

Article

The Calculation and Mapping of the Moisture Indices of the East Kazakhstan Region for the Preventive Assessment of the Climate–Hydrological Background

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Abstract

The assessment of the hydrological functions of landscapes and the landscape–hydrological background is an important instrument for minimizing damage from rivers and preventing water conflicts under conditions of data scarcity for hydrological modeling. To assess the climate–hydrological background of the East Kazakhstan region, the Selyaninov Hydro-thermal Coefficient and the Vysotsky–Ivanov Moisture Coefficient were used. The East Kazakhstan region is a typical continental arid and semi-arid region. The presence of mountain ranges, such as the Altai, makes the climate and environment in the region highly varied. A dataset from 30 weather stations for the period 1961–2023 was used for calculations. Three interpolation methods and landscape extrapolation were used to construct maps of the coefficients. Over the observation period, the values of the moisture indices at the weather stations in the region fluctuated within a wide range. Both coefficients are in the range from extra arid to extra humid climates.

Keywords: moisture indices; Selyaninov Hydro-thermal Coefficient; Vysotsky–Ivanov Moisture Coefficient; landscape–hydrological background; weather station; East Kazakhstan region



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1. Introduction

The derivation of relationships between the rainfall over a catchment area and the resulting flow in a river is a fundamental problem of hydrology [1,2]. A wide range of models is used to identify these relationships. However, the lack of data and the heterogeneity in the available datasets often lead to uncertainties in model predictions [3]. For example, flood risk assessment in data-scarce regions has been a significant challenge due to limited hydrological and meteorological data, which hinder accurate modeling and forecasting [4,5]. There are many instances where estimates of hydrological parameters are required for locations where streamflow data have not been measured or where the available streamflow record is too short to afford a reliable estimate for the parameter of interest, particularly in semi-arid regions in Africa, South America, and Asia [6]. For example, ground-based rain gauges offer relatively precise rainfall data at the point scale,

but their uneven network, due to accessibility and economic constraints, poses difficulty for interpolating the rain distributions accurately over watersheds or mountainous regions with insufficient gauges [5]. In a broad and practical sense, ungauged catchments refer not only to those past streamflow observations but also to catchments expected to experience significant changes in the future, including land use change and climate change [1].

However, the presence of ungauged catchments does not eliminate the need to solve the problems of environmental management. Among them are the minimization of damage from rivers and the prevention of water conflicts. In addition, some questions are traditionally not taken into account in hydrological modeling. They are the biodiversity conservation and the natural and cultural heritage rescue. To solve these problems, runoff modeling should be supplemented by other approaches [7]. Identifying and categorizing dominant catchment functions as revealed through a suite of hydrological response characteristics is considered one of the ways to overcome the lack of information [8–10]. The hydrological response of a catchment is a holistic function that combines structural and hydroclimatic features. However, the hydrological response can be considered not only as a function of the catchment but also as a function of each landscape. The physiographic and climatic characteristics of a landscape can predetermine its hydrological behavior [6,9].

The primary purpose of this study was to characterize the climate–hydrological background of the East Kazakhstan region (EKR) based on the values of the Selyaninov Hydro-thermal Coefficient (HTC) and the Vysotsky–Ivanov Moisture Coefficient (VMC).

In this regard, the following tasks were undertaken:

- Calculation of the HTC and VMC based on “Kazhydromet” weather station data;
- Construction of isolinear maps of these indices, applying different interpolation techniques;
- Preparation of a landscape map based on the correction of previous researchers’ data;
- Extrapolation of map information to unobserved areas, applying the landscape map for the region as an alternative way to spatial data interpretation;
- Comparison of the results obtained by different methods of environmental correlation.
- The flowchart shown in Figure 1 illustrates the logic of the research process.

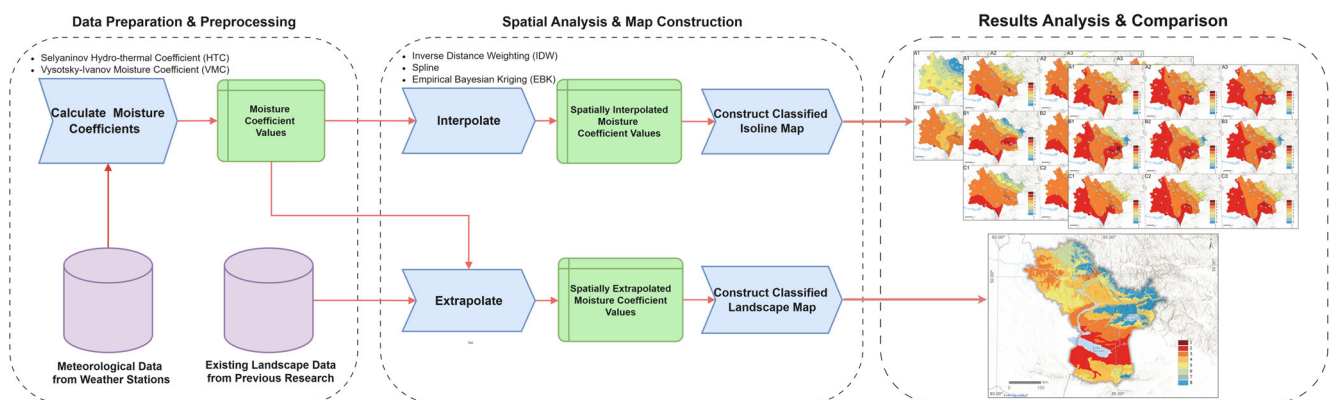


Figure 1. Flowchart illustrating the research process.

The enormous complexity of environmental factors impacting the hydrological response requires initial concentration on dominant (or first-order) characteristics only [8]. Ref. [11] introduced the idea of hydrologic landscapes, which are defined on the basis of similarity of climate, topography, and geology, assuming that catchments that are similar with respect to these three criteria behave similarly in a hydrological sense. We proposed the concept of a landscape–hydrological background for such characteristics [7]. The landscape–hydrological background is presented by static characteristics. The landscape–hydrological

background consists of three components: landscape climate (climate–hydrological background), landscape pedology (soil–hydrological background) and landscape topography (topo–hydrological background). This conclusion is in line with those of others, including [11], who state that hydrologic landscape units should include descriptors of a land-surface form (slope and area), geologic framework (hydraulic properties of geologic units) and climatic setting (in their case, precipitation minus the evapotranspiration balance). The landscape–hydrological background analysis has some advantages over rainfall–runoff models: it allows the preventive assessment of hydrological situations, including critical ones. The paper will focus only on the climate–hydrological background, which is characterized by regional values of precipitation and evaporation.

For the analysis of the climatic–hydrological background, indicators that take into account the heat and moisture ratio (for example, some drought indices) can be used. The ratio of heat and moisture largely determines the magnitude of river runoff. Indices are typically computed numerical representations of atmospheric moisture, assessed using climatic or hydrometeorological inputs, including precipitation and temperature. Various indices are widely used to assess moisture availability [12]: Aridity Index (AI), Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), Selyaninov Hydrothermal Coefficient (HTC), Standardized Precipitation Evapotranspiration Index (SPEI), and Surface Water Supply Index (SWSI).

Maps are indispensable tools that visually represent spatial data and relationships. Isoline maps are traditionally used to classify regions based on climate data. Different interpolation techniques are used for mapping, including nearest neighbor, inverse distance weighted, and kriging [13–19]. Nevertheless, all methods reveal some weaknesses when the weather stations are not densely or evenly distributed or when there is significant topographic variability in the study area [13,20,21].

The concept of landscape provides great opportunities to eliminate these shortcomings. The landscape idea differs in different parts of the world. One of the central aims of landscape theory is to elucidate the impact of landscape structure on ecological processes [22,23]. Streamflow is a combined response of many hydrological processes that includes meteorological forcing (precipitation and temperature), morphological characteristics of the landscapes (slope, elevation), geological attributes of the underground system, and anthropogenic activities [4,24]. Discretization and delineation of landscapes as hydrologically similar units generally involves multiple and opposing considerations [25,26]. Traditionally, features are identified from field measurements and the field mapping of landscape features such as soil, geology, slope, and hydrological processes [25,27].

The landscape units can be different sizes depending on the scale and objectives of the study. The certain characteristics of topography and climate are accepted as homogeneous for units at each level of the landscape hierarchy. In this case, extrapolation is used to project values into an area that is not known.

Extrapolation is a special case of environmental correlation [28–30]. This is spatial prediction from polygon maps, i.e., stratified areas (different land use/cover types, geological units). The results of point observations can be generalized and extrapolated to the area of the entire landscape contour. They may then be extrapolated to the entire landscape type after a selective check of the identity of the indicators in other similar contours [31,32].

The scale of the landscape map should correspond to the scale of changes in the space of indicators that characterize a given phenomenon. The values of the moisture and drought indices can be assumed to be the same within landscapes when mapping at the mesoscale—1:500,000–1:1,500,000 [33].

Research examining the relationship between landscapes and moisture indices remains limited [33]. We hope that our study results can contribute to overcoming the lack of ground-

based hydrological and meteorological data, and that the idea of a climate–hydrological background will help fill gaps in the assessment of hydrological situations, including critical ones.

2. Materials and Methods

2.1. Study Area

The East Kazakhstan region (EKR) occupies an area of 97.8 thousand square kilometers. Foothill and mountain terrain predominate in the EKR [34]. The elevation of relief is observed to be within 250–500 m, mainly in the western part of the EKR, reaching 4500 m in the eastern part (Figure 2).

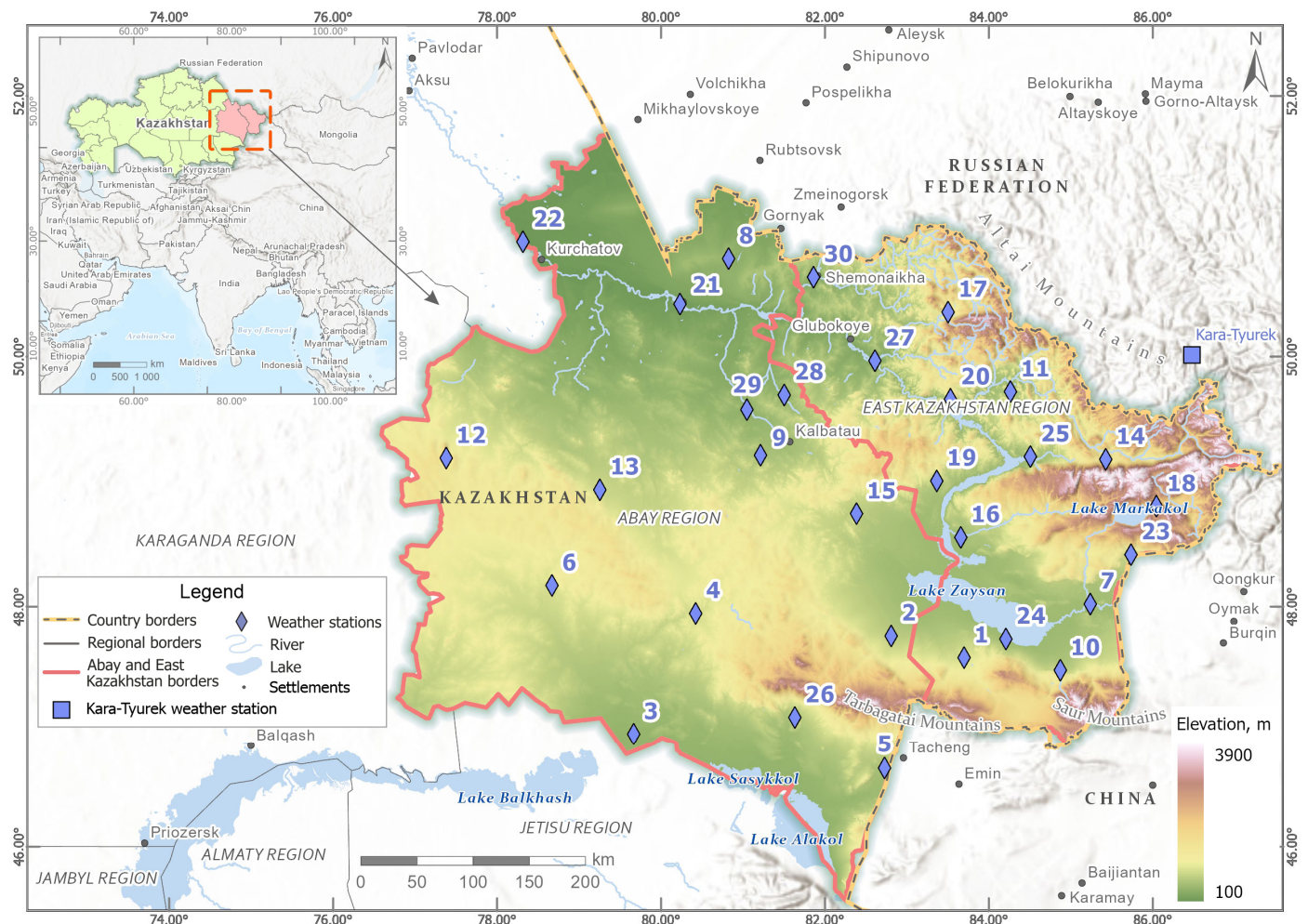


Figure 2. Geographic location of the study area.

The Altai Mountains and their foothills occupy most of the EKR. The Kazakh Altai is divided into several main mountain ranges. The relief of the Altai was shaped by the Quaternary glaciations accompanied by intensive fluvial erosion and gravity slope processes, particularly active in the mountain valleys, with the best-preserved landforms dating to the last glacial stage [34]. The Saur and Tarbagatay Ranges are located in the southern part of the region and provide the communication between the Altai and Tian-Shan Mountains [35]. These ranges are separated from the Altai by the Zaisan Depression. The western part of the EKR is occupied by the Kalbinsky Range, which is a continuation of the Altai Mountains.

The present climate is typically continental, and this is caused by large differences in air temperatures during seasons characterized by cold and long winters and hot summers due to the geographical location in the center of Eurasia. Precipitation increases on the north-western Altai slopes exposed to the Atlantic atmospheric streams. The present snowline lies at 2300 m in the humid western Altai and at 2600–3500 m in the southern Altai, with forest limits at 2100–2400 m above sea level. The increased winter aridity contributes through deep ground freezing to the formation of insular mountain permafrost. At present, isolated corrie glaciers in elevations over 2500 m above sea level persist on the northern exposures of the Naryn Range and the Southern Altai Mountains [34].

The EKR is mainly represented by steppe and semidesert foothill landscapes, forest-steppe, forest, alpine, and nival mountain landscapes [36].

2.2. Data

The dataset was obtained from 30 weather stations managed by the National Hydrometeorological Service of the Republican State Enterprise (RSE) “Kazhydromet” (16 stations from the East Kazakhstan region and 14 from the Abay region). The primary variables included (1) average daily temperature (°C) and (2) daily precipitation (mm). Data were taken from 1961 to 2023. However, some stations had shorter periods of record and gaps due to later installation dates and non-operational years. Table 1 presents the periods for each station that were used in the calculations.

Table 1. Overview of calculation periods and excluded years for meteorological stations.

No.	Weather Station	Calculation Periods	Missing Years
1	Akzhar	1962–2023	1961
2	Aksuat	1961–2023	
3	Aktogay	1962–2023	1961
4	Ayagoz	1961–2023	
5	Bakty	1961–2023	
6	Barshatas	1961–2023	
7	Boran	2022–2023	
8	Dmitrievka	1961–1994, 1996–2023	1995
9	Zhalgyztobe	1961–2023	
10	Zaisan	1961–2023	
11	Zyryanovsk	1961–1986, 2009–2023	
12	Kainar	1961–2023	
13	Karauyl	1961–2023	
14	Katon-Karagay	1961–2023	
15	Kokpekty	1961–1974, 1976–2023	1975
16	Kurshim	1961–2023	
17	Leninogorsk	1961–2023	
18	Markakol Zapovednik	1983–2023	
19	Samarka	1961–2023	
20	Seleznyevka	1968–2023	1967
21	Semipalatinsk	1961–2023	
22	Semiyarka	1961–2023	
23	Terekti	1972–2023	1971
24	Tugyl	1961–2023	
25	Ulken Naryn	1961–2023	
26	Urjar, CAMS	1961–2023	
27	Ust-Kamenogorsk	2008–2023	
28	Shalabay	1961–1974, 1976–2023	1975
29	Shar	1961–2023	
30	Shemonaikha	1961–2023	

There are no high-mountain weather stations in the EKR, but high-mountain landscapes with specific moisture conditions occupy a significant area. Therefore, humidity was estimated from the Kara-Tyurek weather station data [37,38]. This weather station is located in the Russian part of the Katunsky Range, in close proximity to the border with Kazakhstan, at an altitude of 2596 m above sea level.

Three sources were used to create the landscape map for the EKR. They are the landscape map of the USSR [39], landscape map of Kazakhstan [36], and landscape map of the Altai–Khangai–Sayan region [40].

2.3. Methods

The Selyaninov Hydro-thermal Coefficient (HTC) and the Vysotsky–Ivanov Moisture Coefficient (VMC) were used in this study for the following reasons. The HTC is flexible enough, sensitive to dry conditions specific to the continental climates and used for identifying droughts during the active vegetation period and in international climate classifications [12]. The VMC allows us to trace landscape moisture over the annual period and has a significant history of application in the post-Soviet space.

Initially, the dataset was examined for missing entries and anomalies to ensure data accuracy. Years in which significant data gaps were identified—such as missing measurements for consecutive multiple months or key variables—were excluded from the analysis (Table 1). This incompleteness is likely because many of these years correspond to the initial installation periods at the respective stations.

After resolving the data quality issues, the HTC and the VMC were computed for each remaining year and station using a Python script (version 3.9.21) in the Jupyter Notebook environment (version 4.2.5), using the respective formulas (Equations (1) and (2)). In the present study, moisture availability for the summer was assessed via the HTC and for the year via the VMC.

The HTC is defined as the ratio of precipitation to temperature during the vegetative period, divided by 10, giving a figure that characterizes evaporation quite well [41]. It characterizes only wetness, without considering stored soil moisture [42].

$$\text{HTC} = \frac{\sum R_{5-9}}{0.1 \sum T_{5-9}}, \quad (1)$$

where $\sum R_{5-9}$ is the sum of precipitation for May–September, and $\sum T_{5-9}$ is the sum of daily air temperatures above 10 °C for May–September.

The VMC is defined as the ratio of the annual precipitation to the annual evaporation [43,44].

$$\text{VMC} = R_y / E_y, \quad (2)$$

where R_y is the sum of precipitation for year, and E_y is evaporation for year.

The climate normals of the HTC and the VMC for 1961–1990 and 1981–2010 periods were calculated for each weather station. Climate normals are typically defined as 30-year averages of meteorological conditions such as air temperature and precipitation [45]. They are arguably the most fundamental attributes of the climate of a given locale. As a measure of central tendency, climate normals characterize the background state. We used data averaged over the 1961–1990 and 1981–2010 periods as a climatic norm. Finally, we calculated values of the HTC and the VMC for the most recent period (2011–2023). For each of the selected periods, the mean value was computed.

The evaluation criteria gradations via the HTC and the VMC (Table 2) were adapted for the conditions of the EKR based on data presented in earlier works [12,46–49].

Table 2. Criteria for assessing the Selyaninov Hydro-thermal Coefficient and the Vysotsky–Ivanov Moisture Coefficient.

Climate	HTC	VMC
Extra humid	1.40 and more	1.56 and more
Severely humid	1.20–1.39	1.33–1.55
Moderately humid	1.00–1.19	1.00–1.32
Slightly humid	0.8–0.99	0.78–0.99
Slightly arid	0.60–0.79	0.56–0.77
Moderately arid	0.40–0.59	0.33–0.55
Severely arid	0.20–0.39	0.12–0.32
Extra arid	0.00–0.19	0.00–0.12

Because the HTC and VMC reflect the humidification during the warm period and over the year as a whole, respectively, the calculation of the correlation between the two indices for different periods was made. The Shapiro–Wilk test was used to check whether a given dataset follows a normal distribution ($\alpha = 0.05$). Because portions of the dataset were non-normally distributed, both the Pearson and Spearman correlation coefficients were applied. Linear associations were assessed using the Pearson correlation coefficient, whereas monotonic trends were evaluated with the Spearman correlation coefficients, a rank-based, outlier-resistant statistic that may overlook non-monotonic patterns.

The following thresholds for the absolute value of the correlation coefficient were used to describe the strength of the relationship between variables [50]:

- 0.00–0.09—negligible correlation;
- 0.10–0.39—weak correlation;
- 0.40–0.69—moderate correlation;
- 0.70–0.89—strong correlation;
- 0.90–1.00—very strong correlation.

The following libraries were used: NumPy (version 2.0.1) and Pandas (version 2.2.3) for data processing and SciPy (version 1.13.1) for statistical testing and correlation analysis.

Maps of the spatial distribution of HTC and VMC values were made for the periods 1961–1990, 1981–2010, and 2011–2023. Finally, a map was prepared, taking into account the extreme (highest) values of HTC and VMC for each weather station based on observational data for 1961–2023.

Several interpolation and extrapolation methods have been used to construct maps: Inverse Distance Weighting (IDW), Spline and Empirical Bayesian Kriging (EBK). IDW is a deterministic interpolation method that estimates the value of a variable at an unmeasured location based on the values of the nearest measured points. The principle behind IDW is that points closer to the target location have a greater influence on the estimated value than more distant points. The spline interpolation method is a technique used to create smooth curves that pass through given data points. Splines are typically piecewise polynomials that provide continuity and smoothness at the boundaries between segments. Empirical Bayesian Kriging (EBK) is a spatial interpolation method that combines the principles of Bayesian statistics and classical kriging. Unlike traditional kriging, which is based on the assumption of stationarity of the process, EBK allows for uncertainty in model parameters by using empirical data to estimate a priori distributions. This makes the method more robust and flexible to changes in the data [51,52]. The process of data interpolation and subsequent analyses were performed in ESRI ArcGIS Pro 3.3, Geostatistical Analyst module. The landscape map was used as the basis for extrapolation. Calculated data of point observations (weather stations) were extended to map polygons according to landscape classification.

3. Results and Discussion

3.1. HTC and VMC Values for Weather Stations in the Region

Over the observation period, the range of HTC values at weather stations of the region fluctuate within a wide range (Table 3)—from near 0 to 2.31 (1993, Leninogorsk). During the same time, the values of the VMC varied from 0 to 1.76 (2023, Markakol Zapovednik). Thus, both coefficients are in the range from extra arid to extra humid climate.

Table 3. Selyaninov Hydro-thermal Coefficient and Vysotsky–Ivanov Moisture Coefficient values for weather stations in the region.

Weather Station	HTC					VMC				
	1961–1990	1981–2010	2011–2023	Year/Max		1961–1990	1981–2010	2011–2023	Year/Max	
Akzhar	0.43	0.45	0.36	1992	0.88	0.29	0.27	0.23	1966	0.54
Aksuat	0.39	0.42	0.39	1992	0.84	0.23	0.23	0.22	2013	0.36
Aktogay	0.22	0.23	0.21	2003	0.54	0.19	0.18	0.19	2003	0.31
Ayagoz	0.48	0.45	0.53	2016	1.10	0.39	0.34	0.36	1972	0.62
Bakty	0.34	0.37	0.40	2013	0.79	0.28	0.30	0.29	1993	0.48
Barshatas	0.34	0.34	0.39	2009	0.76	0.24	0.23	0.24	1993	0.38
Boran	–	–	0.27	2023	0.35	–	–	0.22	2023	0.29
Dmitrievka	0.61	0.61	0.63	1993	1.13	0.41	0.39	0.44	1993	0.57
Zhalgyztobe	0.50	0.52	0.51	1990	1.00	0.36	0.34	0.33	1966	0.52
Zaisan	0.52	0.55	0.44	1992	1.03	0.33	0.34	0.30	1969	0.55
Zyryanovsk	1.00	1.08	1.08	2009	1.83	0.82	0.85	0.90	2015	1.15
Kainar	0.58	0.57	0.58	2016	1.07	0.35	0.32	0.29	2016	0.50
Karauyl	0.48	0.45	0.51	1967	0.84	0.30	0.27	0.28	1976	0.45
Katon-Karagay	0.95	0.99	0.96	1969	1.91	0.68	0.67	0.64	1969	1.05
Kokpekty	0.47	0.46	0.48	1990	0.95	0.42	0.38	0.39	1966	0.66
Kurshim	0.39	0.39	0.37	1988	0.91	0.29	0.28	0.28	1966	0.45
Leninogorsk	1.37	1.40	1.13	1993	2.31	0.97	0.94	0.87	1992	1.35
Markakol Zapovednik	1.07	1.14	1.29	2013	1.92	1.27	1.15	1.20	2023	1.76
Samarka	0.62	0.58	0.62	1972	1.12	0.45	0.42	0.44	1966	0.8
Seleznyevka	0.74	0.75	0.77	1992	1.49	0.48	0.48	0.50	2009	0.71
Semipalatinsk	0.48	0.49	0.51	1993	1.02	0.32	0.31	0.36	2016	0.52
Semiyarka	0.41	0.41	0.43	2014	0.74	0.25	0.23	0.26	2018	0.45
Terekti	0.45	0.50	0.58	1988	1.09	0.35	0.39	0.44	1971	1.32
Tugyl	0.32	0.33	0.32	2013	0.63	0.21	0.22	0.21	2010	0.35
Ulken Naryn	0.71	0.76	0.74	1992	1.37	0.44	0.46	0.47	1992	0.67
Urjar, CAMS	0.48	0.46	0.51	2016	0.84	0.47	0.45	0.48	1972	0.77
Ust-Kamenogorsk	–	0.81	0.80	2016	1.39	–	0.58	0.55	2009	0.81
Shalabay	0.54	0.57	0.56	1995	1.13	0.39	0.38	0.41	1972	0.53
Shar	0.50	0.49	0.56	1990	1.05	0.35	0.33	0.37	1990	0.48
Shemonaikha	0.75	0.73	0.72	2002	1.35	0.64	0.56	0.57	1976	0.87

According to HTC values, most of the weather stations are characterized by the moderately arid (13 stations), severely arid (7), and slightly arid climate (5). Two stations are located in the slightly humid climate, two stations in moderately humid climates, and one station (Markakol Zapovednik) in the severely humid climate.

The situation is somewhat different according to VMC values, although most of the weather stations also belong to the moderately arid climate (13 stations). There are 12 stations classified as severely arid, 2 stations each as slightly arid and slightly humid, and 1 station as moderately humid (Markakol Zapovednik).

A climate shift toward greater aridity, as indicated by the VMC, is connected with the fact that at all weather stations most precipitation falls in the warm period of the year, which is typical of continental regions. The HTC is responsible for humidification in the warm period, as it is known. This assumption confirms the conclusion made at the end of the 20th century: the fundamental watershed functions (collection of water, storage, and discharge of water as runoff) are not necessarily exhibited with equal power all at the same time [53].

There are no pronounced trends in the values of either moisture index at any weather station while the observation period is quite long. Likewise, for the territory of the Republic of Bashkortostan [54] and for the Western Part of the Altai Territory [55] (Russia), when comparing the changes in the HTC and VMC for the different periods, it was revealed that their trends are multidirectional. Also, there are no differences in the average values of moisture indices among the 1961–1990 and 1981–2010 climate normals, and the modern period (2011–2023), for most weather stations.

3.2. Correlation Analysis

The p -values derived from the Shapiro–Wilk test confirmed that most relationships between the HTC and the VMC are statistically significant at the 95% confidence level ($p < 0.05$). The correlation analyses between the HTC and the VMC are shown in Table 4. They clearly show strong positive correlations between indices for most weather stations. The moderate correlations between the indices in the modern period (2011–2023) are characteristic of few stations only. It is significant that most of these weather stations (Zaisan, Zyryanovsk, Ulken Naryn, Leninogorsk, Markakol Zapovednik, and Terekti) are located either in the Altai Mountains or at the Altai foothills. It should also be noted that the correlation coefficients between the HTC and the VMC are slightly lower in the modern period (2011–2023) than for the 1961–1999 and 1981–2010 climate normals. Only the correlation between the HTC and the VMC for the Markakol Zapovednik weather station in the 1981–2010 period was found to be weakly positive, with a coefficient of 0.18. There are no earlier data available for this weather station. On the other hand, the correlation coefficients for the Markakol Zapovednik weather station in 2011–2023 turned out to be higher.

Table 4. Pearson (r_p) and Spearman (r_s) correlation coefficients between the Selyaninov Hydro-thermal Coefficient and the Vysotsky–Ivanov Moisture Coefficient, including Shapiro–Wilk normality test p -values (p_{SW}), for different periods across weather stations.

Weather Station	1961–1990				1981–2010				2011–2023			
	p_{SW} (HTC)	p_{SW} (VMC)	r_p	r_s	p_{SW} (HTC)	p_{SW} (VMC)	r_p	r_s	p_{SW} (HTC)	p_{SW} (VMC)	r_p	r_s
Akzhar	0.12	0.66	0.78	0.83	0.16	0.86	0.84	0.83	0.00	0.09	0.95	0.84
Aksuat	0.25	0.37	0.81	0.83	0.06	0.47	0.84	0.87	0.01	0.05	0.93	0.84
Aktogay	0.42	0.63	0.65	0.63	0.03	0.88	0.78	0.73	0.60	0.34	0.78	0.71
Ayagoz	0.02	0.17	0.79	0.60	0.00	0.25	0.78	0.59	0.30	0.65	0.91	0.88
Bakty	0.64	0.15	0.72	0.69	0.00	0.25	0.60	0.50	0.14	0.20	0.81	0.65
Barshatas	0.75	0.74	0.84	0.84	0.10	0.10	0.91	0.86	0.08	0.02	0.82	0.59
Boran			–	–			–	–			–	–
Dmitrievka	0.61	0.39	0.71	0.64	0.81	0.95	0.86	0.79	0.90	0.48	0.84	0.79
Zhalgyztobe	0.09	0.85	0.73	0.77	0.12	0.86	0.74	0.74	0.18	0.99	0.90	0.84
Zaisan	0.03	0.76	0.86	0.84	0.07	0.21	0.84	0.76	0.09	0.25	0.67	0.62
Zyryanovsk	0.59	0.90	0.74	0.72	0.13	0.81	0.75	0.74	0.03	0.13	0.69	0.65
Kainar	0.19	0.03	0.77	0.67	0.75	0.13	0.82	0.82	0.27	0.58	0.95	0.88

Table 4. Cont.

Weather Station	1961–1990				1981–2010				2011–2023			
	p_{SW} (HTC)	p_{SW} (VMC)	r_p	r_s	p_{SW} (HTC)	p_{SW} (VMC)	r_p	r_s	p_{SW} (HTC)	p_{SW} (VMC)	r_p	r_s
Karauyl	0.30	0.72	0.85	0.76	0.68	0.95	0.81	0.82	0.17	0.43	0.65	0.67
Katon-Karagay	0.09	0.06	0.85	0.82	0.25	0.98	0.85	0.86	0.10	0.99	0.84	0.78
Kokpekty	0.79	1.00	0.70	0.75	0.01	0.12	0.83	0.81	0.04	0.18	0.84	0.82
Kurshim	0.02	0.36	0.74	0.76	0.00	0.18	0.78	0.72	0.36	0.86	0.77	0.70
Leninogorsk	0.65	0.57	0.76	0.74	0.20	0.67	0.93	0.87	0.46	0.60	0.65	0.58
Markakol	0.68	0.62	–	–	0.51	0.64	0.18	0.18	0.37	0.62	0.67	0.74
Zapovednik	0.29	0.37	0.78	0.83	0.58	0.39	0.81	0.79	0.65	0.72	0.74	0.70
Samarka	0.64	0.23	0.82	0.84	0.07	0.40	0.79	0.79	0.35	0.09	0.75	0.74
Semipalatinsk	0.01	0.58	0.81	0.78	0.09	0.94	0.85	0.78	0.35	0.99	0.95	0.87
Semiyarka	0.02	0.47	0.81	0.81	0.31	0.58	0.86	0.88	0.11	0.15	0.87	0.90
Terekti	0.03	0.06	0.87	0.85	0.17	0.70	0.73	0.65	0.90	0.44	0.68	0.60
Tugyl	0.05	0.64	0.73	0.77	0.13	0.75	0.71	0.70	0.06	0.64	0.85	0.79
Ulken Naryn	0.33	0.50	0.81	0.75	0.90	0.79	0.87	0.84	0.33	0.20	0.74	0.59
Urjar, CAMS	0.47	0.21	0.70	0.69	0.23	0.30	0.78	0.78	0.07	0.12	0.75	0.72
Ust-Kamenogorsk			–	–	0.75	0.72	–	–	0.24	0.15	0.85	0.71
Shalabay	0.85	0.19	0.85	0.86	0.11	0.08	0.85	0.90	0.82	0.47	0.70	0.75
Shar	0.03	0.50	0.84	0.87	0.19	0.84	0.81	0.79	0.99	0.36	0.81	0.76
Shemonaikha	0.85	0.88	0.73	0.66	0.40	0.96	0.70	0.72	0.27	0.47	0.88	0.74

Thus, since the correlation coefficients between the HTC and the VMC were strong in most cases, it suggests that both indices can be used for climate–hydrological background assessment. For reliability, it is best to use the HTC and the VMC together.

3.3. Data Visualizations Produced by Different Interpolation Methods

Figures 3 and 4 and Tables 5 and 6 present spatial distributions of the HTC and the VMC in the EKR and the Abay region. In tables, only the results of indices calculations for the EKR are shown.

Table 5. Areas with different Selyaninov Hydro-thermal Coefficient values in the East Kazakhstan region, calculated based on different interpolation methods.

Climate		1961–1990			1981–2010			2011–2023		
		IDW	Spline	EBK	IDW	Spline	EBK	IDW	Spline	EBK
1	Extra arid (0.00–0.19)									
2	Severely arid (0.2–0.39)	1687.78	16,076.04	251.27	1173.98	13,830.04		11,464.97	20,210.92	18,389.67
3	Moderately arid (0.4–0.59)	31,672.60	22,248.84	34,555.82	29,863.51	22,534.20	34,064.85	20,836.89	17,812.28	16,952.81
4	Slightly arid (0.6–0.79)	27,785.18	21,151.28	21,690.90	26,594.01	21,768.24	20,846.04	27,321.66	20,412.76	21,163.72
5	Slightly humid (0.8–0.99)	26,396.14	10,185.64	17,694.13	26,238.80	9765.92	15,239.09	28,122.05	11,753.40	15,363.94
6	Moderately humid (1.00–1.19)	6371.80	8863.16	16,823.98	9950.96	8300.76	15,825.48	7767.66	10,202.72	17,092.02
7	Severely humid (1.2–1.39)	2205.63	8472.88	5103.02	2297.87	8423.44	10,132.37	605.90	8729.20	6225.94
8	Extra humid (>1.4)		9120.80			11,496.04	11.30		6997.36	931.03

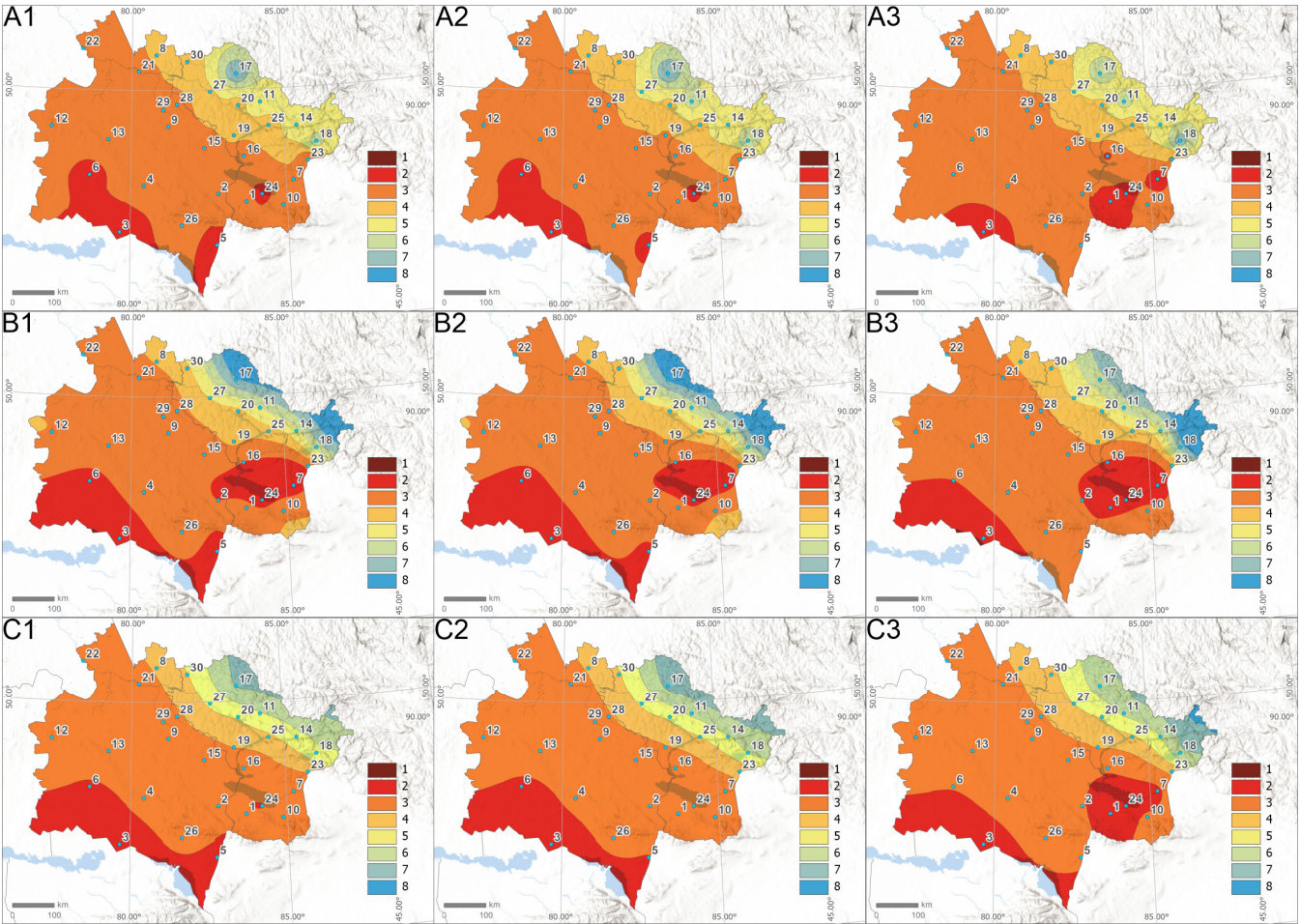


Figure 3. Selyaninov Hydro-thermal Coefficient produced by interpolated values at weather stations ((**A1**)—Inverse Distance Weighting, 1961–1990; (**A2**)—Inverse Distance Weighting, 1981–2010; (**A3**)—Inverse Distance Weighting, 2011–2023; (**B1**)—Spline, 1961–1990; (**B2**)—Spline, 1981–2010; (**B3**)—Spline, 2011–2023; (**C1**)—Empirical Bayesian Kriging, 1961–1990; (**C2**)—Empirical Bayesian Kriging, 1981–2010; (**C3**)—Empirical Bayesian Kriging, 2011–2023). Aridity classes: 1—extra arid; 2—severely arid; 3—moderately arid; 4—slightly arid; 5—slightly humid; 6—moderately humid; 7—severely humid; 8—extra humid.

Table 6. Areas with different Vysotsky–Ivanov Moisture Coefficient values in the East Kazakhstan region, calculated based on different interpolation methods.

Climate		1961–1990			1981–2010			2011–2023		
		IDW	Spline	EBK	IDW	Spline	EBK	IDW	Spline	EBK
1	Extra arid (0.00–0.12)		2961.60							
2	Severely arid (0.13–0.32)	13,362.51	25,567.24	7583.96	13,485.02	27,963.92	9858.20	22,845.95	30,181.92	17,993.81
3	Moderately arid (0.3–0.55)	41,455.66	28,783.88	40,725.32	41,752.81	29,762.84	41,300.26	32,941.13	27,575.48	33,415.87
4	Slightly arid (0.56–0.77)	27,251.39	12,222.16	35,284.97	30,142.97	12,573.04	29,564.50	30,379.64	13,361.36	28,130.95
5	Slightly humid (0.78–0.99)	12,060.56	9446.48	12,524.87	9624.43	9987.44	15,391.98	8610.61	10,277.84	16,115.34
6	Moderately humid (1.00–1.32)	1989.02	10,139.64		1113.90	10,005.00	4.20	1341.81	8545.64	463.16
7	Severely humid (1.32–1.55)		1955.72			2367.40			2278.72	
8	Extra humid (>1.56)		5041.92			3459.00			3897.68	

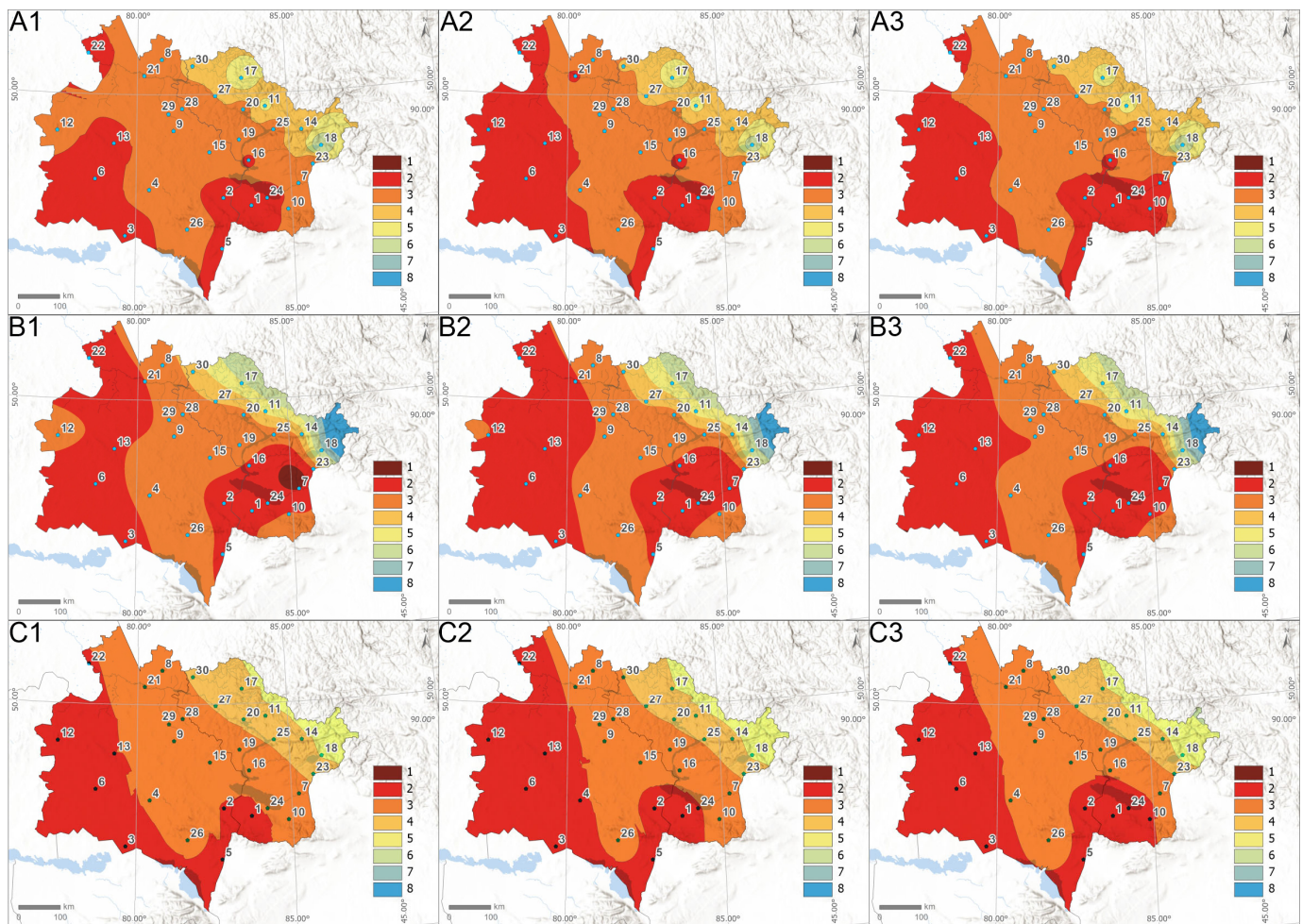


Figure 4. Vysotsky–Ivanov Moisture Coefficient produced by interpolated values at weather stations ((A1)—Inverse Distance Weighting, 1961–1990; (A2)—Inverse Distance Weighting, 1981–2010; (A3)—Inverse Distance Weighting, 2011–2023; (B1)—Spline, 1961–1990; (B2)—Spline, 1981–2010; (B3)—Spline, 2011–2023; (C1)—Empirical Bayesian Kriging, 1961–1990; (C2)—Empirical Bayesian Kriging, 1981–2010; (C3)—Empirical Bayesian Kriging, 2011–2023). Aridity classes: 1—extra arid; 2—severely arid; 3—moderately arid; 4—slightly arid; 5—slightly humid; 6—moderately humid; 7—severely humid; 8—extra humid.

Maps based on VMC values depict a more arid situation than maps based on the HTC when using all interpolation methods. This, as mentioned earlier, is due to the majority of precipitation falling in the warm period of the year. This is more typical for the Abay region, which has lower absolute heights. Similar results were obtained earlier for the Caspian lowland [56] and for the Republic of Kalmykia [57]. For the mountainous EKR, the contrasts are not so significant. At the same time, the territories with values of the moisture indices close to 1 within the EKR (slightly arid and slightly humid) occupy similar areas. The contrasts increase as the values of the moisture indices move away from 1 in both directions.

The situation will be different if we visualize the data of the maximum values of moisture indices ever recorded at weather stations (Figure 5). According to the HTC maximum values, about 60% of the EKR areas are potentially extra humid or severely humid. The maps constructed based on the maximum VMC values show that only the Altai Mountains are extra humid or severely humid.

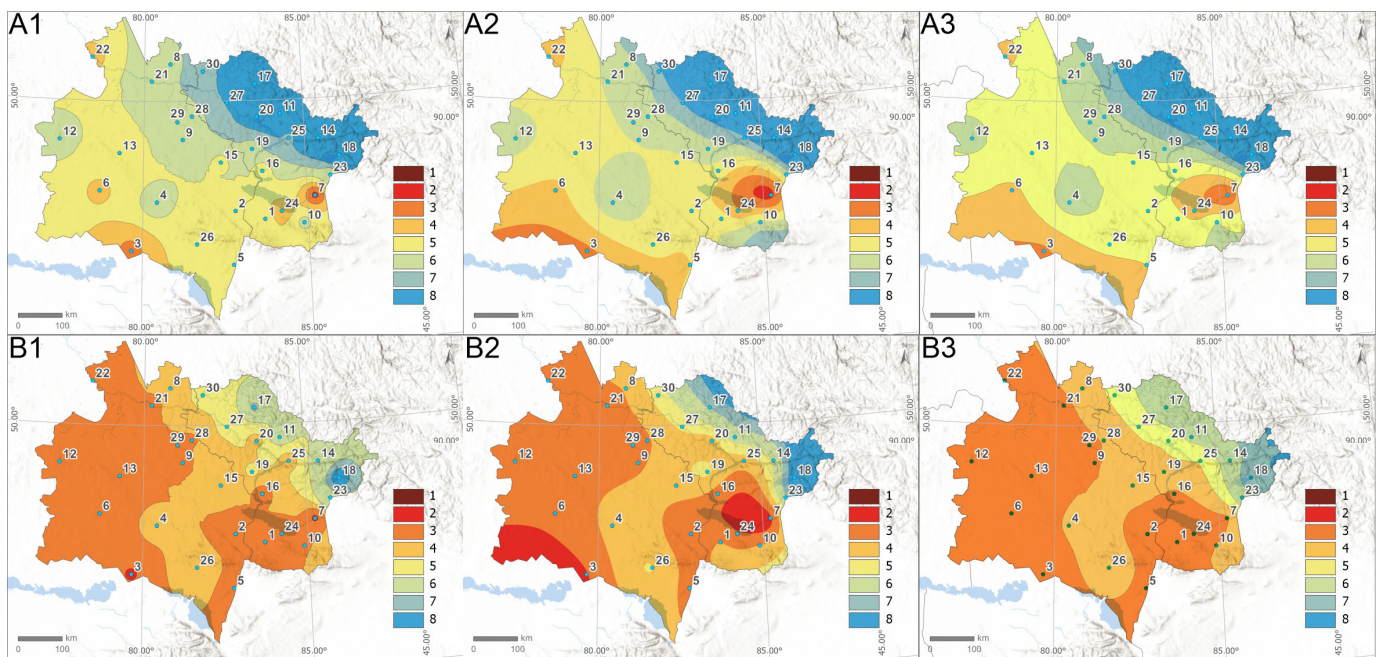


Figure 5. Spatial distribution of moisture indices produced by interpolating maximum values from the weather stations for the entire observation period ((A1)—Inverse Distance Weighting, 1961–1990; (A2)—Inverse Distance Weighting, 1981–2010; (A3)—Inverse Distance Weighting, 2011–2023; (B1)—Spline, 1961–1990; (B2)—Spline, 1981–2010; (B3)—Spline, 2011–2023). Aridity classes: 1—extra arid; 2—severely arid; 3—moderately arid; 4—slightly arid; 5—slightly humid; 6—moderately humid; 7—severely humid; 8—extra humid.

3.4. Data Visualization via Spatial Extrapolation

The landscapes of the EKR are represented by nine altitudinal-belt groups (from top to bottom): glacial–nival, alpine, subalpine, taiga, subtaiga, forest–steppe, steppe, dry–steppe, and semi-desert. The first three groups are united by moisture conditions and are characterized by an extra humid climate. Taiga landscapes correspond to a severely humid climate, subtaiga landscapes to moderately humid, forest–steppe to slightly humid, steppe to slightly arid, dry–steppe to moderately arid, and semi-desert to severely arid. There are no desert landscapes with an extra arid climate in the EKR.

Six types of landscapes are provided with meteorological observation data. Only the highlands of the Altai Mountains with extra humid climate remain underserved by meteorological data. However, analysis of data from the Kara-Tyurek weather station, which is located in the Russian part of the Katunsky Range near the border with Kazakhstan, allows us to fill the gap. The Kara-Tyurek weather station is located at 2596 m a.s.l., and observations have been conducted there since 1940. The annual precipitation at Kara-Tyurek for the climatic normal of 1961–1990 is 582 mm per year (of which 476 mm falls during the warm period), and for the period 1991–2020 it is 593 mm. The value of the VMC in Kara-Tyurek is about 1.5 [37,38], i.e., significantly higher than at all weather stations in the EKR (Table 3). This value of the VMC and the corresponding value of the HTC can be adopted for high-mountain landscapes of the EKR. If we extrapolate this value to high-mountain landscapes, the spatial distribution of indices will have the following form (Figure 6).

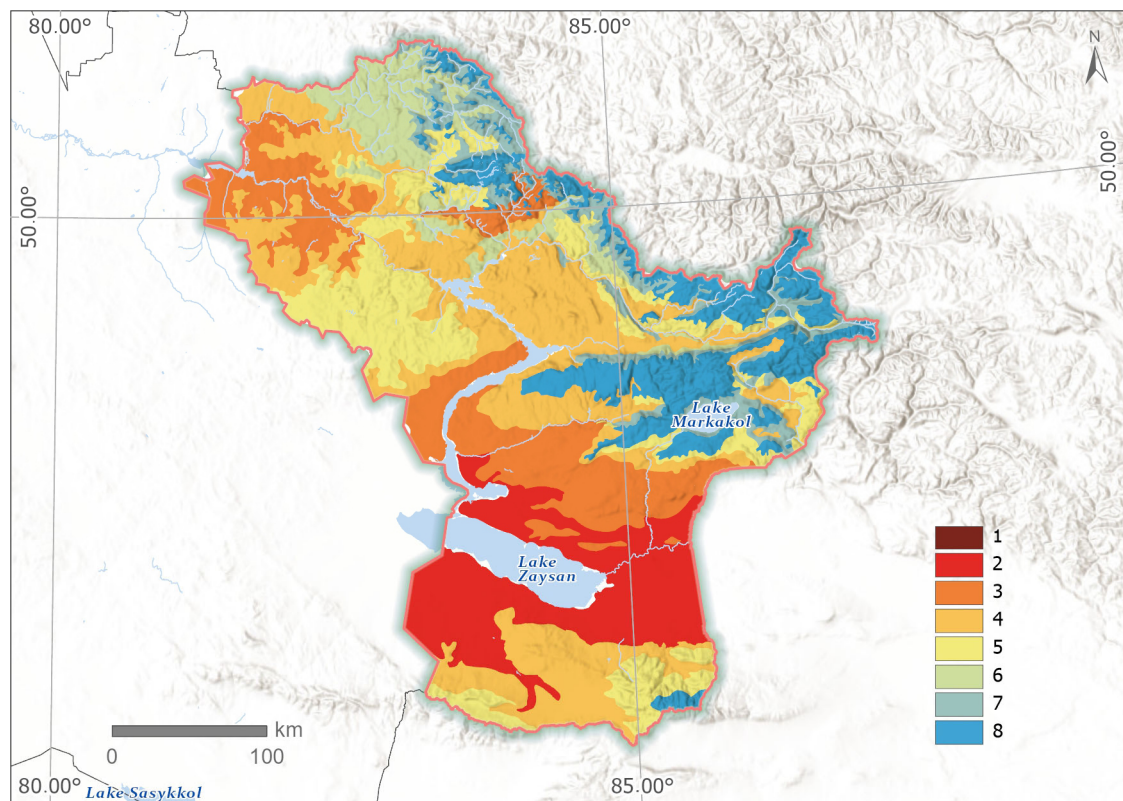


Figure 6. Aridity classes of modern landscapes in the East Kazakhstan region. Aridity classes: 1—extra arid; 2—severely arid; 3—moderately arid; 4—slightly arid; 5—slightly humid; 6—moderately humid; 7—severely humid; 8—extra humid.

Thus, the largest area in the East Kazakhstan region is occupied by landscapes with a moderately humid climate—approximately 27.6% (Table 7). The landscapes of other groups are less frequently represented. However, extra humid and severely humid landscapes in total occupy about 20% of the EKR. These landscapes provide the maximum water runoff into the rivers of the region. The magnitude of the spring flood, including its critical levels, is determined mainly by the snow water equivalent in the Altai Mountains. Altai landscapes, situated at higher altitudes, experience prolonged snow accumulation due to the colder prevailing temperatures and favorable topographic conditions. Other mountainous areas, including the Saur, Tarbagatay, and Kalbinsky Ranges, are less humid. Saur and Tarbagatay are located to the south, in the desert zone, and the Kalbinsky Range has lower altitudes. On the other hand, floods in the summer–autumn low-water period can occur throughout almost the entire territory of the EKR and are associated with local precipitation.

Table 7. The areas of landscapes with different climates in the East Kazakhstan region according to extrapolation to the landscape map.

No.	Climate	km ²	%
1	Extra arid	0	0
2	Severely arid	12,802.49	14.04
3	Moderately arid	15,276.22	16.75
4	Slightly arid	25,164.64	27.60
5	Slightly humid	13,899.57	15.24
6	Moderately humid	6016.33	6.60
7	Severely humid	5724.27	6.28
8	Extra humid	12,304.98	13.49

As it is known, there are advantages and disadvantages to both extrapolation and interpolation. The spatial interpolation method achieves the best estimation when a network of meteorological stations exists. Spatial extrapolation in some cases may be more accurate than interpolation, for example, if the trends in the data are clear and continue in a predictable way [58]. This is especially true for areas with a dissected relief. The restricted number of weather stations in mountainous areas increases uncertainty [59]. In the most reliable extrapolations, response variables tend to be closely associated with environmental features [30], which can be accurately described using a landscape map, for example. In our case it can be assumed that landscape extrapolation more accurately conveys the spatial distribution of the moisture indices values than different interpolation methods. This is especially true for areas with a dissected relief. Thus, the spatial distribution highlights the critical role of elevation and geographic positioning in determining the HTC and the VMC.

4. Conclusions

This study underscores the pressing need for region-specific adaptation strategies for extreme hydrological situations. Plans to manage surface water flood risk based on runoff modeling are insufficient. The lack of data and the heterogeneity in the available datasets often lead to uncertainties in model predictions. One of the most important adaptation mechanisms is the preventive assessment of the hydrological functions of landscapes. The landscape physiographic and climatic characteristics can predetermine its hydrological behavior. The changes in landscape attributes must inform decision-makers about changes in possible hydrological behavior.

Moisture indices are most often used to identify droughts. However, they are also suitable for characterizing the climate–hydrological background. The analysis of moisture indices demonstrates their effectiveness in climate–hydrological background assessment. Together, the Selyaninov Hydro-thermal Coefficient (HTC) and the Vysotsky–Ivanov Moisture Coefficient (VMC) provide a comprehensive understanding of the hydrological functions of landscapes.

The EKR is a typical continental arid and semi-arid region. However, the presence of mountain ranges, such as the Altai, makes the climate and environment in the region more varied. An increase in altitude above sea level leads to an increase in annual precipitation and a decrease in temperature. Ultimately, the overall moisture content of the area increases. The mountain rivers in the EKR have the maximum runoff and contribute to spring floods.

Based on meteorological data from 30 weather stations for 1961–2023, the values of the HTC and the VMC were established. Over the observation period, HTC values at weather stations of the region fluctuated within a wide range—from near 0 to 2.31—and the VMC varied from 0 to 1.76. Thus, both coefficients are in the range from extra arid to extra humid climates. These indices are of great importance for the preventive assessment of the hydrological situation in the region and for preparing population and authorities for extreme hydrological events.

Due to the sparse distribution of weather stations, the search for algorithms for interpreting spatial information holds great significance for regional studies in the EKR. Different techniques are used for spatial analysis and mapping of the climatic characteristics, including various interpolation methods. In this study three interpolation methods and landscape extrapolation were used to analyze the spatial distribution of HTC and VMC values. The landscape extrapolation is one of the most reliable extrapolations and more accurately conveys the spatial distribution of values of the moisture indices in the mountains than other interpolation methods.

The maps constructed based on the maximum HTC values show that about 60% of the EKR's area is potentially extra humid or severely humid. This means that high floods

can form there. More reliable recommendations for decision-makers will require using hydrological modeling in parallel with our results and monitoring.

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Data Availability Statement: Part of the data used in this study was obtained from RSE “Kazhydromet” upon request, while another part was sourced from publicly available records of RSE “Kazhydromet” (available at: <https://www.kazhydromet.kz/>, accessed on 17 April 2025). Additional data and materials may be provided upon written request to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Aridity Index
EBK	Empirical Bayesian Kriging
EKR	East Kazakhstan region
HTC	Selyaninov Hydro-thermal Coefficient
IDW	Inverse Distance Weighting
PDSI	Palmer Drought Severity Index
RSE	Republican State Enterprise
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SWSI	Surface Water Supply Index
VMC	Vysotsky–Ivanov Moisture Coefficient

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