

Article

Hydrological Model for Sustainable Development in the Aral Sea Region

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Abstract: Possible scenarios of the Aral Sea crisis solution are discussed, and a new scenario is proposed. Previous scenarios have provided for the transfer of water from Siberian Rivers to Central Asia and the restriction of unsustainable expansion of irrigation in this region. The scenario proposed in this paper is partly based on the use of Caspian water evaporators located on the eastern coast of the Caspian Sea. Engineering realization of this scenario needs only the construction of the drainage system for the runoff of Caspian waters to the natural evaporators, between which Kara-Bogaz-Gol is the functioning evaporator. This paper shows that realization of this scenario allows the rescue of the Aral Sea and normalization of the water balance in Central Asia. Under this, as the simulation modeling results show, there exist different versions of the scenario depending on the area of evaporators and restrictions for the runoff of Amu Darya and Syr Darya waters to the irrigation systems. Calculation results show that the Aral Sea could be restored within 90–240 years depending on the scenario versions. With only Kara-Bogaz-Gol as the evaporator, the Aral Sea cannot be restored within a century. Additionally, if the anthropogenic runoff of river waters was decreased by 10 percent, the Aral Sea would be restored over about 90 years. Possible versions of the recovery scenario are discussed and assessed.

Keywords: Aral Sea; evaporator; irrigation; scenario; water cycle; hydrological sustainability

1. Introduction

The water balance of Central Asia is widely discussed by many authors and is studied in different institutes, such as the Central Asian Institute for Applied Geosciences, the Faculty of Geography in the Moscow State University, the Department of Geography in the Western Michigan University, etc. [1–12]. The present state of the Aral Sea reflects the catastrophic processes in the Central Asia water balance which are connected with both global climate change and anthropogenic processes, such as the realization of the Kara-Kum Channel Project and damming the water outflow from the Caspian Sea to the Kara-Bogaz-Gol Bay [10,13–17].

The state of the Aral Sea provokes the anxiety of governments of Central Asia and neighboring countries. In actuality, the Aral Sea drying can significantly impact the regional climate, as well as having an influence on the global climate [18,19]. A major problem of confronting countries in Central Asia is the redistribution of water resources and optimization of their usage [20,21]. This problem has arisen because of the diversion of the Amu Darya and Syr Darya rivers for agricultural purposes and energy production. Unfortunately, this action was initially realized without a scientific environmental

impact assessment. Continuation of current policies and practices, with respect to the regional water cycle, is counter-productive to an effective resolution of the existing problems [22,23].

Optimization of using the Syr Darya and Amu Darya waters requires the coordination of strategic solutions by five countries of Central Asia concerning the distribution of restricted water resources [24]. Regional water crises take place as a result of the absence of effective agreements among Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, addressing the coordinated use of the main water source—the Amy Darya River [21]. Over the last century, the Soviet Union has constructed a system of dams and irrigation channels to solve the irrigation problem that was stimulated by the rapidly growing population. The transfer of water from Siberian Rivers to the Aral Sea Basin was discussed as one possible solution of the water crisis in Central Asia [7,8,11,12]. The Soviet Union's disintegration closed the discussion on the resolution of this problem and the Aral Sea water level continues to drop. The water resources of Amy Darya and Syr Darya are formed within the framework of their drainage basin of 534,739 km² and mainly in the high mountains [25]. Data approximations with respect to water consumption associated with population growth in the countries of Central Asia are as follows: Uzbekistan—2596 m³/year/person, Turkmenistan—4044 m³/year/person, Tajikistan—1843 m³/year/person, Kyrgyzstan—1371 m³/year/person, and Kazakhstan—1943 m³/year/person. Approximately 93.4 percent of the Amu Darya River water is used for irrigation [20,26]. Total draw-off from Amu Darya equals 61,500 km³/year. The effectiveness of irrigation systems is about 50 percent [20,21,24].

Many experts proposed different methods for overcoming the Aral Sea water crisis. Spoor [27] discussed the approaches to the efficient water management and sustainable land use in the Former Soviet Central Asia, when decisions were made centrally. In the post-Soviet era, decision making procedures are complicated and the political independence factor of five countries of Central Asia makes water resources allocation possible only through contracts in the framework of collaborative agreements. Micklin [11] analyzed the primary motivations, both climatic and economic, concerning the transfer of the flow of Northern European Rivers southward to Central Asia. Considering different nominally, practically realized projects, Micklin [12] made the conclusion that restoring average river inflow to the Aral Sea at about 56 km³/year needs more than 100 years. Kostianou et al. [28] consider in detail the satellite monitoring possibilities to optimally manage water resources in Turkmenistan, at the zone where Kara-Bogaz-Gol and other important elements of the Aral Sea water cycle are located. It is evident that stabilization of the Central Asia water balance can be realized only by optimal control of existing water resources including the Amu Darya and Syr Darya Rivers. The solution of existing problems is usually realized by means of modeling tools [6,29]. A new method based on the modeling of the water balance of Central Asia and a scenario for its control is proposed in this paper.

2. Method

This paper proposes a new method for the solution of the Aral Sea water crisis and stopping its desiccation process through implementation of an evaporation/precipitation scenario (EPS), foreseeing weighed distribution of existing water resources of Central Asia. This method is based on the use of natural evaporators of Caspian water and rainmaking technology when evaporated moisture is delivered by the wind to the Aral Sea Basin and is artificially precipitated. Rainmaking technology is mainly used in agro-industrial sectors of the agrarian countries with droughty climate [30,31].

2.1. Evaporation/Precipitation Scenario (EPS)

The Aral Sea disappearance is visually demonstrated in Figure 1, where its satellite images are shown for 1960 and 2018. Historical data shows that the Aral Sea had stable levels fluctuating between 50 and 53 m during the last 200 years, prior to 1960 [9,32]. During this period, the Aral Sea surface was 51–61 × 10³ km² and its water balance was supported by Kara-Bogaz-Gol and the Amy Darya and Syr Darya rivers due to precipitation and river outflow [11,33]. Really, 50–60 km³/year is evaporated from the Aral Sea surface, 9–10 km³/year of water arrives with precipitation and 33–64 km³/year is delivered

with river inflow [34]. The hydrological history of some components of the Aral Sea Basin is shown in Table 1 [3,12,32]. A more detailed analysis of historical data shows that the Aral Sea level was changed by 2–3 m relatively, its absolute level of about 59 m above sea level. Hydro-meteorological conditions of Central Asia until 1960 provided enough stability to the Aral Sea level changes. After 1960, population growth in Central Asia republics of Former Soviet Union was the main cause of expansion of irrigation systems and construction of additional water reservoirs. During the next years after 1960, the irrigated area was increased by practically two times, from 4 billion ha to 8 billion ha. All these actions were realized at the expense of the Syr Darya and Amu Darya rivers. The first consequence of reduced river runoff to the Aral Sea was a decrease of its level by about 0.2 m/year from 1961 to 1970. The enormous situation with water use in Central Asia was continued in the 1970s, when only 17 km³/year of river water was reaching the Aral Sea. The 1980s aggravated the situation. In this period, anthropogenic actions such as the construction of a dam between the Caspian Sea and Kara-Bogaz-Gol and the broadening of irrigation systems, gave only about 4 km³/year of average water discharge [35,36].



Figure 1. Aral Sea evolution history. Landsat satellite imagery mosaics showing visible changes of the Aral Sea. Source: USGS/NASA; visualization by UNEP/GRID-Sioux Falls. https://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=108.

Table 1. Hydrological history of the Aral Sea Basin (CAWATER Database of the Aral Sea. www.cawater-info.net>aral>data>index_e [12,17]).

Year	Volume, km ³	Area, km ²	River Runoff to Aral Sea, km ³			Evaporation, km ³	Precipitation, km ³
			Amu Darya	Syr Darya	Total		
1960	1089	67,499	27.6	28.4	56.0	71.1	9.4
1965	1030	63,900	0.6	0.3	0.9	66.1	7.8
1970	927	60,198	0.4	0.2	0.6	54.3	4.3
1975	762	55,900	0	0.2	0.7	57.7	4.9
1980	670	52,400	0	1.2	1.2	38.5	7.1
1985	468	44,398	0	0.3	0.3	47.9	3.5
1990	364	36,400	3.1	3.1	3.1	35.3	5.3
1995	287	33,497	0.4	1.6	4.7	28.5	2.5
2000	183	24,100	3.0	2.7	3.5	23.1	4.2
2005	110	19,000	2.0	4.4	7.4	14.0	3.5
010	81	7143	2.0	2.5	4.5	11.4	3.0
2015	48	6987	1.9	2.3	4.2	9.6	3.2
2018	42	6348	2.1	2.4	4.5	9.7	3.3

Certainly, the Aral Sea water balance depends on the Caspian Sea, the waters of which were earlier evaporated from the Kara-Bogaz-Gol ($\approx 6\text{--}12 \text{ km}^3/\text{year}$) [37]. Anthropogenic impact on the regional water cycle started in 1980, when the blind dam was built between the Caspian Sea and Kara-Bogaz-Gol [38]. Eruption of the dam in 1992 did not stop the Aral Sea shoaling process. Chronology of the Aral Sea Basin events listed by Dukhovny and Sokolov [22] shows the existence of international concern about the competitive water saving program and solutions of the water resource conflict. Different predictions show the water deficit is increasing over the next several decades, due to global climate warming and a consequent decrease of glaciers in the Pamir-Alay system, as a main source of water resources in Central Asia [39].

- Thereby, understanding the Aral Sea evolution is possible through formal description of its hydrologic budget, taking into consideration the main water flows in the Central Asian region. Existing detailed descriptions of the water balance components in the Aral Sea Basin, as it was analyzed by Micklin [9], allow the realistic means for substantially increasing inflow to the Aral Sea Basin;
- Reducing the use of the Amy Darya and Syr Darya Rivers water for irrigation in the drainage basin;
- Elaboration and adoption of economic policies and emerging technologies for improvement and renovation of irrigation systems in all independent republics of Central Asia.

To realize this scenario, it is necessary to have a long-term collaborative agreement among the five countries of Central Asia and it would be preferable if Afghanistan became a party to such an agreement. In actuality, inflow of Syr Darya and Amu Darya water resources to the Aral Sea would only be increased to a negligible extent during the nearest decades. Therefore, additional means are proposed through implementation of the evaporation/precipitation scenario (EPS):

- Create the hydrologic system for the Caspian Sea water evaporation, through additional utilization of the Kara-Bogaz-Gol and natural evaporators-hollows located on the eastern coast of the Caspian Sea;
- Develop the simulation model of the Central Asia water cycle for the dynamic control of water flows and management of the evaporation processes;
- Use the rainmaking technology (i.e., cloud seeding with, for example, silver iodide) for the increase of precipitation above the Aral Sea.

Additional evaporators of the Caspian water could be deployed in numerous hollows such as, Kultuk (−27 m), Karagie (−132 m), Karyn-Zharyk (−75 m), Kaundy (−57 m), Kaidak (−31 m), Chagala Sor (−30 m), and Karin Arik (−70 m). These and other hollows on the eastern Caspian Sea coast are episodically flooded by rain waters, after the drying of which, salt marshes are formed. Artificially infilling these hollows with Caspian water could additionally result in approximately $90 \text{ km}^3/\text{year}$ of evaporated water, that can partly arrive at the Aral Sea zone. Under this, the Kara-Bogaz-Gol, as a natural evaporator, having an area of about $18,000 \text{ km}^2$, provides no less than $18.8 \text{ km}^3/\text{year}$ of evaporated water, when $21.6 \pm 3.1 \text{ km}^3/\text{year}$ is delivered to the Kara-Bogaz-Gol from the Caspian Sea. There exist other ideas as to how collected drainage waters could be delivered to the Aral Sea [17]. For example, water drainage waters can be collected in the Altyn Asyr Lake and can be forwarded to the Karashor Depression, located near the Sarykamysh Lake.

The Principal scheme of the EPS is represented in Figure 2, where numerous water flow studies were detailed and evaluated [3,7–9,11,12,33,40]. For example, basic flows, E_1 and E_6 , are assessed as $370.1 \pm 19.3 \text{ km}^3/\text{year}$ and $69.4 \pm 13.7 \text{ km}^3/\text{year}$, respectively.

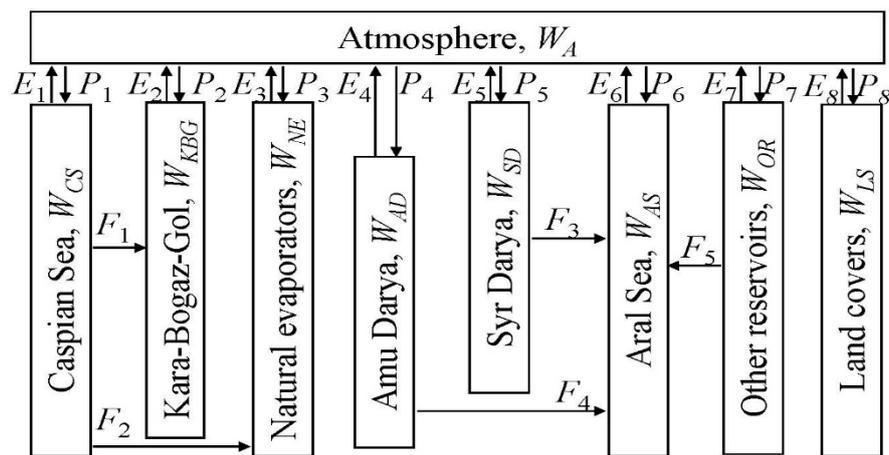


Figure 2. Principal block-scheme of main water cycle components in the Aral Sea zone.

Schematic representation of the water cycle of the Aral Sea zone can help to understand anomalous processes in this zone and to develop a sustainable strategy for this cycle control, taking into account earlier existing variations of the Caspian Sea level. Multiple satellite altimeter measurements deliver data pertinent to both the short term and decadal sea level variations, which would enable operative control of the EPS utilization and the fixation of the sea level trend.

Analysis of remote sensing data and of the peer-reviewed literature shows that the precipitation/evaporation relationship for the atmosphere/land cover system has a minor role in the water cycle of the Aral Sea Basin. Typical land cover includes grasslands, crops and deserts [41,42]. Detailed classification of the land covers was realized within remote sensing measurements, specifically with the flying radiometric laboratory IL-18(Iliushin-18) of the Kotelnikov Institute of Radioengineering and Electronics of the Russian Academy of Sciences [2,5,43]. The measurements were obtained with microwave radiometry at wavelengths $\mu = 0.8, 1.35, 2.25, 3.4, 10, 18, 20, 21, 27$ and 30 cm [4]. Really, about $864,000$ km² of the Central Asia territory is sandy deserts. The total area covered with deserts of all types is $1,474,000$ km² (41.8%). Deserts of Central Asia have their maximum in precipitation during the winter months, when evaporation is minimal. Saxaul forests cover $60,000$ km² in Kazakhstan, $40,000$ km² in Turkmenistan and $20,000$ km² in Uzbekistan. Approximately 70% (2.8×10^6 km²) of the total land area is classified as agricultural sector, including 2.5×10^6 km² of rangelands and 0.3×10^6 km² of croplands. In common cases, relative air humidity is significantly differed above the land covers ($\approx 3\%–6\%$) and water reservoirs ($\approx 42\%–54\%$) [44].

The water losses from irrigation systems mainly divert to the ground waters or other reservoirs [23]. The largest consumers of Amu Darya and Syr Darya waters are Uzbekistan and Turkmenistan. Distribution of the country quotes for the water runoff of the Amu Darya and Syr Darya is as follows: Kazakhstan (0%, 38.1%), Kyrgystan (0.4%, 1.0%), Tajikistan (13.6%, 9.2%), Turkmenistan 43%, 0% and Uzbekistan (43%, 51.7%). Non-optimal water utilization technologies, particularly in agriculture, have resulted in water losses that contribute to flooding and to the formation of new lakes. Remote sensing technologies enable operative control of these processes for their registration during long-term deployment of the EPS.

2.2. Evaporation/Precipitation Model (EPM)

The Aral Sea is functioning in the desert-continental climate under wide-ranging diurnal air temperatures, hot summers, cold winters, and sparse rainfall. Very small water sources exist for the revival of the sea. Really, the Amur Darya and Syr Darya, which earlier feed the Aral Sea, and precipitation are the primary water sources that could potentially revive the Aral Sea to its 1960 level [10]. The scheme in Figure 2 allows the balance equations for the main water cycle of Central Asia, so as to understand the extent of the devastation, to achieve partial rehabilitation of the Aral

Sea, to advance towards regional hydrological sustainability and to maintain water security for the populations of the Central Asian countries. Negative changes in water volume of the Aral Sea can be neutralized in the framework of optimal management of the existing water resources. Before 1960, river runoff played an important role in the variations of the Aral Sea water volume. In this case, precipitation in the sea zone has no determinative importance. Taking anthropogenic factors into consideration, the role of precipitation is to be revised by means of the analysis of the main water balance equations that are basic for the evaporation/precipitation model (EPM):

$$\frac{\partial W_A(t, \varphi, \lambda)}{\partial t} + V_\varphi \frac{\partial W_A(t, \varphi, \lambda)}{\partial \varphi} + V_\lambda \frac{\partial W_A(t, \varphi, \lambda)}{\partial \lambda} = r_C(E_1 - P_1) + \sum_{i=2}^8 (E_i - P_i) \quad (1)$$

$$\frac{\partial W_{AS}(t)}{\partial t} = F_3 + F_4 + F_5 + P_6 - E_6 \quad (2)$$

where, r_C is the correction coefficient (≈ 0.065) reflecting the role of the Caspian Sea in the water balance of the Aral Sea, φ and λ are geographical coordinates $(\varphi, \lambda) \in \Xi = (40^\circ, 47^\circ) \cup (52^\circ, 63^\circ)$, and $V = (V_\varphi, V_\lambda)$ is the wind speed (km/day). Coefficient r_C is calculated based on the minimal difference of modeling results from observed Aral Sea volumes.

Balance equations for other water reservoirs have an analogous view, as in Equation (2). A computer realization of these equations is based on the division of the study area Ξ into discrete spatial elements (pixels) Ξ_{ij} with area $\sigma = \Delta\varphi \times \Delta\lambda$ (km²). The water flows in Figure 2 are described by the analytical, table and graphical functions [4,16,43,45,46]. A reconstruction of the sea surface area σ_{AS} is realized by means of empirical equation:

$$\sigma_{AS} = q_1 W_{AS} - q_2 W_{AS}^2 \quad (\text{km}^2) \quad (3)$$

where, W_{AS} is the sea volume (km³), $q_1 = 137.84$ (km) and $q_2 = 0.0719$ (km^{-1/2}).

The rainfall, P_6 , depends on the water flow, $r_C E_1 + E_2 + E_3$, that is a function of temperature and is stochastically changed during the year under the effects of the wind direction. Wind regime of the Aral Sea region is characterized by the recurrence of the north-east directions ($\approx 30\%$). Integrally, the isobars are oriented from the north-east to the south-west during summer and from the north-west to the north-east during winter. A wind rise of the Aral Sea is formed depending on the climatic factors of Central Asia, where sand deserts play the main role. The Average wind speed was 4–6 m/s in the Caspian coastal zone with variations about 2 m/s, and it can reach 34–36 m/s in pre-mountain plains [47–49]. Figure 3 shows average wind raises for the Aral Sea region. Finally, Gaybullaev et al. [3] showed that precipitations, P_6 , in the Aral Sea zone during the last decades slowly and certainly fall with the following law:

$$P_6 = 213.25 - 0.1047t \quad (4)$$

where, t is the current year between 1956 and 2015. After 2015, precipitations are varied in the range of 2.2–2.4 km³/year.

As it was observed, values of the evaporation, E_2 , from Kara-Bogaz-Gol and precipitation, P_6 , on Aral Sea area are subjected to the following dependency:

$$P_6 = 0.000972E_2^2 - 0.464E_2 + 56.981 \quad (5)$$

Dependencies (4) and (5) show that precipitations above the Aral Sea are falling and are occurring minimally during summer when evaporation from the Caspian Sea and Kara-Bogaz-Gol is maximal. This fact verifies the EPS algorithm for the increase of precipitations in the Aral Sea Basin involving

additional evaporators of Caspian water and rainmaking technology. Dynamics of the Aral Sea water volume are described by the following equation:

$$W_{AS}(t + \Delta t) = W_{AS}(t) + [P_6(t) + F_3(t) + F_4 + F_5(t) - E_6(t)]\Delta t \quad (6)$$

3. Results and Discussion

Drastic changes of the water cycle in Central Asia after known anthropogenic actions seem impassable under existing economical and political systems taking place in five independent republics. Further, the Aral Sea ecosystem degradation will result in further deterioration of the human population's living conditions. Realization of the EPS necessitates their cooperation, including that of Iran. The EPM allows the evaluation of the EPS realization to partially restore the sea's hydrology along with its area stability. It is supposed that current and future climatic trends in the Aral Sea region conform to global climate change [18]. Wind fields in this region are represented in Figure 3 [1,47,50].

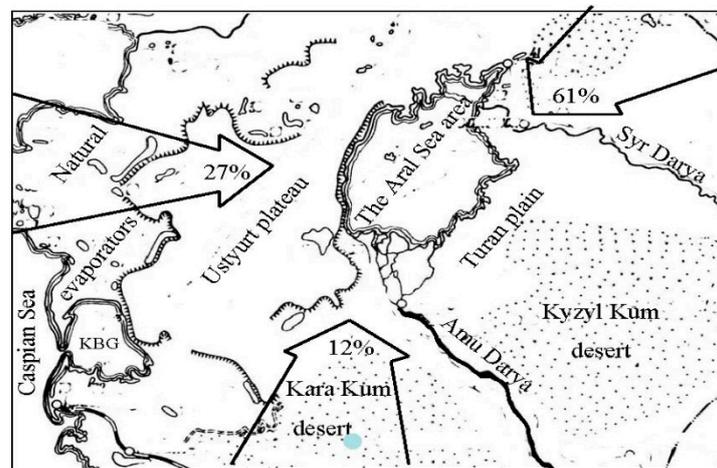


Figure 3. Prevailing wind directions in the Aral Sea zone and their recurrence [47,51].

Simulation experiments are realized for spatial resolution $\Delta\phi = \Delta\lambda = 1/6^\circ$ and temporal scale $\Delta t = 1$ day. Equations (1) and (2) are digitized according to these parameters. Boundary conditions for balance equations are evaluated on the base of existing meteorological and satellite data of Central Asia [28,38,49,52]. The starting time for the EPS realization is $t_0 = 2020$ when, $W_{CS} = 78,200,000 \text{ km}^3$, $W_{KBG} = 15 \text{ km}^3$, $W_{NE} = 75 \text{ km}^3$, $W_{SD} = 38 \text{ km}^3$, $W_{AD} = 79 \text{ km}^3$, $W_{AS} = 42.6 \text{ km}^3$, $W_{OR} = 150 \text{ km}^3$, and $W_{LS} = 0.00011 \text{ km}^3$.

It is accepted that evaporation/precipitation relations for principal water sources to the atmosphere humidity are fluctuated no more than 5% during the next decades and have average assessments, as represented in Table 2. As it was shown by in-situ and remote sensing measurements, the land cover elements play a slight role in comparison with reservoirs in the water balance of Central Asia [4,53,54]. Land surface plays a certain role in the heavily populated areas where agricultural vegetation is prevailing. Total database of land covers in Central Asia was synthesized in a framework of remote sensing measurements by means of flying laboratory IL-18 of the Former Soviet Union [5,55]. This laboratory was equipped by the radio-locators with synthetic aperture, microwave radiometers of different wavelengths, gravimetric and inertial devices, large-format and frame TV, aero-camera and other complementary devices. The land covers and reservoirs are classified with spatial resolution of 200–500 m, depending on the region.

Table 2. Principal elements of the Aral Sea water balance. Notation: $\sigma_{CS} = 371,000 \text{ km}^2$, $\sigma_{KBG} = 18,000 \text{ km}^2$, $\sigma_{OR} = 21,400 \text{ km}^2$, $\sigma_{NE} = 70,000 \text{ km}^2$.

Month	Evaporation, mm/month				Precipitation, mm/month			
	E_1/σ_{CS}	E_2/σ_{KBG}	E_6/σ_{NE}	E_7/σ_{OR}	P_1/σ_{CS}	P_2/σ_{KBG}	P_6/σ_{NE}	P_7/σ_{OR}
I	59	81	83	56	122	15	14	12
II	58	88	91	61	97	13	12	10
III	61	99	103	72	60	8	8	6
IV	64	112	118	88	66	9	9	7
V	67	139	142	103	71	10	9	9
VI	89	204	211	126	102	13	11	10
VII	106	206	212	134	116	15	13	12
VIII	103	211	210	127	129	17	16	13
IX	68	141	144	105	158	21	19	16
X	60	129	133	93	269	35	34	17
XI	58	103	105	71	175	23	23	15
XII	52	91	94	57	124	16	15	13

Practically, water evaporated from agricultural irrigable areas does not arrive at the Aral Sea zone because of the wind rise. Therefore, simulation experiments show that atmosphere/land surface water balance outside irrigable areas is practically neutral.

The following EPS versions are considered:

- EPS-1: Only Kara-Bogaz Gol is used as a natural evaporator.
- EPS-2: Kara-Bogaz Gol and other natural evaporators are used.
- EPS-3: In addition to EPS-2, the river water diversion is decreased by 5% and rainmaking technology is used.
- EPS-4: In addition to EPS-2, the river water diversion is decreased by 10% and rainmaking technology is used.

The precision of simulation results is mainly defined by the climate scenario. Existing scenarios of global climate change propose a wide range of average global temperature change. This problem and its connected discussions are not considered here. Following from Krapivin et al. [5], the next climate change in the Central Asia scenario is accepted. Three climatic zones are marked out: mid-latitude desert, steppe and humid continental. During the last years from 1960, climate change in these zones has increased average annual temperatures in the range from 0.1 °C to 1.1 °C. It is supposed that this trend in change of the average annual temperature is preserved until 2150.

Finally, simulation results are given in Tables 3 and 4, which show hydrological elements of the Aral Sea Basin in their dynamics after the EPS-4 realization. These results demonstrate the existence of an effective strategy for the management of the Central Asia water resources using the EPM manipulations and tools for the big data processing [56].

Certainly, use of the EPS-4 has numerous restrictions and uncertainties. Nevertheless, 10 percent of river flow return is really realized taking into consideration that water losses in irrigation systems of Central Asia are about 50 percent. A quota of 10 percent equals $4.5 \pm 0.2 \text{ km}^3/\text{year}$. Water losses from irrigation systems lead to waterlogging and an increase of the level of ground waters. During the last two decades, the level of ground waters was increased from 3 m to 1.2–1.5 m in many regions of Central Asia [12,35].

Table 3. Recovery chronology of the Aral Sea volume when the Evaporation/Precipitation Scenarios (EPS's) are realized.

Years after Beginning the EPS Realization	Aral Sea Volume, km ³			
	EPS-1	EPS-2	EPS-3	EPS-4
0	42.6	42.6	42.6	42.6
15	78.3	117.8	171.2	209.1
30	82.4	208.9	339.3	430.9
60	131.8	377.8	664.1	1015.4
70	157.6	443.5	755.3	1041.1
80	169.9	457.6	846.2	1054.3
90	183.4	521.6	859.5	1068.8
100	209.7	651.4	976.3	1069.2
120	235.7	780.9	1041.7	1077.4
150	287.8	784.6	1042.8	1079.8

Table 4. The Aral Sea recovery dynamics depending on the area of natural evaporators. Notation: (1) EPS-2 is used and rainmaking with 90% efficiency, (2) EPS-3 is used with the rainmaking efficiency 90%, (3) EPS-4 is used with rainmaking efficiency 60%, (4) EPS-4 is used with rainmaking efficiency 90%.

Area of Evaporators, km ²	Years of the Aral Sea Recovery			
	(1)	(2)	(3)	(4)
20,000	318	243	205	169
30,000	273	210	162	148
40,000	242	173	144	125
50,000	222	147	123	117
60,000	207	128	118	104
70,000	194	119	109	97
80,000	183	113	104	95
90,000	181	102	96	92

Existing separate data shows that the Aral Sea area had been reduced to 78% of its 1960 size and water volume had decreased by about 90%. The most dangerous situation is formed in Central Asia, due to the increased salinity, by more than 12 times the salinity of sea water, which negatively impacts the fishery industry. The salinity of the Aral Sea increased from 10 g/L to 135g/L, depending on separated basins of the Aral Sea [11]. The Aral Sea prior to its modern desiccation had an average salinity around 10 g/L. As a result, the Aral Sea degradation leads to socio-economic and public health problems, taking into account increased sand-storms and desertification [36]. Present-day processes of free salts migration cause negative consequences for agriculture within the Central Asian countries. Remote sensing tools, such as the IL-18 laboratory, can provide regular monitoring of land covers with the assessments of their characteristics and delivering reliable information for decision making offices.

Realization of the EPS-4 gives perspective to partly restore the Aral Sea within this century. Detailed analysis of simulation experiments allows the assessment of different components of the Central Asia water cycle and the understanding of the role of each country in water cycle stabilization. As it follows from Tables 3 and 4, the Aral Sea recovery can be realized under conditions which are to be acceptable for all countries of Central Asia.

The recovery scenario proposed and partly analyzed in this paper opens the perspective to identify a solution to the Aral Sea problem and to overcome the existing contradictions between the

governments of Central Asia concerning optimal and equitable management of water resources. Many experts propose different views on this problem—from optimistic to pessimistic [1,3,35]. An optimistic project is realized in Kazakhstan by means of Amu Darya riverbed management [9].

In actuality, existing runoff of Amu Darya and Syr Darya to the Aral Sea is assessed by $\approx 11\text{--}13\text{ km}^3/\text{year}$ when $43\text{--}47\text{ km}^3$ of river waters are taken away for irrigation (92%), industry (4.3%) and population use (4.4%). The EPS-4 provides for the increase of up to $20\text{ km}^3/\text{year}$ of river runoff to the Aral Sea, together with additional evaporation of the Caspian water and deployment of rainmaking technology, such as cloud seeding with, for example, silver iodide, potassium iodide, frozen carbon dioxide, or liquid propane. In this case, precipitation in the Aral Sea Basin can potentially increase to $\approx 1500\text{--}2000\text{ mm/year}$, depending on the climatic situation under evaporation of $\approx 900\text{--}1000\text{ mm/year}$. The result of the EPS-4 utilization is a function of many uncertain environmental conditions, such as climate change, strategies of the independent republics in the water use, population growth and the river runoffs to the Caspian Sea.

The Aral Sea crisis is to be solved at the expense of a complex approach to the sustainable development of the Central Asian region, taking into consideration an array of scientific, social and ecological aspects. It is evident that the following actions are to be initiated:

- Reconstruction of existing old irrigation systems;
- Development and introduction of effective irrigation technologies such as drip irrigation;
- Reconstruction of municipal water supply systems, and
- Optimization of the drainage runoffs.

Preliminary analysis of the Central Asia water cycle shows that there exist reserves for the improvement of the ecological situation and for ultimate initiation of the Aral Sea recovery process. Existing reservoirs such as Sarykamysh Lake ($\approx 5000\text{ km}^2$), geographically located between the Caspian Sea and the Aral Sea, can be water sources for the Aral Sea. Lake Balkhash ($16,400\text{ km}^2$) can also be considered as an important element of the Aral Sea water balance. Certainly, realization of these actions requires the adequate capital investments and scientific efforts to optimize this process. Principally, global ecoinformatics proposes tools for the solution of such environmental tasks [5,16,57–59]. Realization of the EPS-4 is possible in the framework of the UN Program, when it is possible to focus scientific efforts on the synthesis of global water cycle models, in the framework of which EPM can be used as a sub-block. In this case, the optimal strategy for Central Asia water balance can be defined and realistic monitoring procedures can be identified. Only in this case, social and economic stresses existing in practically all countries of Central Asia will find a solution and human vulnerability will be reduced. Undoubtedly, reliability of these results depends on regional climate change scenarios [18]. Therefore, it will be created in such a manner that information-modeling technology would combine operative monitoring data with the water balance model and with assumptions of timely decision making, to correct regional changes in the agricultural and social strategies.

Certainly, the reliability level of modeling results is an important aspect of the results shown in Tables 3 and 4. Table 5 gives some characteristics for the EPM precision level. Average deviation of the EPM results from the observed volume of the Aral Sea equals 8.3%. The EPM precision can be considered as consistent with the reliable description of the Aral Sea hydrological regime. As it follows from Table 5, the EPM can be considered as a tool for primary assessment of different scenarios for the Aral Sea water balance management. It is evident that practical EPM use needs additional development.

Table 5. Comparison of observed and calculated Aral Sea levels [3,35,60]. EPM = Evaporation/Precipitation Model.

Year	Aral Sea Volume, km ³		EPM Error, %	Historical Data Used in EPM	
	River Runoff to Aral Sea, km ³ /year	Caspian Water Flow to Kara-Bogaz-Gol, km ³ /year		Observed	Calculated
1957	1080.0	1080.0	0	19.4	21.8
1960	1089.0	1067.9	2	42.0	24.2
1965	1030.1	999.2	3	0.3	20.3
1970	927.3	1010.4	9	0.2	15.2
1973	824.2	947.6	15	0.9	10.6
1975	762.4	846.3	11	0.2	12.2
1977	749.2	839.1	12	0.2	7.1
1980	670.4	603.4	10	1.2	1.2
1982	579.8	533.4	8	1.3	0
1984	502.7	457.5	9	0.3	2.4
1985	468.3	505.8	8	0.3	4.9
1987	345.6	383.6	11	1.0	6.8
1989	327.2	363.2	11	3.1	9.6
1990	304.1	337.6	9	3.1	13.0
1992	290.5	255.6	12	10.6	16.4
1995	239.0	262.9	10	4.7	22.5
1996	217.4	236.9	9	6.6	25.2
1998	182.9	195.7	7	31.5	28.9
2000	195.4	218.8	12	9.7	17.7
2001	149.1	193.8	13	3.1	16.4
2002	129.2	118.9	8	13.1	12.5
2003	117.0	125.2	7	20.6	15.4
2004	110.9	118.7	7	15.8	24.3
2005	112.3	105.6	6	7.4	25.2
2006	105.3	96.9	8	5.0	20.6
2007	104.3	114.6	7	7.0	23.7
2008	103.1	93.8	9	6.1	22.9
2009	102.0	109.1	7	5.2	21.6
2010	98.1	105.9	8	4.5	20.8
2015	48.3	52.6	6	2.3	19.3
2018	42.2	46.0	9	2.4	22.1

The results of Table 3 show that separated water bodies of the Aral Sea, existing at the present time, will be merged after 35–40 years of EPS-4 realization. It shows that a principal solution of the Aral Sea problem exists, and its volume of the 1960's can be reached during visible time. Versions of the Evaporation/Precipitation Scenario, considered here, will help to form the recovery strategy [6,12].

Overcoming the Aral Sea crisis needs preliminary solutions of socio-economic problems existing in Central Asia, which at the present time is a barrier for the constructive consideration of alternative plans. Many publications propose different methods to search for the solution to the Central Asia water problem, including scenarios and models [5,6,16,42,51]. It is evident that the Aral Sea does not exist in isolation from the Caspian and Black Seas, and the Don and Volga Rivers. Therefore, these

water resources are to be taken into consideration under the improvement of the method considered in this paper.

4. Conclusions

Water resources play a key role in the economies of the five Central Asian countries. The Central Asia Climate Change Conference in partnership with the World Bank (24–25 January 2018, Almaty, Kazakhstan) again poses the question, “what is the extent of the water crisis in Central Asia and what are the possible solutions for the communities living in those areas?” The answer to which is possible with the attraction and development of new information-modeling technologies [5,40]. This paper proposes one of the possible approaches to this purpose.

The mathematical model of Equations (1)–(6) takes into account the different elements of the Central Asia water cycle, including glaciers, rivers and Caspian Sea water flow to the Kara-Bogaz-Gol. Simulation results represented in this paper provide a platform for the discussion of possible approaches to the solution of Central Asia water problems. It is evident that the Aral Sea crisis is a local problem of Central Asia. The hydrological restoration of the Aral Sea to a previous higher water level can be realized by means of coupled consideration of the Central Asia water cycle model and a global climate model. Undoubtedly, any global climate model needs additional information and, as a rule, needs to introduce elements of information uncertainties and instabilities. Therefore, this study uses a simple climate model by Mintzer [61] that reduces a considerable uncertainty.

The governments of Central Asia have begun to intensively discuss a possible joint program for the revision of existing strategies for the optimization of the restricted water resources. A perfection of the water control technologies can be realized by means of using existing information-modeling tools [5]. Using the Equations (1)–(6) model simulations shows that a principal solution for the Aral Sea problem exists. The model verification is realized by a comparison of historical data about the Aral Sea volume dynamics and modeling results during 1957–2018, which shows that the model error is no more 15 percent (see Table 5), depending on the variations of the historical data. Certainly, this precision can be improved when the EPM is used together with more detailed descriptions of topographic and ecological parameters of the Aral Sea Basin. It can be realized in the framework of the UN initiative on overcoming the water crisis in Central Asia [62].

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