ON THE PROBLEM OF THE CASPIAN SEA LEVEL FORECASTING

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Abstract

Stochastic fluctuations of climate and hydrological regime caused by both natural and anthropogenic factors are the main reason for the big uncertainty of long-term hydrological forecasts. Consequently, they cause the necessity to reconsider the risk of economic activities at inland sea coasts towards its increase. To estimate such a risk some sources of uncertainty arising under the sea hydrological regime forecasting are considered in the paper. By use of digital models of a region, some features of morphometric characteristics (depending on the sea level) are revealed, and their contribution to the level regime variability is appreciated.

Introduction

The forecast of long-term fluctuations of an inland water body level such as the Caspian Sea is the most complicated geophysical problem. It demands knowledge both of features of a hydrometeorological regime of the region, and of mechanisms for the occurrence of long-term climate and runoff fluctuations. Their definition is associated with different types of mistakes arising because of unreliable measurements, imperfection of the modeling representations, the approximate character of hypotheses, limitation of access to observation materials of recent years, etc.

Model

Fluctuations of an inland (closed) water body level represent poorly predicted natural phenomenon, which nevertheless can be described on the basis of stochastic models of hydrometeorological processes and representations about its water balance.

Fluctuations of a water level (h) of a closed water body can be described with the help of the known water balance equation [4,5]:

$$\frac{dh}{dt} = \nu(t) / F(t) - e(t), \qquad (1)$$

Where ν(t) is water inflow per unit time, e(t) is a amount of effective evaporation (evaporation minus precipitation), F(t) is the water surface area.

To solve the equation (1), the linearized analogue is offered in [5]:

$$\frac{dh}{dt} + (b\nu(t)/a^2)h = \nu(t)/a - ae(t), \qquad (2)$$

where *a* and *b* are the coefficients of linear dependence of water surface area on the level. Assuming the coefficient constant under *h,* we receive Langeven linear differential equation [11]:

$$\frac{dh}{dt} + \alpha h = g(t)\,, \qquad (3)$$

where $\alpha = b\bar{v} / a^2 = Const, \quad g(t) = v(t) / a - e(t)$.

Assume that at the initial moment *t=0* the level equals to h_o relative to the so-called equilibrium value $\tilde{z} = \frac{1}{b}\left(\frac{\bar{v}}{\bar{h}} - a\right)$, where $\bar{\nu}$ and $\bar{h}$ are water inflow and evaporation expectations.

The solution of the equation (3) can be presented as [11,5]:

$$h_t = h_o e^{-\alpha t} + e^{-\alpha t}\int_0^t e^{-\alpha\xi} g(\xi)d\xi\ . \qquad (4)$$

Averaging the right and the left parts in (4), we receive

$$\bar{h}_t = h_o e^{-\alpha t}\,, \qquad (5)$$

as $\bar{g}(t) = o$.

The solution (4) of the equations (3) being considered as a linear operator transforming the random function g(t), the expression for the correlation function of the process h is received in [5,11] assuming the entrance process g $(R_{g(t)} = \sigma_g^2 e^{-\beta t})$ to be the Markov one. This expression being too bulky, we limit ourselves here only by the formula for the dispersion of level fluctuations:

$$\sigma_h^2(t) = \sigma_g^2\{(\beta - \alpha) - (\alpha + \beta)e^{-2\alpha t} + 2\alpha e^{-(\alpha+\beta)t}\}/\alpha(\beta^2 - \alpha^2) \qquad (6)$$

At *t→0* the following expression is true for the correlation function

$$R_h(t) = (\beta e^{-\alpha|t|} - \alpha e^{\beta|\tau|})/(\beta - \alpha). \qquad (7)$$

For the dispersion:

$$\sigma^2_h = \sigma^2_g / \alpha(\alpha+\beta). \qquad (8)$$

The data

From the beginning of regular observations over the Caspian Sea regime during about one century, its levels were insignificantly fluctuating near the mark of -26 m. In 30th years of 20th century a catastrophic decrease of the level on 1.7m occurred. Further, the decrease of the level continued but much more slowly and in 1979, the level has reached -29m. The increase begun after that was observed until 1995, annual average levels exceeding -27 m.

One of the most important problems of the data analysis is the representativity of the existing observation series of the Caspian Sea level and the reliability of the statistical conclusions received on the limited data.

Researches of fluctuations of river runoff and evaporation from water body surface and the precipitation analysis have shown that the so-called simple Markov chain can be accepted as the mathematical model of these processes [6,8,9]. Simulation of the Caspian Sea level series executed on the basis of the corresponding numerical algorithms [7], allows to make a conclusion, that probability distribution in an interval from 0,1 up to 99,9 % is well approximated by the normal distribution law. At the same time, it is necessary to note, that the histogram of the observed sea levels sequence has the two-modal form.

Hypothesis of the Stationarity of Climatic Conditions

Along with other hypotheses, one can find the explanation of the Caspian Sea abnormal behavior in a context of a climatic change problem. Climatic conditions are known to be essentially non-stationary on long time intervals (more than centuries). For example, according to some estimations, during last post-glacial period the World Ocean level has grown on 130 m. Instrumental measurements has demonstrated ocean level growth approximately on 15 - 20 cm for 100 years as well. However, this figure lies within the limits of measurement accuracy and can hardly serve as the evidence of essential modern climatic changes (or their indicator).

The indirect characteristic allowing estimating of the "stationary" hypothesis acceptability is the average duration of time when the sea level is above or below the set level (occurrence probability of series of years with extreme level values). It is found from the outlier probability distribution for the prescribed stochastic model. The solution of this problem for the Caspian Sea has shown [6] that the recurrence of long series (up to 50 years and over) in relation to the gravitation level is essential. The existing stochastic runoff fluctuation model seems to be advanced in the framework of some quasi-stationary theory by the account of long-term tendencies in the process of the Caspian Sea basin humidation, but such models have not been offered yet.

Recently, the trends discovered in wind speed on the coastal stations called the hypothesis of the climatic condition stationarity in question. The evaporation value is known to depend on wind speed as well as on air temperature and humidity. The lowered evaporation observed in last decades would be logically associated with fluctuations of these climatic characteristics. The researches carried out by a number of scientists have not revealed any of significant tendencies in air and water temperature and air absolute humidity. As for the module of a wind speed, the conclusion about the presence of a negative linear trend for the period 1960-1990 has been made [2].

On the basis of the observations on meteorological stations in the Caspian region, average monthly values of air temperature and surface wind speed for the period of 1961-1999 has been received for Izberg, Makhachkala and Tuleniy. These stations are located at the western coast of the Caspian Sea closely to each other. Thus, if any tendencies in change of climatic characteristics take place all over Caspian region, they should be shown equally at these stations.

On Fig.1 graphs of surface wind speed module for these three meteorological stations for January, April, July and October are presented.

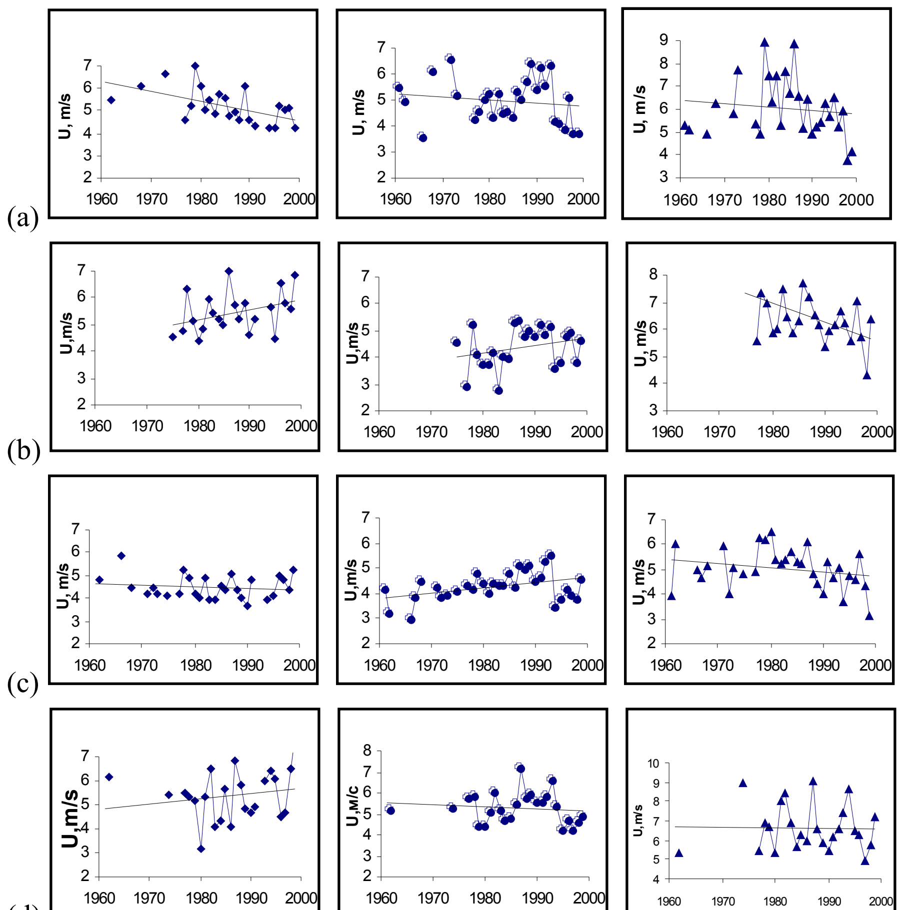

Figure 1. Long-term changes of wind speed module on stations: Tuleniy (♦), Izberg (●), Makhachkala (▲) for January (a), April (b), July(c), October(d), 1960-1999

At Tuleniy station, one can see the negative trend in surface wind speed in January; in April and to a lesser degree in October the positive one is observed, while in July no essential change is revealed. At Izberg station, on the contrary, in January and October no any essential change is observed, in April and in July obviously expressed positive trend is observed. At Makhachkala station in January and October wind speed is practically the same for the given period, in April and - to a lesser degree - in July wind speed decreases. Thus, at three closely located stations wind speed turns to behave differently. It is necessary to notice as well that during the considered period differences in meteorological observations carrying out on the stations took place. So, at station Makhachkala during the period up to 1968 observations were carried out 4 times a day, then up to 1986 - 3 times a day (9, 15, 21h.), then again 4 times a day. Up to 1993, the observations were carried out at 3, 9, 15, 21h, from 1994 - at 0, 6, 12, 18h. This could lead to fluctuations of average wind speed within the limits of 0.5 m/s that corresponds to approximately 10 % of average norm.

Thus, the analysis of change for last 40 years does not give us an opportunity to draw a conclusion about the existence of strongly pronounced tendencies of the meteorological characteristics that would determine evaporation from the Caspian Sea and changes of its level. On the contrary, the researches carried out can be regarded as the support of the hypothesis of climatic conditions stationarity.

Morphometric Dependences

Some other ideas explaining the "anomaly" of the Caspian Sea are connected with mistakes of the accepted modelling representations. So, in linearized differential water balance equations linear dependence of the water surface area upon the sea level is used (the so-called morphometric dependence). Modern level of computer facilities allows not limiting oneself by opportunities of standard topographical maps when searching morphometric dependences. To solve such problems, it is necessary to automatize the access to elevation data. With this purpose, the relief digital model (a matrix of altitudes with a geographical fixation) was used with the grid step of 30 seconds, with smooth approximation along height. Calculations of the Caspian Sea morphometry are represented further without taking into account the Kara Bogas Gol gulf water area. The Caspian Sea is divided into three parts: Northern (to the north of 44°30' N), Middle (from 40°N up to 44°30' N) and Southern (from 40° N to the south).

Let us consider the distribution of areas occupied by various bathymetric steps. The most significant part of the area - 66.6 % - has the depths less than 100 meters, 42.4 % of it (28.2 % of the total sea area) located mainly (70 %) in the Northern part of the Caspian Sea having the depth less than 10 m. Depths more than 900 m occupy about 1 % of the area. The reminder area is distributed rather regularly between 200 and 800 m depths approximately by 4-5 % per 100m of depth. The general character of depths distribution is well seen on the bathygraphic curve of the sea (fig.2). One can see two smooth breaks at the depths of 500 and 100 meters and various inclinations: very flat one in the upper part, very steep one in the middle and less steep one in the lower part of the curve.

If to consider the part of the bathygraphic curve corresponding to the heights of -40 - -20m abs in more details (Fig. 2B), a presence is obvious of a bathygraphic curve excess at about -28 m abs. It is the Northern part of the sea that is responsible for the excess, while curves of the Middle and the Southern parts of the Caspian Sea have no peculiarities within these altitudes. Such behavior of a curve is explained by high flatness of the relief in the coastal zone and of the Northern Caspian Sea coast. These relief features do not allow using linear interpolation in the field of a coastal zone area for the problems of forecasting of the sea level change and the coastal zone flooding.

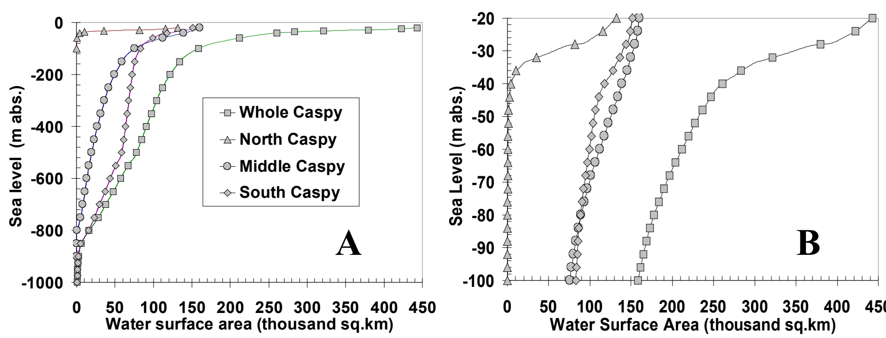

*Figure 2. Dependence of the water surface area (thousand km²) of The Caspian Sea on the level (m abs.). **A** – for level from –1000 to 0 m abs. **B** – for level from –100 to –20 m abs.*

The account of "new" morphometry of the Caspian Sea in problems of the long-term level forecast results in the underestimated values (quantile) with small excess probability compared with the "linear" problem.

The Forecast

With the modern level of scientific knowledge, it is impossible to make the forecast (long-term) of water balance hydrometeorological components for concrete calendar date. Hence, the method of the long-term calendar forecasting of a sea level is impossible as well. Only probability forecasts are possible, for example, the one of the average sea level position and the deviation from it of the position of the given probability (quantile).

In Table 1, the quantils of the conditional distributions of level probability for the nearest decades are presented. As follows from this table, the range of possible level values is wide enough. The mark - 26 m should be taken into account as one having the exceedence of 1 % when designing engineering protection actions. Low sea levels on marks - 28,-29 m are also probable.

Table 1. Probability forecast of the Caspian Sea level (irrevocable withdrawals = 25 km³/year; the initial level=-27.0m)

Year Probability of exceedence	2001	2003	2005	2010	2020	2030	2040	2050
0.1%	-26.53	-26.11	-25.87	-25.59	-25.48	-25.48	-25.54	-25.63
1%	-26.66	-26.37	-26.20	-26.04	-26.02	-26.06	-26.13	-26.21
5%	-26.77	-26.59	-26.50	-26.44	-26.51	-26.58	-26.66	-26.73
Average	-27.05	-27.14	-27.22	-27.40	-27.67	-27.83	-27.92	-27.98
95%	-27.32	-27.69	-27.93	-28.37	-28.84	-29.07	-29.19	-29.23
99%	-27.43	-27.91	-28.23	-28.76	-29.33	-29.59	-29.71	-29.75

For the periods until 2005, 2010, 2020, 2030 etc. the average forecasting level (with 50 % probability of exceedence) is from -27.05 m (that practically corresponds to the modern coastal line position) up to -27.98 m for 2050 (actually up to the level, which is considered safe). The most adverse forecast with 0.1 % probability of exceedence for the same periods is -25.48 m, and the most adverse forecast with 1 % probability of exceedence is -26.02 m.

Bayes Forecast Estimations

The risk in economic development of coastal territories arises both as a consequence of stochastic character of influences as mid-annual or extreme levels and owing to a wide set of uncertainties, that should be taken into account when accepting some design (or organizational) decisions. The models presented above take into account the basic kind of uncertainty - probability character of inducing hydrometeorological processes. At that, parameter errors resulting from estimating by short samples are not considered.

Let us consider the influence of sample properties of model parameters estimations. Being functions of time, expressions for sea level expectation and dispersion enable to predict future fluctuations of the sea in the form of confidence intervals or the given probability values (the conditional density being approximated by the Gaussian law). The latest form of the forecast is used at a substantiation of actions and designing of constructions of coastal territories engineering protection. We remind that expressions (5) and (6) has been received in the assumption that estimations of stochastic models parameters are known exactly and the received conditional distributions reflect only stochastic character of hydrometeorological processes variability. However, those parameters estimations are known to possess the so-called sample properties and to be characterized by errors in the simplest case.

The simple approach leading to results easy to be interpreted is based on Bayes ideology supposing the construction of the so-called forecast density of required value x as the conditional distribution $\pi(x|y)$ with the given observations of y.

In accordance with the terminology [9], let us introduce the probability model for x as $g(x|\theta)$ dependent on some parameter θ determined by available values of y. Further, assuming that posterior distribution density of this parameter $p(\theta|y)$ is known and x and y are independent, the forecast probability density can be received from the following expression:

$$\pi(x \mid y) = \int_{\theta} g(x \mid \theta) p(\theta \mid y) d\theta \qquad (9)$$

Calculations according to the equation (9) are carried out by numerical integration with either sample distribution of a parameter (estimation), or the distribution of an estimation on homogeneous objects group (water bodies, lakes, meteorological stations, etc.) used as the distribution density *p*. As it was mentioned above, as *g*- function it is possible to use the normal distribution law with parameters determined by formulas (5) or (6) depending on parameters estimations of stochastic models of river inflow and water body evaporation. The results of the calculations are presented in Tables 2 and 3 for cases when the sample dispersion of estimations of inflow and evaporation average values and the autocorrelation coefficient estimation are accounted.

Table 2. Probability forecast of the Caspian Sea level with the account of sample properties (error) of the inflow expectation estimation (irrevocable withdrawals = 25 кm³/year; an initial level = -27.0m)

Year Probability of exceedence	2001	2003	2005	2010	2020	2030	2040	2050
0.1%	-26.53	-26.11	-25.86	-25.56	-25.40	-25.36	-25.40	-25.48
1%	-26.66	-26.36	-26.20	-26.01	-25.97	-25.97	-26.02	-26.10
5%	-26.77	-26.59	-26.50	-26.42	-26.47	-26.51	-26.58	-26.65
Average	-27.05	-27.14	-27.22	-27.40	-27.68	-27.83	-27.92	-27.98
95%	-27.32	-27.69	-27.94	-28.39	-28.89	-29.14	-29.27	-29.31
99%	-27.43	-27.92	-28.24	-28.79	-29.39	-29.68	-29.82	-29.86

Table 3. Probability forecast of the Caspian Sea level with the account of the sample properties (errors) of the inflow and evaporation expectation estimations (irrevocable withdrawals = 25 кm³/year; an initial level = -27.0m)

Year Probability of exceedence	2001	2003	2005	2010	2020	2030	2040	2050
1%	-26.6	-26.36	-26.19	-26.00	-25.94	-25.94	-25.96	-26.01
99%	-27.43	-27.92	-28.24	-28.80	-29.40	-29.70	-29.86	-29.92

Conclusions

The problem of the Caspian Sea level forecasting is closely connected both with the research of natural hydrometeorological processes variations and with transboundary character of this water object. The changed status of the sea has led to essential degradation of the observation network and, correspondingly, to the growth of hydrological forecasts uncertainty and zones of risk.

As the result, the conclusion is obvious about the necessity of close international cooperation of scientists in the Caspian region with participation and under the support of UNESCO, UNEP, etc.

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