Simulation System for Investigation of the Aral-Caspian Water Regime

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ABSTRACT

Remote measurements of different environmental parameters received during last 30 years are used for the synthesis of a Complex Simulation Model (CSM) describing the combined water regimes of the Aral-Caspian System (ACS) including the consideration of aquatic and climatic natural processes. The problem of stabilizing the sea levels of these two water bodies is modelled and a solution obtained through implementation of a modeling system, including the CSM, remote measurements database, data processing sub-block, surface cover recognition sub-block, and user interface. A set of scenarios to control the ACS water regime is investigated. The role of remote sensing methods for the estimation of water balance components and synoptic situations is also evaluated. The main purpose of the computer experiments is in the search of a scenario for control of the water regime in the ACS under the realization of which the Aral Sea level will increase and the Caspian Sea level will decrease. The results of this research indicate that there is a regime for ACS water control under which it is possible to stabilize the Aral and Caspian Sea levels at their 1960 level within twelve to fifteen years. This would be implemented by the transport of water from the open portion of the Caspian Sea into saline lowlands and the Kara-Bogaz-Gol Gulf, located on its eastern shore, thus facilitating rapid evaporation followed by the movement of atmospheric moisture into the Aral Sea basin. The scenario "evaporation/precipitation" when the Caspian Sea level is lowered by increasing the flow of its waters to other reservoirs/evaporators is evaluated. Such reservoirs are the area of saline lands and depressions situated in the East Caspian Sea coast. Their absolute levels are below the recent Caspian Sea level. The results of this investigation show that the formation of an adaptive measurements system with the interchange of remote measurements and mathematical modeling provides a reliable evaluation of the ACS. This will lead to the creation of a system capable of predicting the dynamics of natural processes and assessing long-term consequences of large-scale global-change effects on the ACS.

KEYWORDS: *environmental modelling, water control, Arial-Caspian system, percipitation cycle*

THE NATURE OF THE PROBLEM

One of the dramatic aspects of anthropogenic activity is its influence on the biosphere water cycle. Presently, this influence occurs on a global level and is composed of a hierarchy of regional changes, especially in the arid districts. The control of the biosphere water systems is one element of climate system monitoring. The Aral-Caspian System (ACS) attracts the intense attention of scientists as an economically and ecologically significant sub-system of the biosphere which has been subject to rapid changes due to human activities. The catastrophic state of this water system is well known [3,10].

In the opinion of many authors the recent anomalous increase in the Caspian Sea level and the decrease of the Aral Sea level have global implications. According to the existing data the Aral Sea level remained fairly stable, fluctuating between 50 and 53 m with inter-year deviations up to 1 m during the last 200 years prior to 1960. At that time the Aral Sea area was $(51-61) \cdot 10^3$ km². About 55 km³yr^{-1} evaporated from the surface, precipitation on the surface was 9-10 km³yr^{-1}, and river inflow was between 33 and 64 km³yr^{-1}. A steady drop in the level of the Aral Sea began in 1961 at a rate of 21 cm•yr^{-1} up to 1970, then increasing to 58 cm•yr^{-1} until 1980 and nearly 80 cm•yr^{-1} after 1980. The Aral Sea level dropped from 53 m in 1960 to 41.4 m in 1985. By 1994 the Aral Sea had fallen by 13 m from its level in 1960.

The stability of the Caspian Sea has also changed dramatically in recent years. In earlier times when anthropogenic interference in the water regime of the Middle Asia region was insignificant, the Caspian Sea level fluctuated not far from -28 m. Its area was 375,000 km² and evaporation from the surface was close to 380 km³yr^{-1}. Detailed measurements of the Caspian sea level exist from 1837 to the present. During this time the changes in the sea level can be characterized by four distinct periods: 1) During the period 1837-1928 the level fluctuated between about -25.5 and -26.5 m. 2) During the years 1929-1941 the level dropped rapidly from -25.96 m to -27.84 m at a rate of about 16 cm•yr^{-1}. 3) During the years 1942-1977 the level dropped at a more moderate rate of 3.3 cm•yr^{-1} to a low mark of -29.04

m. 4) Since 1977 the level has risen at a rate of 16-18 cm•yr^{-1}. By 1995 the Caspian sea level had risen by 3 m to return to its pre-1929 level and the area had increased to 440,000 km2.

The unstable hydrometeorological situation at the present time in the ACS makes urgent the task of finding new methods for stabilizing the system, including the quest for new methods of halting the above catastrophic tendencies and for the synthesis of new modelling algorithms of the ACS which can help bring about a change-over to a controlled stable state. This report proposes an approach for the solution of this task. The proposed structure of the Aral-Caspian system study is based on the Complex Simulation Model (CSM). This model incorporates the use of GIMS technology [4,6]. It has remote monitoring and simulation units which function to alternately switch between measurements and prognosis procedures. Temporal parameters of the switching process are determined by means of empirical procedures [1,9]. For this analysis and study the ACS area Ξ is chosen, limited by the geographical coordinates of [41-47]°N × [50-70]°E. Within Ξ the water regime is described by the CSM. Out of the area Ξ it is described by the Nature-Society System Model (NSSM) [5].

REMOTE MONITORING DATABASE

The ACS territory was studied during the last twenty-five years by means of in-flight laboratories of the Institute of Radio Engineering and Electronics of the Russian Academy of Sciences . The measurements were obtained by microwave radiometry at wavelengths µ= 0.8, 1.35, 2.25, 3.4, 10, 18, 20, 21, 27, and 30 cm. It was shown that these microwave measurements enable the reliable classification of this area for land cover, the indication of ground water level, and the estimation of water content in the atmosphere over the ACS area [1,8]. On the basis of these measurements, carried out in Central Asia, a remote database was formed with a three level structure: 1) position measurements, 2) data processed by means of various algorithms (spectra, statistical characteristics, classification of subjects, correlation models), 3) data maps

obtained using spatial-temporal interpolation methods. All data are organized with the cartographic identification procedure after its processing with specific algorithms (Fig.1 All images precede the references). The database levels were created by data processing algorithms from the results of the radiophysical monitoring. Brightness temperature contrast measurements were performed from aircrafts over regions of Central Asia at cm and dm wavelengths. Essential negative brightness temperature contrasts were observed in flights over moist areas. The measurements obtained at wavelengths of 0.8, 3.4, 10, and 20 cm indicated a clear correlation between soil moisture content and brightness temperatures. Conducting measurements of the same regions over a prolonged time period allowed the observation of brightness temperature variations for different fields indicating an increase and decrease in moisture content.

COMPLEX SIMULATION MODEL OF THE ARAL-CASPIAN AQUAGEOSYSTEM

The basic elements of the ACS water balance are given in Fig.2. The functional representations of the water flows H_i ($i=1,...,38$) are given [4,7]. The water flows having anthropogenic origin are described with simple models: $H_{15} = f_{15}G$; $H_{11} = f_{11}G$, where G is the population density; f_{11} and f_{15} are proportionality coefficients ($f_{11} \approx 0.25$ m³man⁻¹day⁻¹; $f_{15} \approx 0.85$ m³man⁻¹day⁻¹). Flows H_{22} and H_{23} are formed as functions of the soil-plant formation type [4,5,9]. The water flows not included in this scheme are considered negligible. A computer realization of this scheme is based on the division of the study area Ξ into discrete elements Ξ_{ij} with area $\sigma_{ij} = \Delta\varphi_i \cdot \Delta\lambda_j$. The $\Xi_{ij} \sqsubset \Xi$ are characterized by specific soil-plant formation, geophysical structure and socio-economic parameters. Each element Ξ_{ij} has a subset of the water flows $\{H_k\}$ and associated data given by the set of identifiers $\{A_s\}$. The set of A_s exhibits an information database structure and forms the elements of the water balance equations

for the water volumes W_{ij}: where $v=(v_\varphi, v_\lambda)$ is the water velocity; Iij and Jij are identifiers of the evaporation and precipitation flows, respectively, on the area Ξ_{ij}; $E=(K,C,A,\Phi,D,S,B,M,Z,Y,G)$ is the specific water repository (see Fig.2); ω_s and γ_s are binary identifiers reflecting the presence ($\omega_s = 1$, $\gamma_s = 1$) or absence ($\omega_s = 0$, $\gamma_s = 0$) of inflowing and outflowing processes for each element E respectively. For example (from Fig.2), if $E=A$ (Aral Sea), $\omega_s = 1$ only for $s=8,33$ and $\gamma_s = 1$ only when $s=7$. The repository L (water for human use) is a special case that is not associated with an area σ.

To solve equations on the whole territory $\Xi = \cup\Xi_{ij}$ initial and boundary conditions are needed. Initial data either are included in the database or are formed by the user of the CSM in conformity with his scenario. Boundary conditions either are formed by the NSSM or are given by the user. The water flows H_k ($k=1,...,38$) are described by the analytical, table and graphical functions. The evaporation from land and transpiration are described by empirical correlations from [2]. The evaporation from the Aral Sea surface (H_7) and shallow reservoirs (H_4, H_{18}, H_{20}, H_{37}) is calculated using the equation of Kohler [2] adopted to the empirical data: $H_i = 3.27a_0(e_s - e_2)v$ ($i=4,7,18,19,20,37$), where es is the maximal saturation vapor pressure at the temperature of the water surface (mb); e_2 is the vapor pressure in the atmosphere at the height of 2 m (mb); $a_0 = (597.3 - 0.57T)^{-1}/\rho_w$ where T is the atmosphere temperature in degrees Celsius and ρ_w is the water density (g•m⁻³). The evaporation from the Caspian Sea surface (H_5) is described by the Penman equation. The flow H_6 describing the river water influx to the Caspian Sea has a normal distribution with average value 290 km³•yr⁻¹ and standard deviation 30 km³•yr⁻¹. The model does not include all possible inflows and outflows between the water reservoirs shown in Fig.2. Those omitted are considered negligible and are lacking reliable estimations of their volume and spatial distributions.

$$\sigma_{ij}\left(\frac{\partial W_{ij}}{\partial t} + v_\varphi \frac{\partial W_{ij}}{\partial \varphi} + v_\lambda \frac{\partial W_{ij}}{\partial \lambda}\right) = \sum_{s \in I_{ij}} H_s^{ij} - \sum_{s \in J_{ij}} H_s^{ij} \; ; \; \sigma_{ij}\frac{dE_{ij}}{dt} = \sum_{s=1}^{38}(\omega_s - \gamma_s)H_s^{ij} \; ; \frac{dL_{ij}}{dt} = H_{15}^{ij} - H_{16}^{ij} - H_{17}^{ij}$$

The motion of the atmospheric moisture over the territory Ξ is described by the standard system of finite-difference balance equations including only the wind component. The parametrization of H_k and control of the CSM are realized by means of the software described in [7]. For the CSM validation, the ACS dynamics were calculated over a long period of time from 1960 to 1985. The flows H_5, H_6, H_7, H_8, H_{30} and H_{33} were taken from the literature data as table functions with $\Delta t = 1$ year. The other flows H_i were calculated with the models described in [2,4,7]. An adaptive criterion for the CSM was realized in the framework of the simulation procedure shown in Fig.1. This is based on evolutionary modeling procedures that are described in [9].

The Aral Sea aquatory plays an important role in the ACS water regime. That is why one of the CSM subunits describes the hydrological processes of the Aral Sea during the ice-free period of the year. Another subunit simulates the water and salinity cycles of the main evaporator of the Caspian Sea waters, which is the Kara-Bogaz-Gol (KBG) gulf. A unit KBG realizes the scheme represented in Fig.3.

SIMULATION EXPERIMENTS

The main purpose of the computer experiments is in the search of a scenario for control of the water regime in the ACS under the realization of which the Aral Sea level will increase and the Caspian Sea level will decrease. Let $\Delta\varphi = \Delta\lambda = 0.5°$, $\Delta t = 10$ days. We consider the scenario EP (evaporation + precipitation) when the Caspian Sea level is lowered by increasing the flow of its waters to other reservoirs/evaporators. Such reservoirs are the area of saline lands and depressions situated in the East Caspian Sea coast. Their absolute levels are below the recent Caspian Sea level (- 25.7 m). The following depressions correspond to this condition: 'Lifeless Kultuk' (- 27 m), 'Kaidok' (- 31 m), 'Karagie'(- 132 m), 'Kaundy' (- 57 m), 'Karin Arik' (- 70 m), 'Chagala Sor' (-30 m), and 'Kara-Bogaz-Gol Gulf' (-32 m). Let us assume that the Caspian Sea water volume which is diverted to the above evaporators is ς. This water volume is evaporated at a rate which is a function of the wind and temperature. Thus, the water content in the atmosphere is increased. As a result of this the atmospheric moisture over the Aral Sea can also increase. The procedure of forced precipitation over the Aral Sea watershed is realized. The flows H_i (i=6,8,11,15,24) are fixed at their state in the year 1985. The historic data indicate that northwest (NW) , west (W) and southwest (SW) winds prevail over the ACS territory during 130-160 days per year with a high degree of regularity. Hence, the atmospheric waterway in the direction of the Aral Sea zone is realized by a statistically stable system. It is considered that the evaporators are filled from May to September. During the remainder of the year the winds are variable.

The results of the simulation experiments are given in Fig. 4. Here the model makes use of the wind and temperature distributions recorded during 1981-1996 by the Russian Meteorological Agency. The evaporators are filled during the summer months when the atmospheric temperature is no lower than 15°C. After 10-12 years the levels of the Aral and Caspian Seas stabilize within a range comparable to that observed during the years 1950-1960. We can see that the Caspian Sea level decreases by 1.2 cm•yr^{-1} under the following conditions: the value of ς is uniformly distributed in the interval [50,60] km^{3}yr^{-1}, the atmospheric temperature is no lower than 15°C and the NW, W and SW wind directions prevail 50% of the time during $\tau \geq 80$ days. Under these conditions, which occur during the summer months, 0.6-1.3 km^{3}day^{-1} of atmospheric moisture comes to the Aral Sea depression directly from the Caspian Sea aquatory (flow H_5) and 0.1-0.2 km^{3}day^{-1} is added at the expense of the evaporators (flow H_{38}). As a result it is possible to have precipitation of 0.5-1.5 km^{3}day^{-1} in the Aral Sea depression. This allows the Aral Sea level to reach stability within the absolute range of 50-53 m in 7-12 years, as can be seen in Fig. 4. During this time period the Caspian Sea level stabilizes at about 28 m.Moreover the positive balance of water transport across the east boundary of the ACS territory is increased by 4% stimulating growth in the river flow to the Aral Sea by up to 40 km^{3}yr^{-1} ($34 \leq H_8 \leq 50$ km^{3}yr^{-1}). The east wind increases the precipitation in the Aral Sea zone by 4-7% at the expense of the returning atmospheric moisture.

The results of this study suggest the possibility to propose the following scheme for aero-orbital monitoring of the water balance in the Middle Asia arid zone under the influence of the Aral and Caspian Seas. A monitoring system registers the water balance parameters by means of episodical measurements using remote sensing systems and land observations. The CSM is used during the intervals between the measurements as shown in Fig.1. The operator of the monitoring system analyzes the value of the deviation between the measured and predicted ACS parameters and makes a decision about the suitable moment for filling the evaporators, so as to result in the forced precipitation over the Aral Sea zone.
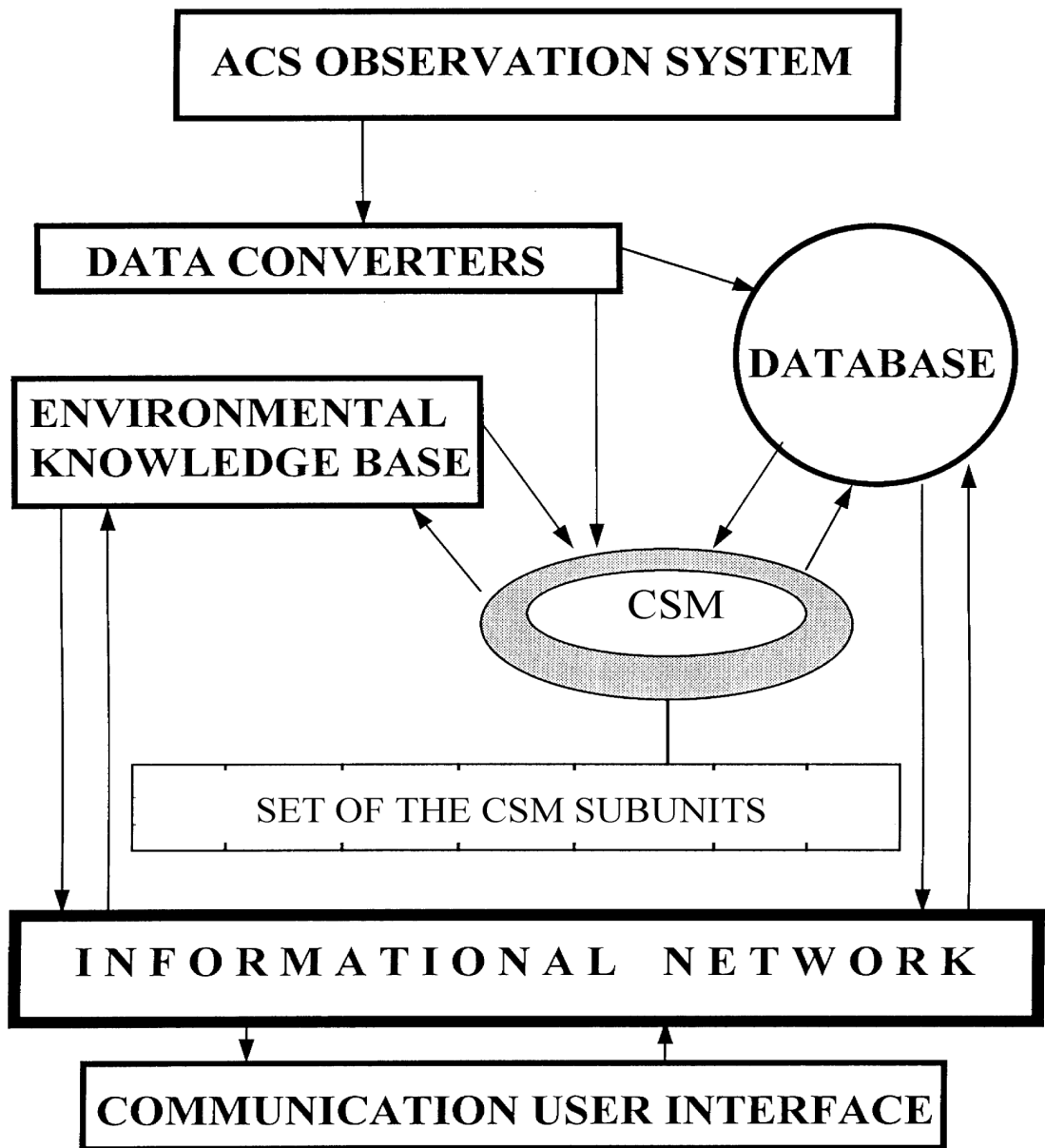
Fig.1. *Structure of the adaptive environmental monitoring system, based on the set of models and implementing the evolutionary computer algorithms.*
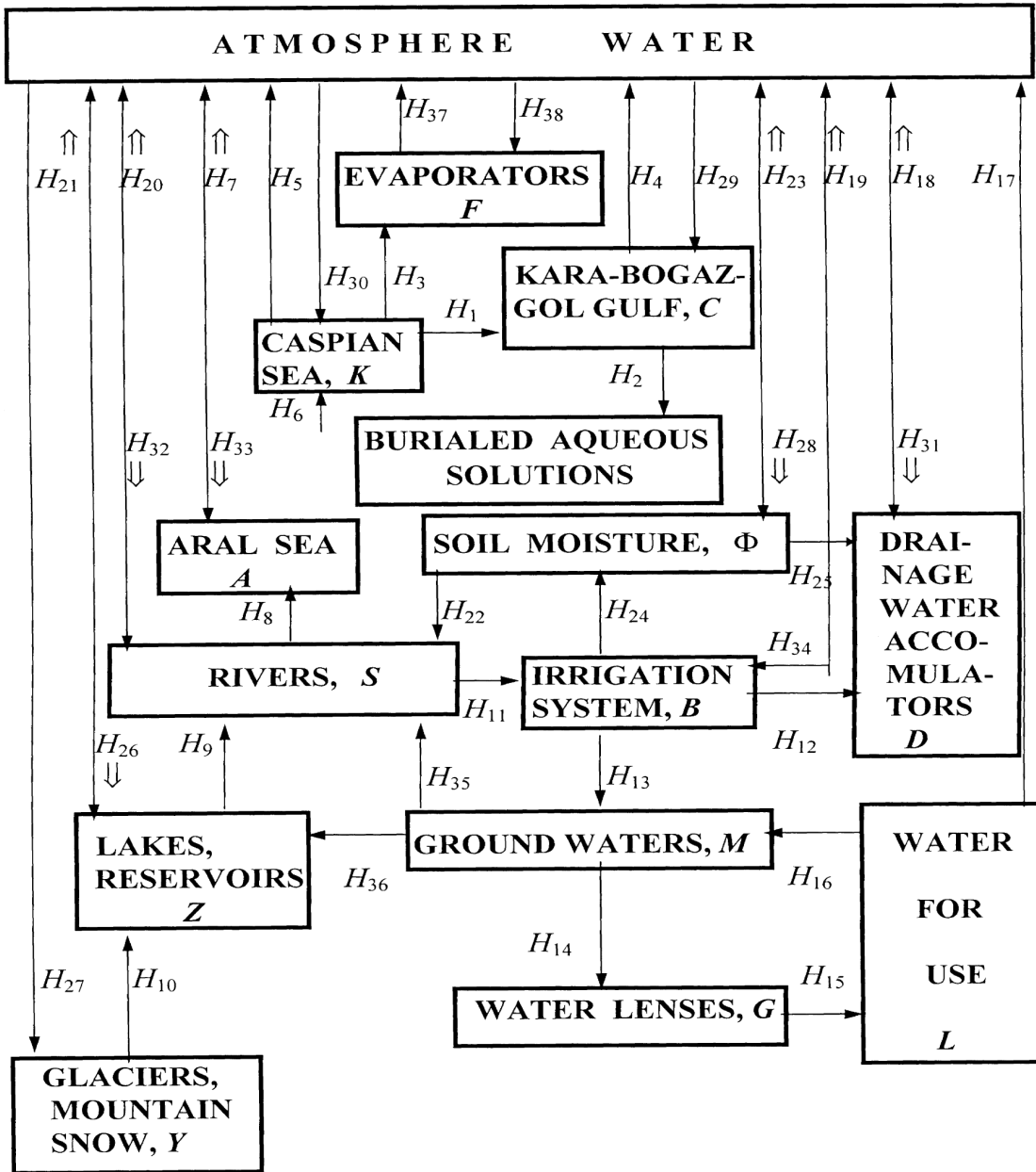
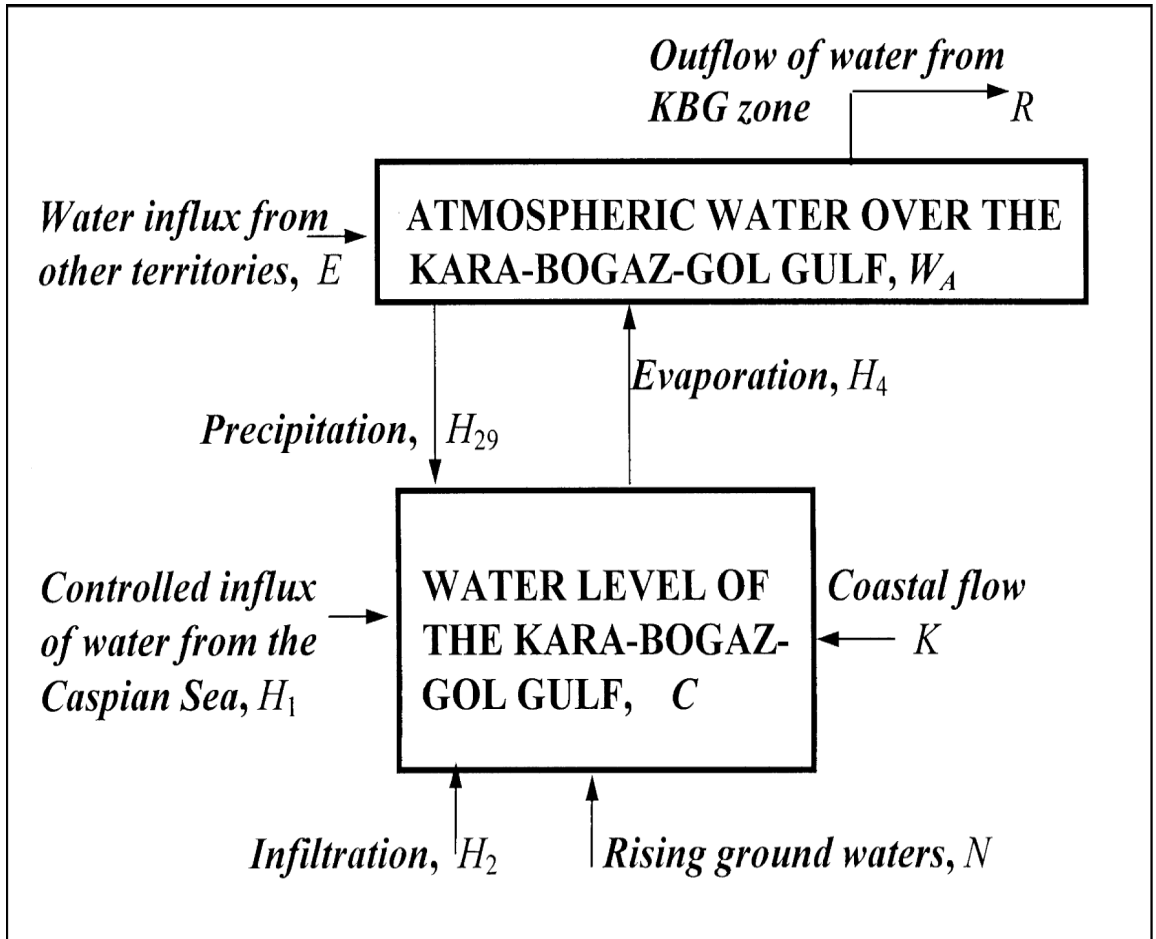**Fig.2.** *Block diagram of the ACS water balance as represented in the framework of the CSM.*

Fig.3. *Implementation of the regional water balance schheme for the Kara-Bogaz-Gol Gulf zone.*
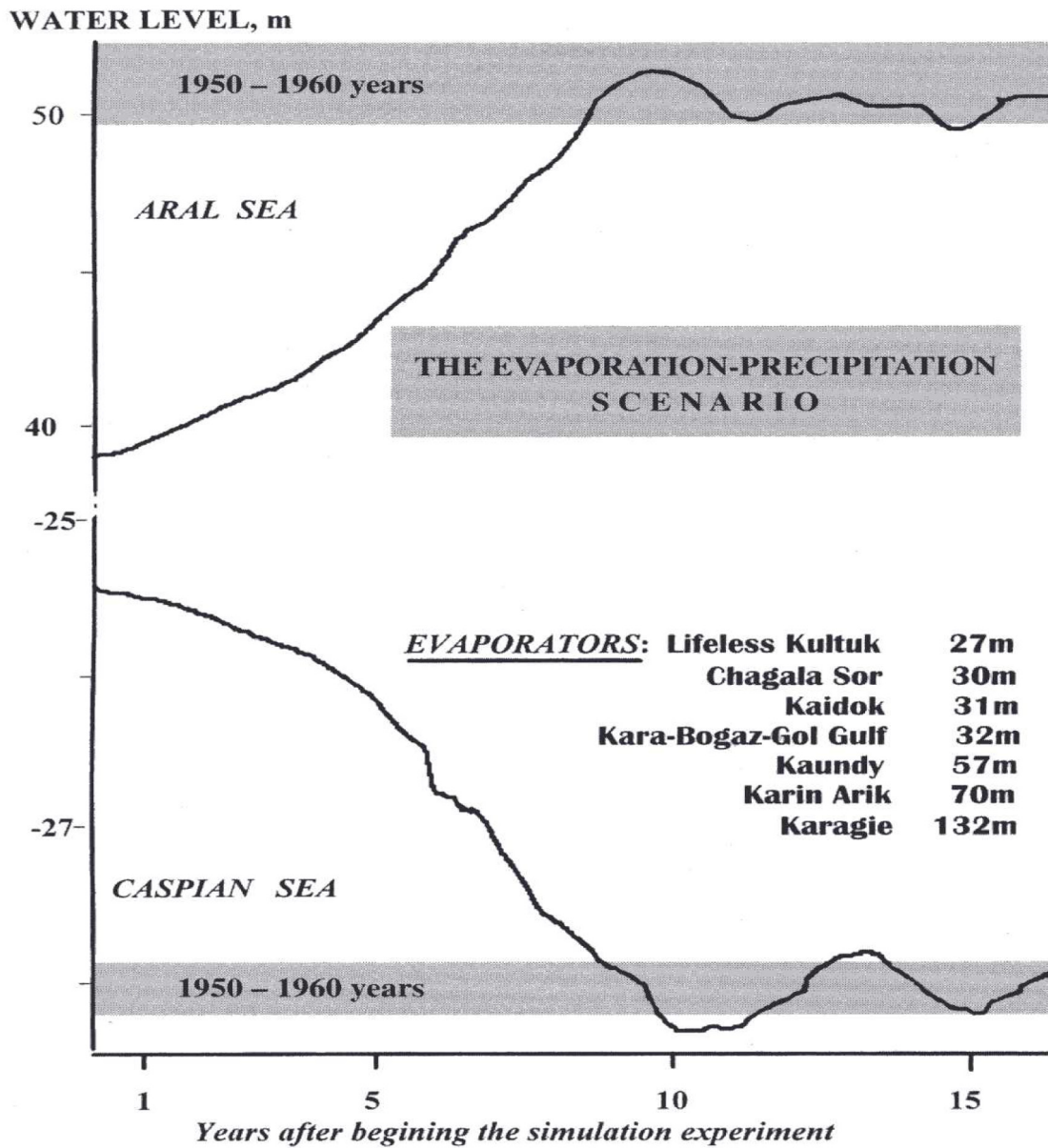
Fig.4. *Results of the simulation experiment for the evaporation-precipitation scenario showing the changes in the water levels of the Aral and Caspian Seas.*

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