Interannual Variability of Evaporation from Reservoirs in Arid Regions

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Abstract. *This article is devoted to assessing the interannual variability of evaporation from the surfaces of reservoirs located in arid climatic regions. The problem is investigated using the Tozakul Reservoir as a case study. The evaporation depth and evaporation volume from its surface were determined for the period 1981–2025. The calculations were based on observational data from the Bukhara meteorological station and the ETo Calculator software. The ETo values were adapted for estimating the evaporation depth from the surface of the studied reservoir using a correction coefficient determined in the authors' previous studies. The study analyzes the interannual variability of air temperature, relative humidity, wind speed, and other key meteorological factors, and assesses their influence on the rate of evaporation.*

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1. Introduction

In arid and semi-arid regions of the world, including the Republic of Uzbekistan, reservoirs play an important role in meeting the water demands of agricultural irrigation, large industrial enterprises, and the population's need for safe drinking water. Under arid climatic conditions, the limited availability of water resources necessitates an accurate assessment of water losses from reservoirs, particularly those resulting from evaporation from the water surface. In arid regions, high air temperatures, low relative humidity, strong winds, and high levels of solar radiation contribute to increased evaporation intensity from reservoir surfaces. As a result, the amount of water lost through evaporation from reservoirs is considerably higher than in humid climatic regions [1, 4, 7, 8]. Therefore, studying evaporation processes from the surfaces of reservoirs located in arid regions is of significant scientific and practical importance for ensuring the efficient use of water resources and underscores the relevance of the present study.

The main objective of this study is to assess the interannual variability of water losses due to evaporation from reservoirs located in the desert zones of Uzbekistan, taking into account the dynamics of their water surface areas, using the Tozakul Reservoir (formerly known as the Kuyimozor Reservoir) as a case study. Within the framework of this objective, the following research tasks were defined and addressed during the study: (1) to identify a representative meteorological station located

near the Tozakul Reservoir and collect the necessary hydro-meteorological observation data, including mean monthly, maximum, and minimum air temperatures, relative humidity, wind speed, and other relevant meteorological variables; (2) to perform preliminary processing and generalization of the collected data and establish a standardized hydro-meteorological database; (3) to calculate the daily, and subsequently monthly and annual, reference evapotranspiration (ETo) from the reservoir surface using the ETo Calculator software and to determine the actual evaporation depth by applying the correction coefficient; and (4) to assess the interannual variability of the actual evaporation depth and evaporation volume from the surface of the Tozakul Reservoir. The Tozakul Reservoir is located in Kiziltepa District of Navoi Region, Uzbekistan. It was constructed and commissioned during 1953–1957. According to the initial design, the reservoir had a storage capacity of 280 million m^3, a water surface area of 16.2 km^2, a maximum width of 5 km, and an average depth of 17 m. In 1968, the shoreline of the reservoir basin was raised by constructing a dam more than 2 m higher than the original level. As a result, the reservoir's storage capacity increased to 310 million m^3, while its water surface area reached 17.2 km^2. The reservoir is a diversion-type reservoir. Until 1965, water was supplied from the Zarafshan River through a specially constructed canal 18 km in length. In addition, a small canal was constructed to convey water from the Amu-Bukhara Machine Canal (ABMC) using the Kuyimozor pumping station, with a capacity of 40 m^3/s. Since 1965, the Tozakul Reservoir has been replenished primarily with water from the ABMC. Water stored in the Tozakul Reservoir is distributed to irrigation networks and other water users through a 72-km-long canal with a discharge capacity of up to 100 m^3/s. The reservoir's water is used to supply drinking water to the cities of Bukhara, Kogon, and Qorovulbozor; to provide industrial water for the Bukhara Oil Refinery and Mubarek Gas Processing Plant; and to irrigate agricultural lands in Vobkent, Peshkhu, Romitan, Kogon, Bukhara, and Jondor districts of Bukhara Region.

The Bukhara meteorological station, located at a distance of 22 km northeast of the studied reservoir, is the nearest meteorological station and was selected as the reference meteorological station for this study. At this meteorological station, data on mean monthly, maximum, and minimum air temperatures, relative humidity, and wind speed measured during 1981–2025 in accordance with established standard requirements were collected. The collected data were subjected to preliminary processing, systematized, and used to establish a hydro-meteorological database. These data were then entered into the ETo Calculator software to determine the evaporation depth from the surface of the studied Tozakul Reservoir. Detailed information on the ETo Calculator software and its application has been comprehensively described in the authors' previous studies [11].

To determine reference evapotranspiration from the surface of the Tozakul Reservoir using the ETo Calculator software, the meteorological variables measured at the Bukhara meteorological station were first converted into a format compatible with the software. Subsequently, the reference evapotranspiration was calculated according to the sequence specified in the ETo Calculator. Based on the calculated daily reference evapotranspiration values, monthly and annual evaporation depths were determined. The actual evaporation depth was calculated by multiplying the monthly reference evapotranspiration values by the

corresponding monthly correction coefficients (Kc) [11, 12, 14].

2. Materials and Methods

For this purpose, the interannual variability of the mean annual air temperature, wind speed, and relative humidity determined from the data measured at the Bukhara meteorological station was analyzed (Figures 1–3).

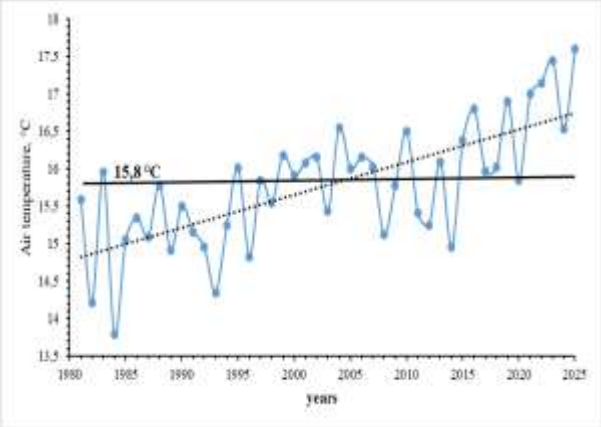

Figure 1. Interannual variation in mean annual air temperature at the Bukhara meteorological station.

The analysis showed that the minimum mean annual air temperature of 13.85°C occurred in 1984, whereas the maximum value of 17.5°C was recorded in the final years of the study period, specifically in 2025. Over the study period, from 1981 to 2025, the calculated mean long-term air temperature was 15.8°C. The trend line shown in the graph also confirms an increasing tendency in air temperature during the study period based on the data from the Bukhara meteorological station. The increase in air temperature indicated by the trend line over this period was 1.73°C. Thus, during the study period, air temperature increased at an average rate of 0.039°C per year.

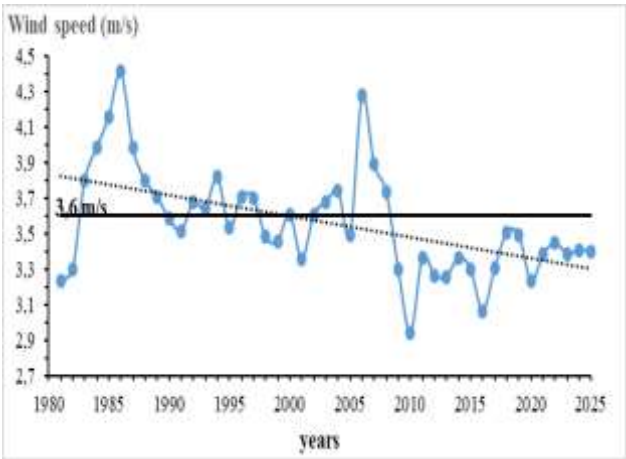

Figure 2. Interannual variability of mean annual wind speed at the Bukhara meteorological station.

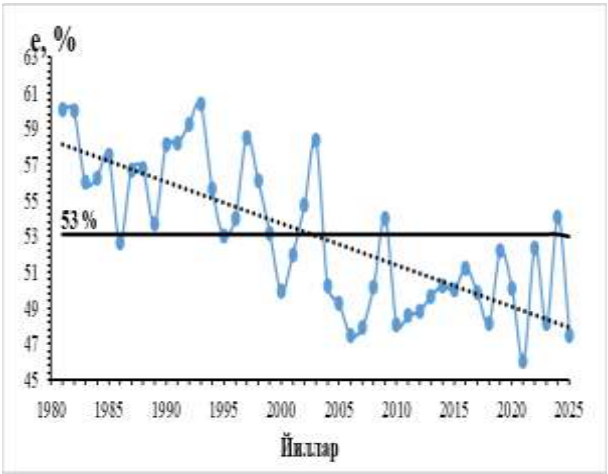

Figure 3. Interannual variability of mean annual relative humidity at the Bukhara meteorological station.

The mean annual wind speed observed at the Bukhara meteorological station during the study period varied within the range of 2.9–4.4 m/s. The highest value, 4.4 m/s, was recorded in 1986, while the lowest value, 2.9 m/s, was observed in 2010. Overall, no sharp changes in wind speed were observed during the study period; however, a relatively decreasing trend became apparent after the 2000s. This may contribute to a slight decrease in the intensity of evaporation (Figure 2).

At the Bukhara meteorological station, relative humidity varied between 46% and 60% during 1981–2025. The highest value, 60%, was recorded in 1981, 1982, and 1993, whereas the lowest value, 46%, was recorded in 2021. Overall, a decreasing trend in relative humidity was observed over the long-term period, particularly after 2000, when relative humidity generally remained within the range of 48–54%. This indicates a tendency toward increasingly dry atmospheric conditions and, together with the rise in air temperature, may create favorable conditions for an intensification of the evaporation process.

3. Results.

To determine reference evapotranspiration from the surface of the Tozakul Reservoir using the ETo Calculator software, the meteorological variables measured at the Bukhara meteorological station were first converted into a format readable by the software. Subsequently, the reference evapotranspiration was determined according to the sequence specified in the ETo Calculator. Based on the daily reference evapotranspiration values calculated by the software, monthly and annual evaporation depths were determined. The actual evaporation depth was calculated by multiplying the monthly reference evapotranspiration values by the corresponding monthly correction coefficients (Kc) [11, 12, 14].

During the study period (1981–2025), the minimum evaporation depth was 1,538 mm in 1981, while the maximum evaporation depth reached 1,994 mm in 2006. The long-term mean evaporation depth was 1,796 mm. These variations are clearly reflected in the graph constructed based on the results of the calculations (Figure 4).

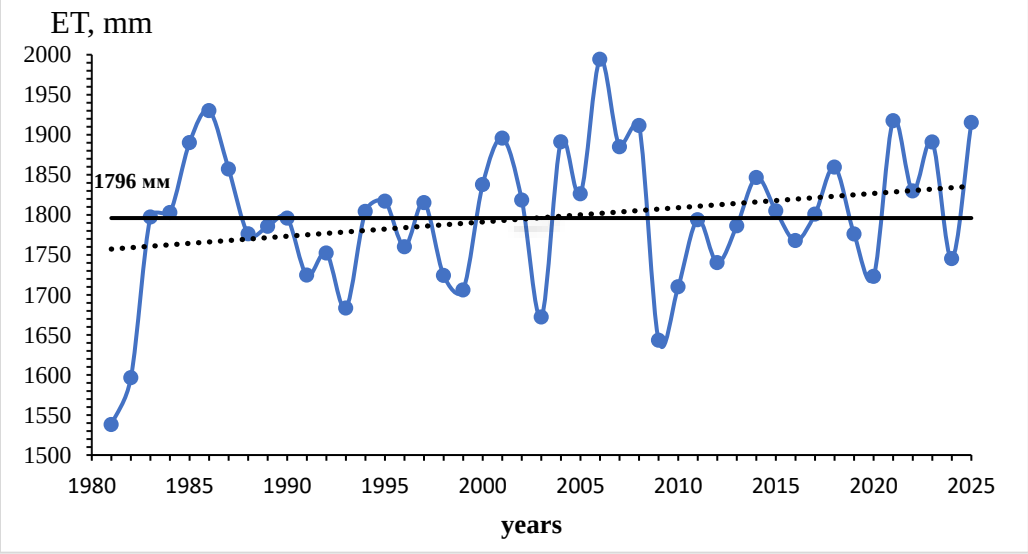

Figure 4. Interannual variability of annual evaporation depth from the surface of the Tozakul Reservoir.

Based on the annual evaporation depth data from the reservoir surface, the annual evaporation volumes were calculated using the following equation:

$$V_{zy} = Z_y \cdot F_y, \text{ mln. } m^3 \quad (1)$$

where (Zy) is the annual evaporation depth, expressed in 10^{-3} m; (Fy) is the mean annual water surface area of the reservoir corresponding to the mean annual water level (Hy), m, expressed in 10^6 m².

The mean annual water surface areas corresponding to the reservoir's mean annual water levels were determined from the reservoir area–volume curves (Figure 5).

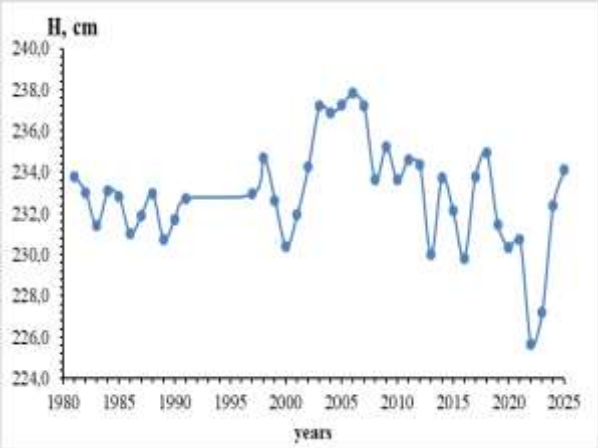

Figure 5. Interannual Variability of the Mean Annual Water Level of the Tozakul Reservoir

The calculation of water volumes lost from the reservoir due to evaporation was carried out in the following sequence: (1) the average values of meteorological elements were determined for each month; (2) monthly evaporation depths (Zhi) were calculated using the ETo Calculator software, and the annual evaporation depth was determined as the sum of the monthly values; (3) the average annual water levels of the Tozakul Reservoir (Hy, m) were determined from the interannual fluctuations in water level (Fig. 5); (4) the average annual water surface areas (Fy) corresponding to the average annual water levels (Hy, m) were determined from the reservoir area–elevation curve; and (5) the annual volume of water lost from the reservoir due to evaporation was calculated using Equation (1), expressed in volumetric units.

The water level and water surface area of the Tozakul Reservoir varied from year to year in close interrelation, and these variations directly affected the volume of evaporation. The evaporation volume depended on the combined variation in the water surface area and evaporation depth. The maximum evaporation volume of 36.4 million m³ was recorded in 2006, whereas the minimum value of 20.4 million m³ was observed in 2022. Overall, the results indicate that interannual variations in the reservoir water surface area and meteorological conditions had a significant influence on the quantitative characteristics of the evaporation process (Fig. 6).

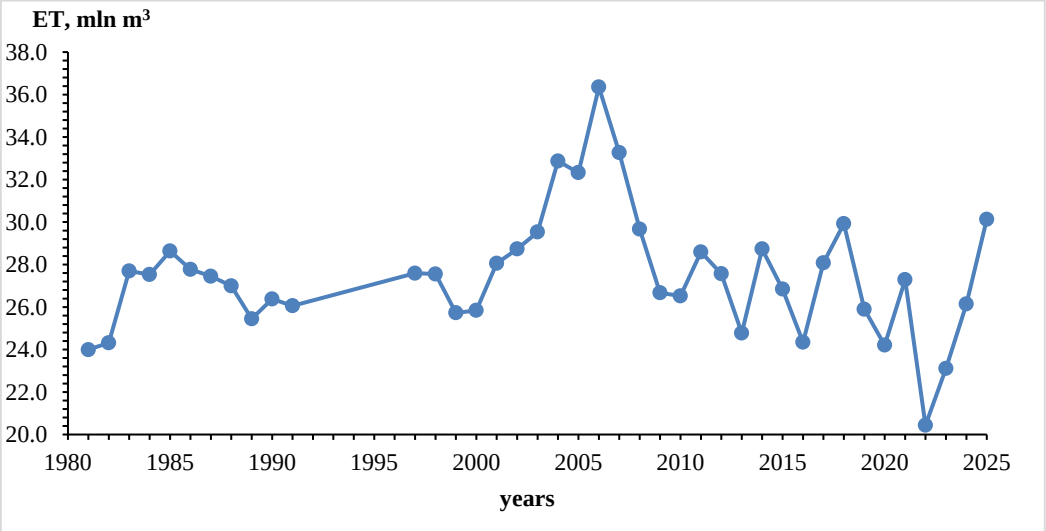

Figure 6. Interannual variation in the evaporation volume from the Tozakul Reservoir surface

4. Discussions.

Evaporation depth from reservoir surfaces depends on the climatic conditions of the region where the reservoirs are located. More specifically, its values are determined by the meteorological characteristics of the region, including air temperature, water surface temperature, wind speed, and vapor pressure deficit, as well as by the morphometric characteristics of the reservoirs.

It was found that the minimum annual air temperature of 13.9°C occurred in 1984, whereas the maximum value of 17.5°C was recorded in the final years of the study period, specifically in 2025. During the study period (1981–2025), the long-term mean annual air temperature was 15.8°C. The mean annual wind speed varied from 2.9 to 4.4 m/s. The highest value, 4.4 m/s, was recorded in 1986, while the lowest value, 2.9 m/s, was observed in 2010. A relatively decreasing trend in wind speed became evident after the 2000s. Relative humidity varied between 46% and 60%. The highest value of 60% was recorded in 1981, 1982, and 1993, whereas the lowest value of 46% was observed in 2021. After 2000, relative humidity generally fluctuated within the range of 48–54%.

During the study period (1981–2025), the minimum evaporation depth was 1,538 mm, recorded in 1981, while the maximum evaporation depth of 1,994 mm was observed in 2006. The long-term mean evaporation depth was 1,796 mm.

The evaporation volume depended on the combined variation in the water surface area and evaporation depth. The maximum evaporation volume of 36.4 million m³ was recorded in 2006, while the minimum value of 20.4 million m³ was observed in 2022. During the study period, the long-term mean annual evaporation volume was 27.5 million m³. This amount corresponds to 8.9% of the design storage capacity of the Tozakul Reservoir.

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