Sea Basin (Micklin 2007)

45,000 km^2 in 1960 to 87,000 km^2 in 2010 (Dukhovny 2010). As a result, each year the wind spreads 45 million metric tons of salty and contaminated dust into the atmosphere; dust plumes can be 400 km long and 40 km wide, while the range of dust storms can reach 300 km (Alikhanov 2010). This altered atmosphere is salty and dust spoiled, and is polluting the Aral Sea region, resulting in serious public health problems (US Geological Survey 2007). This massive environmental disaster affects approximately 5 million people (Kostianoy 2006; UNDP 2007; Micklin and Aladin 2008), and every second female suffered from inflammation of the gastroenteric of the vulva, vagina as disbiosis and bacterial vaginosis in the Aral Sea region (Elpiner 1999; Alieva 2008). Decreasing water levels of the Aral Sea has also resulted in the loss of fishery (20 species in 1960, and, 5 species in 1980), the significant change in the climate of area (hotter summers and colder winters), and the loss of wild animals (58 heads in 1960, 14 heads in 2000) (Alikhanov 2010; Forkutsa 2006; US Geological Survey 2007; Elpiner 1999).

The water balance method has been widely used in water resources engineering, particularly in farming applications. Monthly water balance models have been used for examine the various components of the hydrologic cycle (e.g., precipitation, evapotranspiration and runoff). Monthly water balance models were first developed in the 1940’s by Thornthwaite (1948). Recently, they have been employed to explore the impact of climate change (McCabe and Ayers 1989), estimate the global water balance (Mather 1969; Legates and McCabe 2005), river runoff (Wolock and McCabe 1999) and soil moisture storage (Mintz and Serafini 1992), and to develop climate classifications (Thornthwaite 1948) and irrigation demand (McCabe and Wolock 1992).

The objectives of this study are as follows:

1. To determine the total water volume lost from the Aral Sea since 1957–2010;
2. To extrapolate river runoff, evaporation, and precipitation data by regression equations, and to predict future the Aral Sea volume reduction from 2010 to 2031.

Materials and methods

Study area

The Aral Sea is a saline endorheic basin in Central Asia. The Aral Sea basin includes Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and near the Caspian Sea, occupied an area of 68,000 km^2 and had a volume of 1.093 km^3 in 1960 (Micklin 2004; Fig. 2). The Aral Sea has been gradually shrinking since the 1960’s after the rivers that fed it were diverted by Soviet Union irrigation projects. In the last half century, the Aral Sea level has fallen by 16 m (small Sea) and 23 m (large Sea), the water surface decreased by 80 %, the water volume reduced from 1.093 to 98.1 km^3 (Fig. 2) and water salinity increased to 130 g/L (Alikhanov 2010). As a consequence, the Aral Sea has virtually turned into a ‘dead’ Sea. The Aral Sea exposed dry seabed has reached 87,000 km^2 in 2010.

The Amu Darya River is at the south of the Aral Sea basin, and has a mean annual flow of 70–80 km^3/year. The river is 2,400 km long, with a basin area of more than 300,000 km^2. The Syr Darya River runs in the north of the basin. Its annual flow is half of the Amu Darya. The Syr Darya is the longest river in Central Asia, 2,790 long, with a basin area of almost 300,000 km^2.

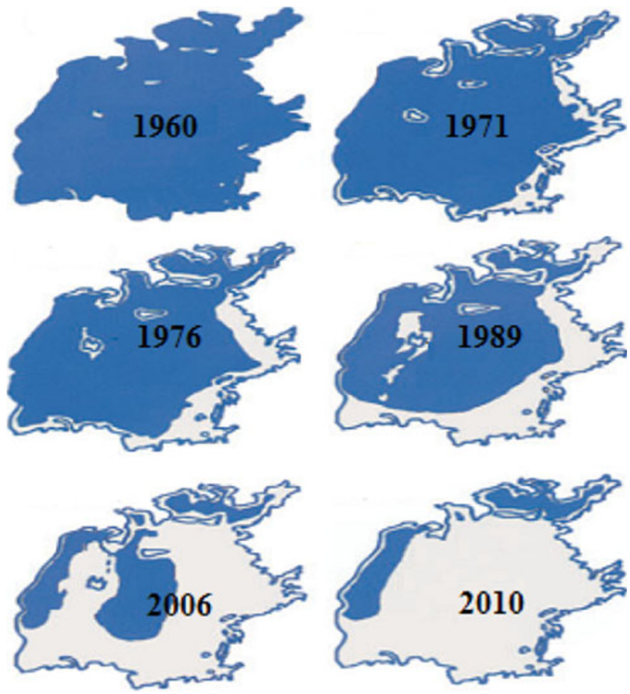

Fig. 2 Changing profile of the Aral Sea 1960–2010 (UNDP 2007)

Summer temperatures reach 40 °C and winter temperatures fall to −20 °C. Precipitation is minimal, and the average annual precipitation is approximately 100 mm, which is partial to spring and fall, and is a typical continental climate. The main volume of water comes from high glaciers feeding into the main rivers of the Amu Darya and the Syr Darya, which flow into the Aral Sea from the north and south, respectively.

Data collection

Data on evaporation, river runoff (RO, including surface water and groundwater runoff), water volume, precipitation and salinity observation of the Aral Sea from 1960 to 2010 were collected (Aralgenefund 2011; Aladin and Potts 1992; Bjorklund 1999; Central Asian States 2000; Jarsjo and Destouni 2004; Mikhailov et al. 2001; Oroud 1999; UNDP 2007, 2008; UNESCO 2000; Zavialov et al. 2003), as a result shown in Table 1. The Aral Sea eventually separated into two sub-divisions: namely, the Large Aral Sea located to the south, and small Aral Sea located to the north. This occurred over a 26 years period from 1961 to 1987 during which river inflow reduced to approximately zero into the Aral Sea. After the Aral Sea separation, water flow from the Amu Darya and Syr Darya rivers into the Aral Sea increased from 1988 to 2004. Table 1 shows that the runoff was 31.5 km^3 in 1988. However, the rivers' annual flow into the Aral Sea decreased to 15.8 km^3 in 2004 and then reduced to 4.5 km^3 in 2010. In 1987, the evaporation was 36.8 km^3, water volume was 345.6 km^3, precipitation was 6.2 km^3, and salinity was 25.0 g/L of the Aral Sea as shown in Table 1. However, the water volume decreased to 98.1 km^3, precipitation reduced to 3 km^3, evaporation decreased to 11.4 km^3, and salinity increased to 130 g/L in 2010.

Water balance

Figure 3 depicts water volume reduction within the Aral Sea based on a volume change ΔV over time interval Δt formula, more clearly expressed in Eq. (1) below:

$$\Delta V = P + RO - E \quad (1)$$

where P is the precipitation, RO is the runoff (including surface water and groundwater), E is the evaporation, and ΔV is the changes of the Aral Sea water volume.

The Nash–Sutcliffe model efficiency coefficient was used to assess the predictive power of the hydrological models. It is defined as:

$$C_{eff} = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2} \quad (2)$$

where $O_i$is the observed data, P_i is the predicted data, and $\bar{O}$ is the mean of observed data. The Nash–Sutcliffe coefficient of efficiency ($-\infty \leq C_{\text{eff}} \leq 1$) (Nash and Sutcliffe 1970) is a relative assessment of the model performance, and was adopted to evaluate the estimation of water volume. If $C_{eff} = 1$, then the pair of observed and estimated data match well.

Results and discussion

Data in Figs. 4, 5, 6, and 7 were estimated according to Table 1 observations by interpolation equation calculation. Combined, these figures show that estimated values of water volume reduction were very high during 1960 to 2005. This severe water volume reduction was directly linked to reduced river runoff into the Aral Sea, reduced precipitation rates, increased evaporation rates, and increased use of the Aral Sea for irrigation purposes.

Precipitation

Decreasing of the Aral Sea water levels has caused losing soil degradation, water salinity, and local climate change (Elpiner 1999). Increased greenhouse gas emissions, combined with vegetation growth throughout the dry Aral Seabed facilitated an increase in atmospheric temperature (hotter summers and colder winters; Forkutsa 2006). Consequently, precipitation magnitude has reduced (Fig. 4). Figure 4 shows that the precipitation was 9.4 km^3 in 1960

Table 1 Hydrological observation data of the Aral Sea, 1957–2009

Period	River runoff, R (km^3)			Evaporation, E (km^3)	Water volume, V (km^3)			Precipitation, P (km^3)	Salinity (g/L)
	Amu Darya	Syr Darya	Total		Small Sea	Large Sea	Total		
1957	9.5	9.9	19.4	68.1			1,080.0	8.5	10.0
1960	20.7	21.3	42.0	71.1			1,093.0	9.4	10.0
1973	0.6	0.3	0.9	60.0			824.2	4.4	13.4
1977	0.0	0.2	0.2	45.7			749.2	5.0	15.4
1982	0.0	1.3	1.3	38.5			579.8	8.5	18.8
1984	0.0	0.3	0.3	47.9			502.7	3.5	21.9
1987	0.0	1.0	1.0	36.8	22.4	323.2	345.6	6.2	25.0
1989	0.0	3.1	3.1	35.3	20.3	306.9	327.2	5.3	30.0
1992	7.4	3.2	10.6	31.9	20.3	240.2	260.5	5.4	35.0
1995	3.1	1.6	4.7	28.5	21.8	217.2	239.0	2.5	38.0
1996	5.0	1.6	6.6	25.7	21.8	195.6	217.4	3.0	39.0
1998	23.9	7.6	31.5	24.6	27.0	168.4	195.4	6.0	42.0
2001	0.4	2.7	3.1	23.1	17.9	131.2	149.1	2.5	58.6
2002	6.7	6.4	13.1	37.1	18.4	110.8	129.2	4.0	82.0
2003	11.4	9.2	20.6	36.7	19.8	97.2	117.0	5.4	86.0
2004	5.9	9.9	15.8	24.8	22.4	93.5	115.9	3.0	91.0
2005	3.0	4.4	7.4	14.0	22.5	89.8	112.3	3.5	98.0
2006	1.5	3.5	5.0	11.8	24.0	81.3	105.3	2.8	109.0
2007	2.5	4.5	7.0	11.9	23.2	81.1	104.3	3.0	112.0
2008	2.0	4.1	6.1	10.1	23.0	80.1	103.1	2.5	117.0
2009	2.1	3.1	5.2	8.3	22.8	79.2	102.0	3.2	120.0
2010	2.0	2.5	4.5	11.4	22.6	75.5	98.1	3.0	130.0

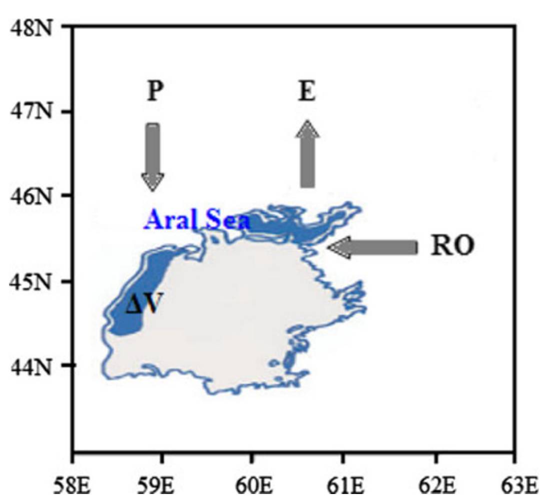

Fig. 3 Illustration of water balance changes in the Aral Sea with decreasing volume

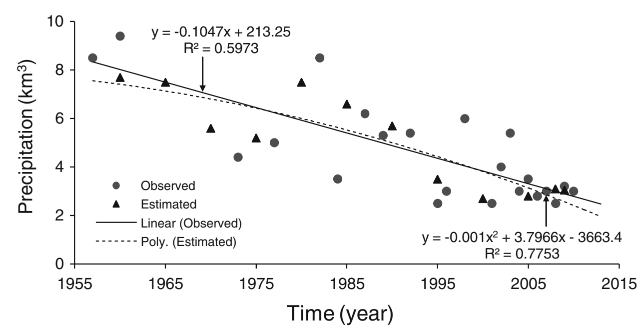

Fig. 4 Observed and estimated variations of precipitation in the Aral Sea

(Aralgenefund 2011). The precipitation was 3.5 km^3, water volume was 502.7 km^3, and river runoff into the Aral Sea was 0.3 km^3 in 1884 (Aralgenefund 2011), as a consequence, the Aral Sea separated two parts. Precipitation linearly decreased ($R^2 = 0.5973$) from 9.4 km^3 in 1960 to 2.1 km^3 in 2010. Estimated precipitation was 7.7 km^3 in 1960, which is less than the result for 1960 in Fig. 4, and it was 3.5 km^3 in 1995, which was higher than the result for 1995 from Fig. 4, and it has been polynomially reduced ($R^2 = 0.7753$) to 3.05 km^3 in 2009.

River runoff

Observed river runoff into the Aral Sea was 42 km^3 in 1960 as shown in Fig. 5. Water flow polynomially decreased ($R^2 = 0.2665$) from 0.2 km^3 in 1977 to 0.3 km^3 in 1984, comparing the estimated data, which was two times less than the observed result from Fig. 5. Estimated river runoff similarly reduced polynomially ($R^2 = 0.5915$) to 4.8 km^3 in 2009. After separation of the Aral Sea, water from Amu Darya and Syr Darya rivers flowed into the Aral Sea was increased between 1998 and 2004. However, river inflow was decreased to 4.5 km^3 in 2010.

Evaporation

The observed evaporation value was 71.1 km^3 in 1960, and fell exponentially ($R^2 = 0.7411$) to 11.4 km^3 in 2010 (Fig. 6). Estimated evaporation was 66.6 km^3 in 1960, which is less than the observed result for 1960 in Fig. 6. Estimated evaporation was 9.7 km^3 in 2008, which was less than the observed result for 2008 from Fig. 6. It has been decreased exponentially ($R^2 = 0.9214$) to 10.5 km^3 in 2009. The Aral Sea evaporation reduction was caused by water volume and water surface area alteration.

Salinity

The Aral Sea water salinity was 10 g/L in 1960 (Aralgenefund 2011) and it is polynomially increased ($R^2 = 0.9692$) to 130 g/L in 2010 (Alikhanov 2010). The water volume, water surface area and river runoff changes, and evaporation can produce corresponding salinity indicators that are consistent with resulting data in Fig. 7. Our estimation of the Aral Sea water salinity was polynomially increased from 10.6 g/L in 1960 ($R^2 = 0.9601$) to 122.5 g/L in 2009, which is higher than the result for 2009 in Fig. 7. Briefly, the increased water salinity is dependent upon precipitation, river runoff and evaporation.

Water volume

Reduction of water volume from 1960 to 2010 is given in Fig. 8. The water volume of the Aral Sea was 1,093 km^3 in 1960, exponentially decreased ($R^2 = 0.982$) to 102 km^3 in 2009. Further predicted values of water volume with the regression equations (Figs. 4, 5, 6, 7, 8) were used to estimate corresponding magnitudes of precipitation, runoff, and evaporation from 2011 to 2031. These magnitudes were also used to estimate the water volume based on Eq. (1). Figure 8 shows that the water volume will decrease to approximately 75.4 km^3 by 2031. The C_{eff} value of water volume was 0.7647 (Fig. 8). According to our prediction, the water quality and volume will continue aggravated in the next decade. Suggested solutions for these problems in the past years are mainly improving the quality of irrigation canals, charging farmers to use the water from the rivers, redirecting water from the Volga, Ob and Irtysh rivers, and pump and dilute water from the Caspian Sea via pipelines. Implementing these projects needs sufficient budget and

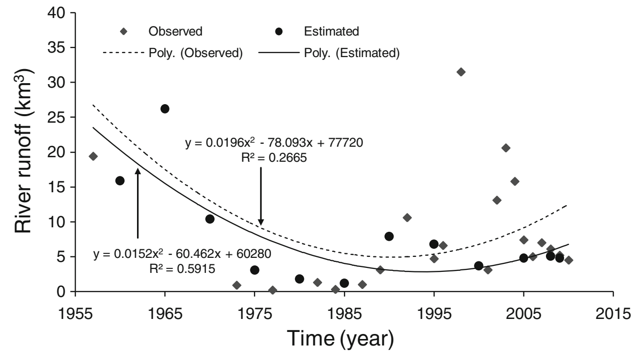

Fig. 5 Observed and estimated variations of runoff into the Aral Sea

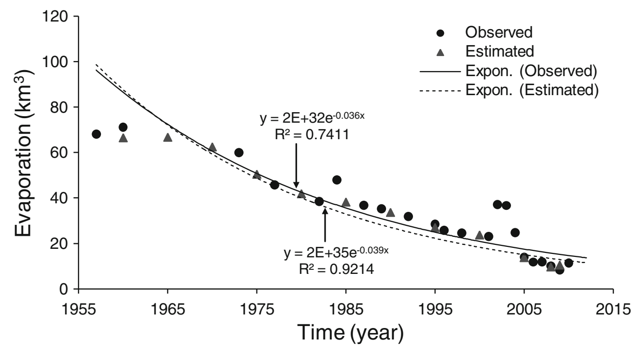

Fig. 6 Observed and estimated variations of evaporation in the Aral Sea

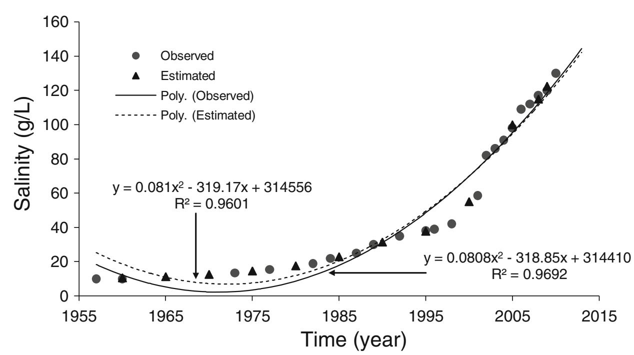

Fig. 7 Observed and estimated variations of salinity in the Aral Sea

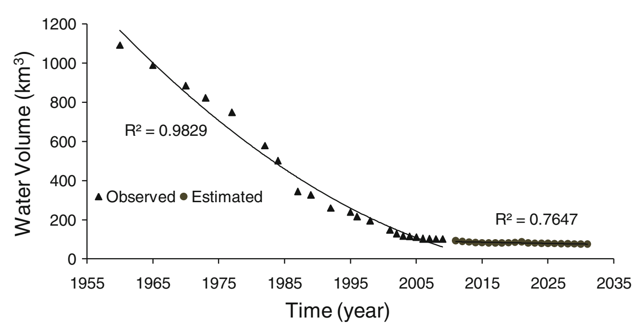

Fig. 8 Estimated versus observed values of water volume in the Aral Sea

investments. UNESCO in its forecast for 2025 anticipates that the basin will need to save 23 km^3 of water annually for the surface area of the Aral Sea to stabilize at its current level (UNESCO 2000).

Conclusions

The Aral Sea is a saline lake, located in the middle of Central Asia. This brackish water body was the world's fourth largest lake before it started to shrink in the 1960's due to water withdrawal for land irrigation. Consequently, the Aral Sea divided into two parts: Large Aral Sea and Small Aral Sea in 1987. Observed water salinity increased from 10 g/L in 1960 to 120 g/L in 2009 ($R^2 = 0.9692$) and our estimated water salinity was 10.6 g/L in 1960 to 122.5 g/L in 2009 ($R^2 = 0.9601$). Observed evaporation decreased from 71.1 km^3 in 1960 ($R^2 = 0.7411$) to 8.3 km^3 in 2009. Our estimated value was 66.6 km^3 in 1960, which is less than the observed value, and it was 10.5 km^3 in 2009, which was higher ($R^2 = 0.9214$). Since 1960, during this period, the water surface area was reduced by 3 times, and water volume was reduced almost 14 times. We have obtained regression parameters using observed data for the estimation of corresponding magnitudes of precipitation, runoff, and evaporation from 2011 to 2031. Our prediction suggests that water volume of the Aral Sea will decrease approximately to 75.4 km^3 in 2031.

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