

Article

Detection and Attribution of a Spatial Heterogeneity in the Temporal Evolution of Bulgarian River Discharge

Natalya A. Kilifarska ^{1,*} , Gergana I. Metodieva ^{1,2} and Antonia Ch. Mokreva ²

¹ Climate, Atmosphere and Waters Research Institute at Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria; antmokreva@gmail.com

² National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria; gerri7@abv.bg

* Correspondence: nkilifarska@cawri.bas.bg or natalyakilifarska@gmail.com

Abstract: The hydrosphere is an element of the climate system and changes in the latter are reasonably projected over the river outflow. Climatic changes, however, are unevenly distributed over the Earth, and understanding their regional imprint on the hydrosphere is of great importance. In this study, we have conducted a statistical analysis of the monthly maximum and minimum river discharge recorded in 22 hydrological stations located on 19 of the Bulgarian rivers during the period 1993–2022. We have found that in half of the river basins, the trend of the spring maximum discharge is significantly positive ($\alpha = 0.05$). In the other half of the stations, the trend is neutral. The stations with a positive trend are not randomly distributed but grouped, forming a pattern crossing the country from northwest to southeast. This pattern of trend distribution raises questions about the causes of the irregular hydrological response to the rising global near-surface temperatures. A comparison of hydrological data with some climatic variables (i.e., temperature, precipitation, and ozone at 70 hPa), combined with neural network analysis results, suggests ozone as a possible reason for the heterogeneous hydrological response. Its effect could be explained by an imposed episodic warming of the near-surface temperature due to fluctuations in the ozone density near the tropopause, which in turn favours the faster melting of ice and snow in the corresponding river basins.

Keywords: lower stratospheric ozone; river discharge; trend; surface temperature; precipitation



Academic Editor: Luca Mao

Received: 5 December 2024

Revised: 16 December 2024

Accepted: 1 January 2025

Published: 5 January 2025

Citation: Kilifarska, N.A.; Metodieva, G.I.; Mokreva, A.C. Detection and Attribution of a Spatial Heterogeneity in the Temporal Evolution of Bulgarian River Discharge. *Geosciences* **2025**, *15*, 12. <https://doi.org/10.3390/geosciences15010012>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

River discharge, which plays a key role in the hydrology of any river basin, is a product of surface–atmosphere interactions. The complexity of this material–energy exchange is usually related to the specific characteristics of the catchment (e.g., altitude, lithology, groundwater level, vegetation, human regulation of the land surface, etc.), as well as to the spatial-temporal variability of the atmosphere. Consequently, global warming is expected to affect the hydrology of river basins. For the Mediterranean and the Balkan Peninsula, the most advanced climate models predict a decrease in precipitation and drying. The reduced amount of precipitation should be clearly visible in river flows, as precipitation is one of the main sources of surface runoff. Thus, according to the water balance Equation (1), the variations in the amount of precipitation directly affect the river discharge,

$$P = Q + ET + \Delta S \quad (1)$$

where P in Equation (1) is atmospheric precipitation, Q is the water streamflow, ET is evapotranspiration, and ΔS is the change in the water storage (in soil, bedrock, or groundwater). On long time scales (e.g., 5–10 years) ΔS is assumed to be zero.

On the other hand, in addition to precipitation, the river outflow also depends on the near-surface temperature (which affects evapotranspiration from the soil and vegetation, snow and ice melt, etc.). The evapotranspiration (ET) is influenced by many factors, such as the availability of energy and water, humidity gradient above the surface, biophysical parameters of vegetation, stomatal resistance, soil characteristics (i.e., heat capacity, albedo and soil chemistry), etc. [1]. However, for a given climatic region, evapotranspiration follows the seasonal variation in solar radiation reaching the surface and the resulting air temperature (see the surface energy balance Equation (2) and [2]).

$$ET = R_n - G - \rho c_p \frac{(T_s - T_a)}{r_a} \quad (2)$$

R_n in Equation (2) represents the gain of energy by the surface from radiation (known as a net surface radiation); G —is the soil heat flux, describing the loss of energy by heat conduction through the lower atmospheric boundary (its positive direction is toward the ground); T_s and T_a are surface and air temperatures, respectively. The aerodynamic resistance r_a to the heat transfer is a function of wind speed, atmospheric stability and roughness lengths for momentum and heat; ρ is the atmospheric density; c_p is the specific heat of air at constant pressure.

On climatic time scales, the main energy supply from the Sun remains unchanged, as does the thermal conductivity of the soil. On the other hand, the changes in near-surface temperature—imposed by various factors affecting greenhouse warming (including ozone at the tropopause level)—are irregularly distributed over the world [3–5]. Consequently, Equation (2) shows that the spatial heterogeneity of near-surface temperature and its temporal variations are among the most influential factors determining the spatial irregularities of surface-emitted latent heat flux and, consequently, river discharge (see Equation (1)). This suggests that irregularly distributed climate change is imprinted on river discharge.

Human activities exert other fluctuations linked to changes in underlying conditions and actual evapotranspiration, which strengthen or weaken additionally the natural variations [6]. So, without a holistic understanding of the basin's hydrology, particularly the river discharge variability and its causes, the risk for sustainable management and planning of water resources is quite high.

One of the main objectives of this research is to analyse the spatial distribution of the temporal evolution of river flows, estimated for the last climatic epoch (1993–2022), with the clear awareness that the situation may be completely different in the next climatic period. In the context of the regionality of climate change, a detailed picture of the spatial distribution of river runoff is certainly more useful than its integral estimates. Achieving this goal, however, is not straightforward—not only because of the regional specificity of each river's flow but also because of the local characteristics of its catchment, such as size, altitude, groundwater table, lithology (i.e., soil and bedrock properties, including their absorptivity and permeability, etc.). These ambiguities could be partly overcome by estimating the flow trend, although the estimates of this trend could be inflated by data outliers (especially the linear trend).

For Bulgaria, we found a knowledge gap regarding the spatial distribution of river discharge during the recent period of increasing global temperature. For example, most studies on the variability of river discharge in Bulgaria focus either on specific catchments [7,8] or on the spatially averaged records of river discharge [9,10]. This was the main motivation for conducting this research, which aims to detect trends in the temporal evolution of river

discharge in 19 of the most important Bulgarian rivers. The spatial irregularities in these trends are also analysed, and potential influencing factors are attributed.

2. Materials and Methods

2.1. Studied Area

The territory of Bulgaria is 110,994 km², and almost half of it (5.2 million ha) is agricultural land, of which ~30% is irrigated. In this study, we analysed 19 of the largest river basins, which drain into two catchment areas: the Black Sea (which receives 42% of all Bulgarian rivers) and the Aegean Sea (which receives 58% of the rivers' flow). Bulgaria has two climatic regions: a continental climate in the north of the country and a Mediterranean climate in the south. The Mediterranean climate tends to be hot and dry in the summer and cool in the winter. The average monthly temperature in the country is in the range of $-1\text{ }^{\circ}\text{C} \div 22\text{ }^{\circ}\text{C}$. The coldest temperatures are experienced in the winter months of December and January, and the warmest in the summer months of July and August. The average monthly rainfall is between 40 and 71 mm, with seasonal variations. May and June are the wettest months, while two periods (February–March, and August–September) are the driest in the annual cycle.

2.2. Data

This study uses public monthly data of registered river discharge provided by the National Institute of Meteorology and Hydrology. Our analysis is based on the monthly discharge values of 19 Bulgarian rivers, measured at 22 hydrological stations during the period 1993–2022 (see Figure 1). In an attempt to disentangle climate from human influence, we decided to work with the spring maximum and summer minimum of river discharge. The main rationale for this approach is that anthropogenic forcing is significantly reduced during winter and early spring when rivers have their maximum flow. Thus, we assumed that the maximum river discharge is mainly controlled by climatic variables (precipitation and near-surface temperature). Conversely, minimum river flow is found in late summer and early autumn. During this period, all human activities, including irrigation, electricity generation, domestic needs, etc., are greatly intensified, while precipitation is significantly reduced. Thus, the minimum streamflow is obviously influenced by both climatic variables and anthropogenic factors.

The trends in the temporal evolution of the flowing surface water were estimated at each measurement point and used to detect irregularities in their spatial distribution. The number of measurements for each hydrological station used for the statistical analysis is given in Table 1.

Table 1. Results from the tests for normality (i.e., Kolmogorov–Smirnov with Lilliefors probabilities, and Shapiro–Wilks) conducted on the maximal and minimal river discharge time series. Statistically significant values of the test are bolded. Note that statistically significant test' values indicate that the null hypothesis (assuming a normality of the time series' distribution) should be rejected. N is the number of measurements in each data record.

Normality of $Q_{\max}$				Normality of $Q_{\min}$			
$Q_{\max}$ Station Name	N	<i>p</i> -Value Lilliefors	<i>p</i> -Value Shapiro–Wilks	$Q_{\min}$ Station Name	N	<i>p</i> -Value Lilliefors	<i>p</i> -Value Shapiro–Wilks
Vasilovci_Apr	29	$p > 0.20$	0.873	Vasilovtsi_Sep	30	$p > 0.20$	0.068
Grozdevo_Mar	26	$p > 0.20$	0.798	Grozdevo_Nov	29	$p > 0.20$	0.562
Karantsi_Mar	29	$p > 0.20$	0.705	Karantsi_Oct	30	$p > 0.20$	0.022
Kobiliak_Mar	26	$p > 0.20$	0.286	Kobilyak_Sep	30	$p < 0.10$	0.021
Orehovica_Apr	29	$p > 0.20$	0.076	Orehovitsa_Sep	30	$p < 0.05$	0.000
Izgreva_Apr	30	$p < 0.15$	0.083	Izgreva_Sep	31	$p < 0.15$	0.248

Table 1. Cont.

Normality of $Q_{\max}$				Normality of $Q_{\min}$			
$Q_{\max}$ Station Name	N	p -Value Lilliefors	p -Value Shapiro–Wilks	$Q_{\min}$ Station Name	N	p -Value Lilliefors	p -Value Shapiro–Wilks
Svilengrad_Apr	30	$p > 0.20$	0.831	Svilengrad_Sep	30	$p < 0.05$	0.016
gara Sindel_Feb	26	$p < 0.05$	0.096	gara Sindel_Sep	29	$p < 0.10$	0.460
Disevica_Apr	28	$p < 0.01$	0.001	Disevitsa_Oct	28	$p < 0.05$	0.002
Marino pole_May	28	$p > 0.20$	0.413	Marino pole_Sep	29	$p < 0.05$	0.000
Elhovo_Feb	29	$p > 0.20$	0.559	Elhovo_Oct	30	$p > 0.20$	0.583
Rudozem_Mart	28	$p > 0.20$	0.525	Rudozem_Sep	28	$p > 0.20$	0.585
Momina kula_May	29	$p < 0.15$	0.073	Momona kula_Sep	30	$p > 0.20$	0.731
Bozichen_Mart	28	$p > 0.20$	0.514	Bozichen_Aug	30	$p < 0.20$	0.356
Novi Iskar_Apr	25	$p > 0.20$	0.262	Novi Iskar_Sep	27	$p < 0.05$	0.001
Teteven_Apr	29	$p > 0.20$	0.005	Teteven_Oct	29	$p > 0.20$	0.126
Pavel banya_Apr	27	$p > 0.20$	0.895	Pavel banya_Oct	24	$p < 0.15$	0.104
Plovdiv_Mart	29	$p > 0.20$	0.862	Plovdiv_Sep	31	$p < 0.01$	0.001
Beronovo_Mart	20	$p > 0.20$	0.964	Beronovo_Aug	22	$p > 0.20$	0.419
Zidarovo_Feb	28	$p < 0.10$	0.303	Zidar_Aug	19	$p > 0.20$	0.278
Poibrene_Apr	30	$p < 0.20$	0.108	Poibrene_Sep	31	$p < 0.05$	0.011
Bobosevo_Apl	24	$p > 0.20$	0.271	Boboshevo_Aug	29	$p > 0.20$	0.469

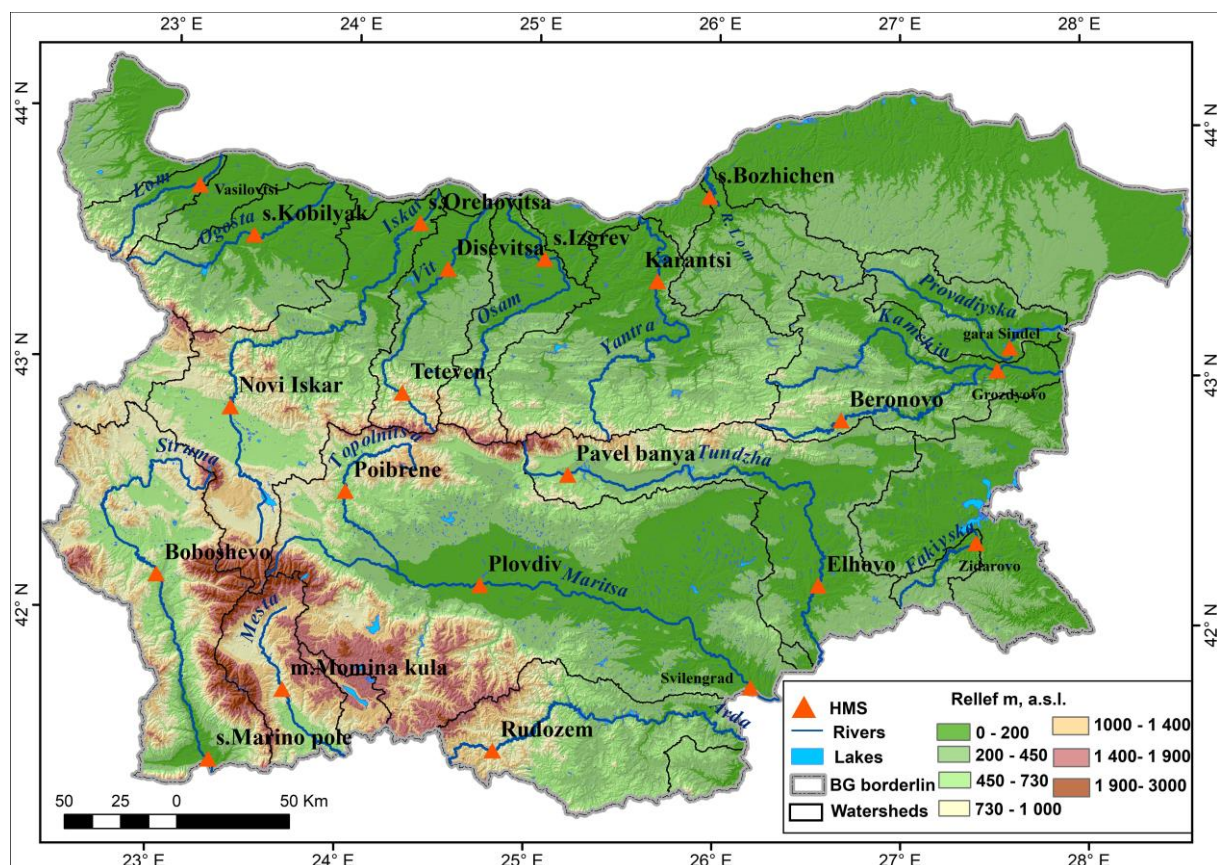


Figure 1. Location of the Bulgarian river basins used in the current study, together with the hydrological stations measuring river discharge.

The streamflow data were compared with the temporal evolution of climatic data, i.e., total precipitation, near-surface temperature and ozone mixing ratio at 70 hPa (monthly means), provided by the ERA 5 reanalysis (<https://registry.opendata.aws/ecmwf-era5> (accessed on 15 December 2023, 29 January 2024 and 7 February 2024)), in a grid with a spatial resolution of 0.25 deg. Taking into account the non-stationary nature of climate data,

we calculated monthly mean deviations from their dynamically evolving decadal means for precipitation, temperature and ozone. We call these deviations ‘dynamic anomalies’, and they have no trend or long-term variations. The analysis of dynamic anomalies provides information about the deviations of a given variable from its mean, taking into account.

2.3. Trend Estimation

Among the different tests for trend estimation, the non-parametric Mann–Kendall test is one of the most used in hydrological analyses because it does not require any prior knowledge about the data distribution. However, the non-parametric methods are less powerful compared to the parametric ones because they use less information (e.g., mean and standard deviation of the time record), and their conclusions are based on the data ranking or values of the compared pairs. Furthermore, the Mann–Kendall test is best suited for monotonic time series. However, examining the streamflow time series at all observation points indicates that they are far from monotonic.

For this reason, we decided to apply the parametric linear regression approach, which also has some limitations. The independence of data and the normality of their statistical distribution is one of the most severe limitations of the application of the regression method for trend detection. The analysis of the normality of the climatic time series shows that climatic variables are normally distributed in each hydrological station during both seasons (spring and autumn).

However, the results for river discharge are not as clear-cut, as the distribution of the raw data is not normal at some stations. However, after applying logarithmic transformations (which reduce the effect of outliers by compressing the range of data variability and bringing the extreme values closer to the mean), both data sets (maximum and minimum discharge or their logarithmic transformations) passed the Kolmogorov–Smirnov test for normality, with Lilliefors probabilities. In addition, the maximum discharge also passed the Shapiro–Wilks tests (except for Teteven and Dissevitza stations; see Table 1).

On the other hand, the minimum streamflow did not pass the Shapiro–Wilks tests at 40% of the stations (see Table 1), even after the logarithmic transformation was applied. However, graphical analyses show that the distribution of the log-transformed data is close to normal. This, together with the independence of the discharge measurements, suggests that linear regression could also be used for trend analysis of minimum streamflow.

The linear regression method, applied for the estimation of the linear trend, finds the best-fitting line to the analysed data. The fitting line is chosen to minimize the sum of squared errors between the actual and modelled values. With other words, for a given record of measurements $y_1, y_2, \dots, y_t$, being an independent realisation of variable $y(t)$, for every moment t are calculated constants $\hat{a}$ and $\hat{b}$ determining the trend line $\hat{y}(t) = \hat{a} + \hat{b}t$ fitted to the data, in such a way that the Equation (3) is minimized:

$$\sum_{t=1}^N [y(t) - (\hat{a} + \hat{b}t)]^2 \quad (3)$$

where N is the number of all measurements in the record, and minimization of (3) is achieved through applying the least square method. The slope of the trend line $\hat{b}$ defines the changes in river stream flow per unit time. As we are working with seasonal data (i.e., one value per year) and flow is measured in m^3/s , the flow trend units are $\text{m}^3/\text{s}/\text{year}$.

The independence of the streamflow measurements (ensured by the analysis of their autocorrelation functions), and the absence of any cyclic influences, allow us to apply the t -test for statistical significance of the slope of fitted trend line, with $N-2$ degrees of freedom. The t -score is defined by the formula:

$$t = \frac{\hat{b}}{SE_{\hat{b}}} \quad (4)$$

where $SE_{\hat{b}}$ is the standard error of a slope coefficient, defined as follows:

$$SE_{\hat{b}} = \sqrt{\frac{1}{N-2} \sum_{t=1}^N [y(t) - (\hat{a} + \hat{b}t)]^2} / \sqrt{\sum_{t=1}^N (y(t) - \bar{y})^2} \quad (5)$$

with $\bar{y}$ denoting the mean of all realizations of $y(t)$. Considering that the denominator of Equation (5) is equal to the unbiased standard deviation of the sample (σ), multiplied by $\sqrt{N-1.5}$. Formula (4) could be rearranged into a more convenient form, which was used to estimate the significance of the trend:

$$t = \hat{b}\sigma \cdot \sqrt{(N-2)(N-1.5)} / \sqrt{\sum_{t=1}^N [y(t) - (\hat{a} + \hat{b}t)]^2} \quad (6)$$

2.4. Methods Determining Connectivity Between Runoff and Climatic Variables

The temporal synchronization between river runoff and climatic variables (total precipitation, near-surface temperature and O_3 mixing ratio at 70 hPa) was estimated using a non-linear regression technique, namely an artificial neural network. It maps the set of input data $X(X_1, X_2, X_3, \dots, X_N)$ onto the target, e.g., the river discharge $Y(Y_1, Y_2, Y_3, \dots, Y_N)$. The exact form of the function mapping X onto Y is determined by the internal structure of the neural network (i.e., the topology and the choice of activation functions), and by the values of a set of parameters called weights ($w_1, w_2, \dots, w_t$). The process of determining the values of these parameters is often called learning or training. So, the neural network mapping could be written in the form:

$$Y = Y(X; w)$$

which denotes that Y is a function of X , being itself parameterized by w [11]. We have used two of the most popular neural network architectures, namely the multilayer perceptron (MLP) and the radial basis function (RBF). The most appropriate model (among the large number of possibilities provided by the ANN) is selected by optimization between the following criteria: (i) maximizing the model performance (i.e., correlation coefficients) derived for each of the training and test subsamples, and (ii) minimizing the model error of both samples. Since we are interested only in the relation between regressed variables (but not the prediction), the coefficients equal to or higher than 0.5 will be interpreted as a high degree of similarity between given variables (correlation).

The spatial distributions of runoff trend, streamflow, and ozone anomalies, as well as the result of applied ANN in each hydrological station, are mapped by Golden Software's Surfer 8 application with radial basis analysis as the gridding procedure.

3. Results

3.1. Analysis of Runoff Trends

Climate models predict that the increase in global surface temperature will be accompanied by a negative trend in surface runoff, as the higher temperature affects both precipitation and evapotranspiration. In addition to climatic changes, river flow is also influenced by human activities, which divert part of the flow for irrigation, industrial processes, domestic needs, electricity generation, etc. However, many of these activities are highly seasonal, which leads us to believe that the maximum river flows (recorded in

February–April) are mainly influenced by climatic factors. On the other hand, the minimum flow (Aug–Oct) is influenced by both climatic and anthropogenic factors.

Most of the methods based on the Budyko hypothesis for separating climate and human influence on river discharge are only applicable to annual data of precipitation, runoff and evapotranspiration, ignoring their seasonal variability. Instead, we choose to separately analyse the spring maximum and autumn minimum of river discharge, thus preserving the specificity of the seasonal characteristics and taking into account their interannual variations.

The first step in the analysis of the Bulgarian rivers' hydrology was the estimation of the trends of the maximum spring and the minimum autumn discharge of each river analysed, using the linear regression method. The results of this analysis are presented in Table 2. In addition, Table 2 compares the trend of the raw data with that of the logarithmically transformed ones—for the months of maximum and minimum runoff. It can be seen that the trends of both series are identical for the maximum spring discharge. Examination of the estimated values shows that in half of all hydrological stations, the trend of the maximum spring discharge is positive and statistically significant (at $\alpha = 0.05$, two-tailed test). In the remaining stations, the trend is not significantly different from zero, and in only one station (Boboshevo), it is significantly negative. Graphical analysis of the time series shows that the calculated trends are not distorted by strong outliers.

Table 2. Names and coordinates of the hydrological stations on the rivers analysed and the linear trend estimated by the linear regression technique for the period 1993–2022. Statistically significant trends ($\alpha = 0.05$) are shown in bold.

1	2	3	4	5	6	7	8	9	10
River's Name	Location	Long	Lat	Month of $Q_{\max}$	$Q_{\max}$ Trend	$\ln(Q_{\max})$ Trend	Month of $Q_{\min}$	$Q_{\min}$ Trend	$\ln(Q_{\min})$ Trend
Lom	Vasilovtsi	23.14	43.71	Apr	0.06	0.06	Sep	0.025	−0.01
Ogosta	Kobilyak	23.45	43.52	Mar	0.83	0.83	Sep	0.065	0.01
Iskar	Orehovitsa	24.36	43.59	Apr	0.20	0.20	Sep	0.166	0.01
Vit	Disevitsa	24.60	43.20	Apr	0.08	0.08	Oct	0.205	0.08
Osam	Izgrev	25.05	43.46	Apr	−0.01	−0.01	Sep	−0.025	0.01
Yantra	Karantsi	25.67	43.38	Mar	2.25	2.25	Oct	0.179	0.01
Rusenski Lom	Bojichen	25.95	43.72	Mar	0.10	0.10	Aug	−0.016	0.00
Provadiyska reka	Sindel	27.60	43.12	Feb	0.02	0.02	Sep	−0.021	−0.03
Kamchiya	Grozdyovo	27.53	43.03	Mar	0.06	0.06	Nov	0.072	0.01
Tundja	Elhovo	26.56	42.17	Feb	0.07	0.07	Oct	0.018	0.00
Marica	Svilengrad	26.20	41.76	Apr	1.49	1.49	Sep	1.395	0.03
Arda	Rudozem	24.83	41.49	Mar	0.15	0.15	Sep	0.008	0.00
Mesta	Momina kula	23.70	41.71	May	0.30	0.30	Sep	−0.027	0.00
Struma	Marino pole	23.32	41.42	May	0.50	0.50	Sep	− 0.303	−0.02
Struma	Boboshevo	23.00	42.15	Apr	− 0.51	− 0.51	Aug	−0.024	0.00
Topolnica	Poibrene	24.00	42.51	Apr	0.11	0.11	Sep	0.050	−0.01
Beli Vit	Teteven	24.29	42.91	Apr	−0.05	−0.05	Oct	−0.001	0.00
Tundja	Pavel banya	25.20	42.60	Apr	−0.01	−0.01	Oct	−0.026	−0.02
Fakiyska reka	Zidarovo	27.41	42.34	Feb	−0.08	−0.08	Aug	−0.010	−0.07
Luda Kamchiya	Beronovo	26.68	42.83	Mar	0.30	0.30	Aug	−0.021	−0.05
Marica	Plovdiv	24.74	42.15	Mar	1.40	1.40	Sep	0.592	0.02
Iskar	Novi Iskar	23.36	42.83	Apr	0.62	0.62	Sep	− 0.132	−0.01

The trends of minimum discharge—calculated from raw and logarithmically transformed data—are very different. In one-third of the stations, the trend of the raw data is significant (at $\alpha = 0.05$), while the trend of the logarithmically transformed data is not significantly different from zero in all hydrological stations (see columns 9 and 10 in Table 2).

The spatial distributions of the linear trends in the raw river discharge records are shown in Figure 2a,b. The positive and statistically significant (at $\alpha = 0.05$) trends are shaded with a red-orange colour. Note that the stations with a significantly positive runoff

trend are not randomly distributed over the territory of Bulgaria. Instead, there is a specific pattern running across the country from northwest to southeast, which is statistically significant for maximum river discharge (at $\alpha = 0.05$). The trend of minimum streamflow (in autumn months) is significant only in the southeastern region. After correcting the time series for the normality of their statistical distribution, the trend of minimum discharge becomes insignificant everywhere. This allows us to conclude that the trend of minimum discharge of Bulgarian rivers is not significantly different from zero in the period 1993–2023.

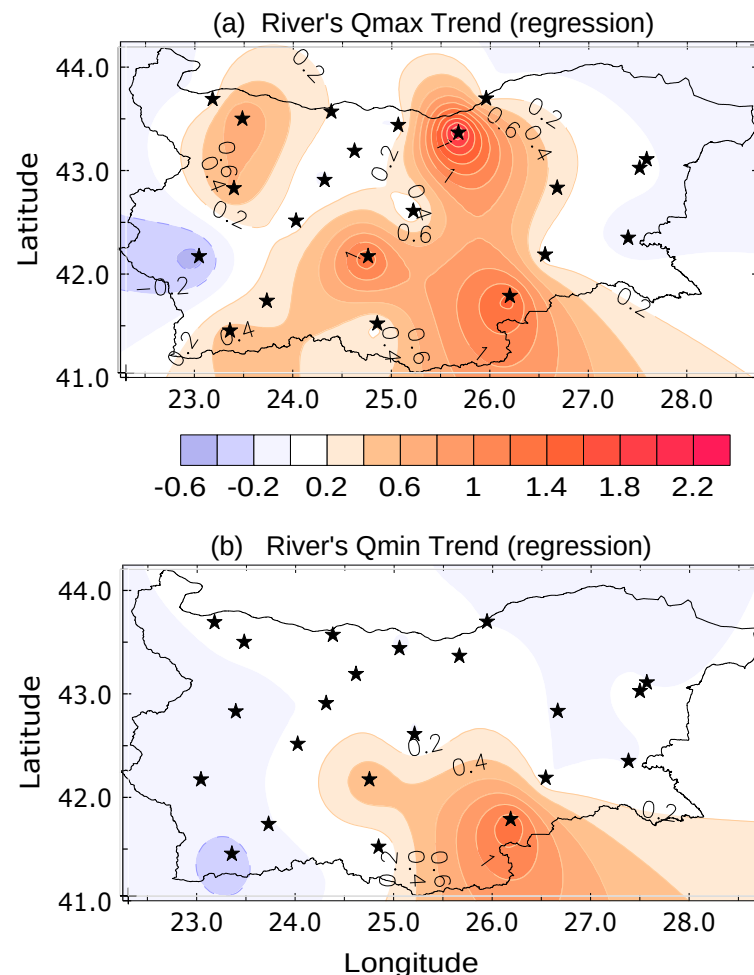


Figure 2. Maps of river discharge trends: (a) maximum discharge (spring); (b) minimum discharge (autumn) on the territory of Bulgaria, calculated by linear regression. Values higher or lower than ± 0.15 [m³/s/yr] are statistically significant at $\alpha = 0.05$. Stars indicate the location of hydrological stations.

This result does not support the conclusions of [8], which is based on the analysis of a much longer period but ending at the beginning of our time window, i.e., 1890–1995. The authors claim that the negative response of river discharge is strongest in the west-north-west direction of Bulgaria, with a gradual weakening of the effect towards east-south-east. They suggest that the spatial heterogeneity of the climatic impact on the hydrological regime is related to the direction of the atmospheric circulation, predominantly oriented from west to east. Our results show that since 1993, there has been a clear increase in the maximum discharge of spring rivers in half of the hydrological stations studied. In the other half, the trend is not significantly different from zero. Similarly, no trend was found for minimum autumn discharge at all stations.

The separate analysis of maximum and minimum streamflow allowed us to conclude that their different temporal evolution could be attributed to the seasonality of climate impact.

Thus, the positive trend of the maximum flow, obtained in half of the hydrological stations, could be reasonably attributed to the regional specificity of the climatic impact—since most human activities are significantly reduced in this season (Feb–Apr). On the other hand, the trend of minimum flows in autumn does not seem to be influenced by either climatic factors or human activities.

3.2. Attribution Analysis of the Maximum Runoff Spatial Irregularities

The irregular distribution of the maximum streamflow trend over the territory of Bulgaria raises the question of the forcing factors that lead to this heterogeneity. As mentioned in the introduction, river discharge is directly related to precipitation and surface temperature. In order to reveal some similarities in the temporal evolution of maximum river discharge ($Q_{\max}$), precipitation and temperature, we conducted an artificial neural network analysis in each hydrological station. The spatial distribution of the calculated correlation coefficients between modelled values of $Q_{\max}$ and its predictors, i.e., precipitation, surface temperature and ozone, is shown in Figure 3. To facilitate comparison, the contours of the maximum streamflow trends are superimposed on the regression maps.

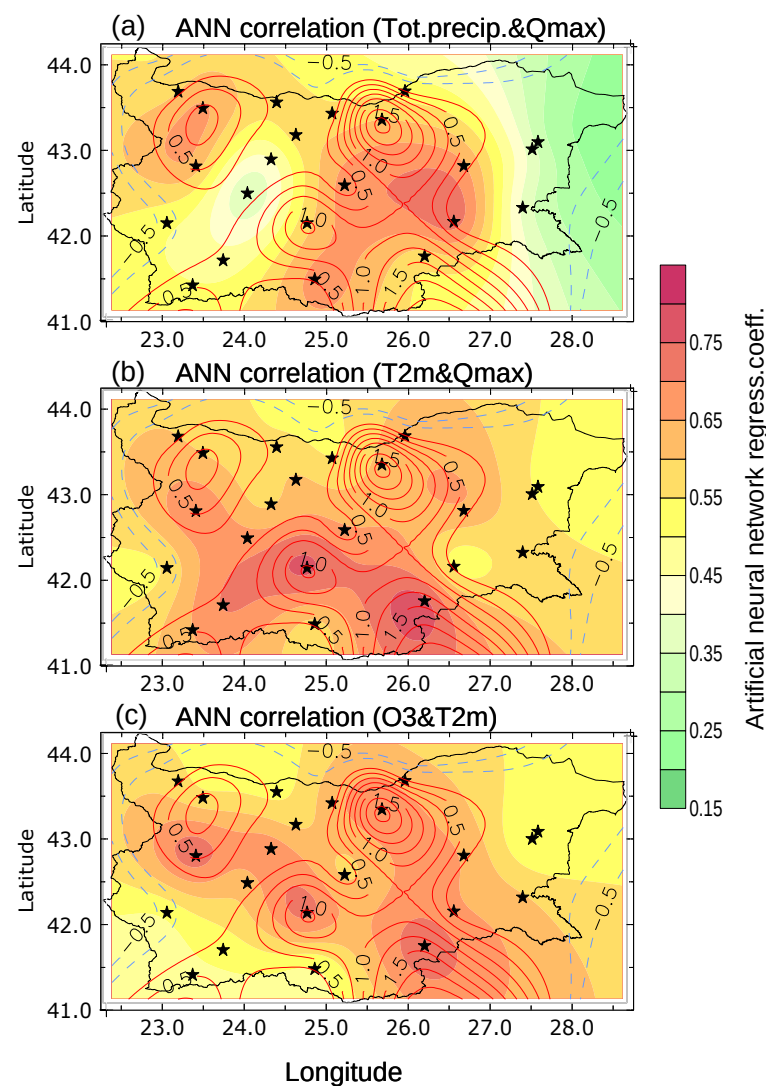


Figure 3. Spatial distribution of the correlation between modelled and measured maximum streamflow as a function of total precipitation (a), temperature at 2 m above the surface (b) and ozone at 70 hPa (c). maximum streamflow trends (shown in Figure 2). Stars indicate the location of the hydrological stations.

It is easy to see that the regions with the strongest covariance between river discharge and precipitation do not coincide with the spatial distribution of the trend maxima (Figure 3a). In addition, our analysis of winter–spring precipitation shows that there is a negative trend in two-thirds of the stations analysed, although not significant. Previous analyses report a statistically significant negative trend in winter precipitation at mountain stations in Bulgaria [12]. Studies in neighbouring Serbia also indicate a decrease in winter–spring precipitation [13]. Moreover, at most hydrologic stations, the maximum runoff is observed during the period February–April, which is one of the driest episodes of the annual cycle [14].

On the other hand, the regions of stronger correlation between near-surface temperature and the highest spring streamflow coincide quite well with the spatial distribution of the positive streamflow trend (Figure 3b). This suggests that at most stations, the maximum spring discharge should be related to the melting of snow and ice, which is closely related to surface temperature. However, the latter is irregularly distributed over Bulgaria. Figure 4 shows the average distribution of the near-surface temperature anomalies during the analysed period 1993–2022. Note that the areas with negative temperature anomalies (Figure 4a) are very similar to the areas with positive spring discharge trends.

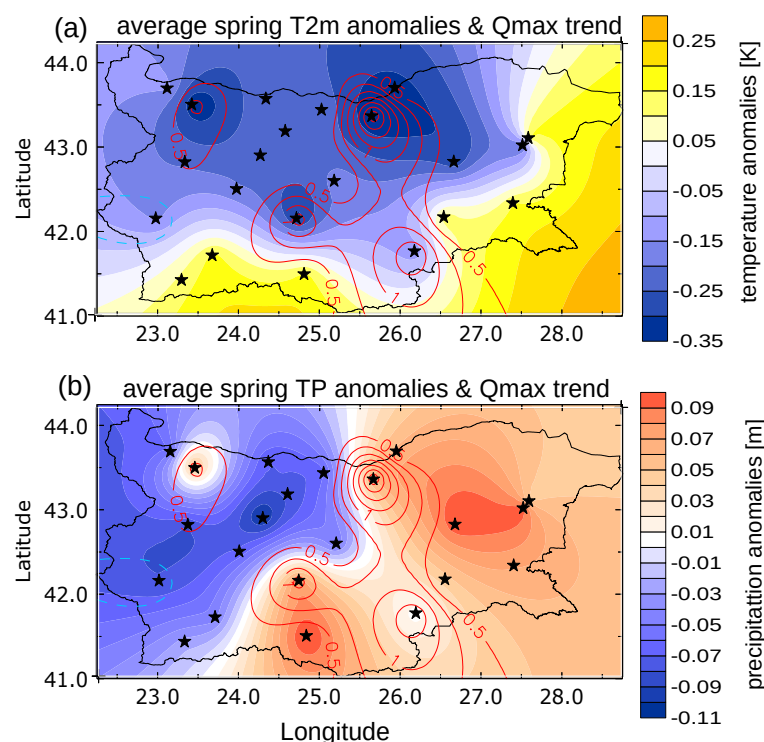


Figure 4. Maps of near-surface temperature (top) (a) and total precipitation (bottom) (b) dynamic anomalies calculated for the period 1993–2022 (coloured shading). The spring outflow trend, shown in Figure 2, is overlaid (contours). Stars indicate the location of hydrological stations.

When comparing with the map of rainfall anomalies (Figure 4b), it is also apparent that some of the centres of the positive trend are located in areas with weak positive rainfall anomalies but far from their maximum positive anomalies. Thus, Figure 4 provides an additional indication that the positive trend in spring runoff is most likely related to the local irregularities in near-surface temperature.

On the other side, statistical evidence shows that the regional character of the surface temperature changes could be related to corresponding irregularities in the ozone density just above the tropopause [3,15]. Therefore, we compare the time variations of the near-surface temperature with those of the ozone at 70 hPa, using the artificial neural network at

each observation point. The result is shown in Figure 3c. It is easy to see that the maxima of the covariance between temperature and ozone corresponds very well to the maxima in the positive trend of the spring outflow. Furthermore, a comparison of the maps of ozone and near-surface temperature dynamic anomalies shows a good antiphase correspondence between them, i.e., the minima of the temperature anomalies resemble the maxima of the ozone anomalies (Figure 5).

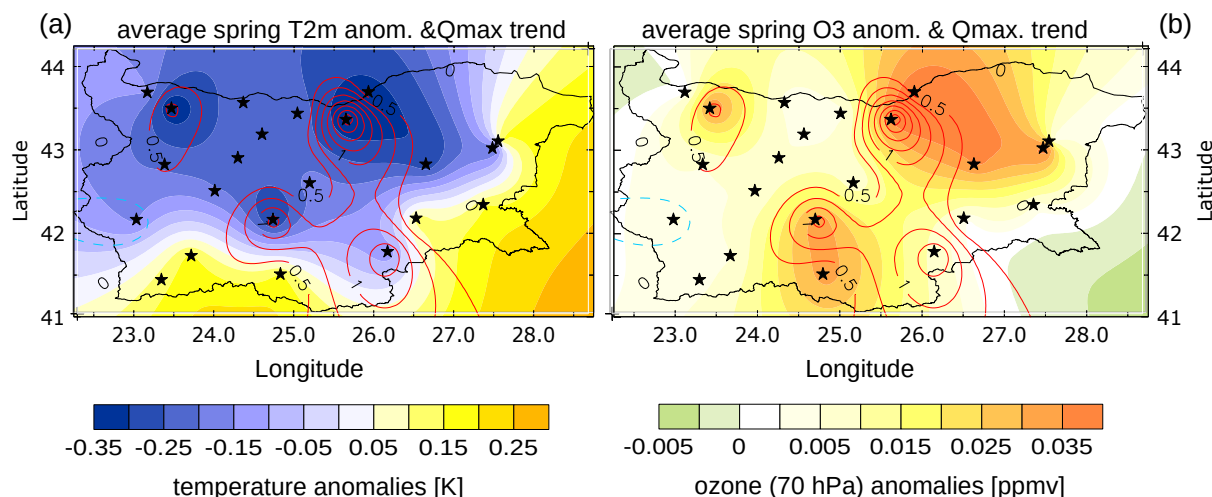


Figure 5. Maps of the spring near-surface temperature (a) and ozone at 70 hPa (b) dynamic anomalies, calculated for the period 1993–2022 (coloured shading). The red contours represent the spring outflow trend, shown in Figure 2. Stars indicate the location of hydrological stations.

This result requires an explanation of the possible mechanism of the ozone's influence on the near-surface temperature and, consequently, on the river discharge. Such a mechanism is described in the following subsection.

3.3. Mechanism of O_3 Influence on the Near-Surface Temperature and River Runoff

The absorption of solar radiation by ozone near the tropopause affects the temperature at this level. For example, ozone abundance warms, while its depletion cools the tropopause, thus altering the stability of the upper troposphere [16,17]. More specifically, a warmer tropopause reduces the temperature lapse rate and stabilises the atmosphere. In a statically stable atmosphere, vertical motions are suppressed, leading to a gradual drying of the upper troposphere due to the interruption of water vapour supply from the lower atmospheric layers. The cooler tropopause, on the other hand, destabilises and moistens the upper troposphere by lifting water vapour from the lower, wetter levels.

In other words, ozone variability in the lowermost stratosphere alters the humidity below the tropopause. Moreover, the amount of water vapour at these levels is critical because it accounts for 90% of the total atmospheric water vapour contribution to the greenhouse warming of the planet [18–20]. Consequently, ozone abundance at the tropopause level is projected as a temperature cooling due to the reduced amount of upper tropospheric moisture and limited greenhouse warming [21]. Conversely, ozone depletion is followed by surface warming due to the wetter upper troposphere and enhanced greenhouse effect.

The rest of the link between ozone and river discharge is easy to understand—additional surface warming in spring forces snow and ice to melt, increasing river flow. A schematic drawing of the links of changes related to the variations of the ozone at the tropopause level is provided in Figure 6. Climatological studies show that the months with the highest spring runoff are characterised by minimum precipitation [12–14]. Consequently, the highest surface runoff should be attributed to melting snow and ice.

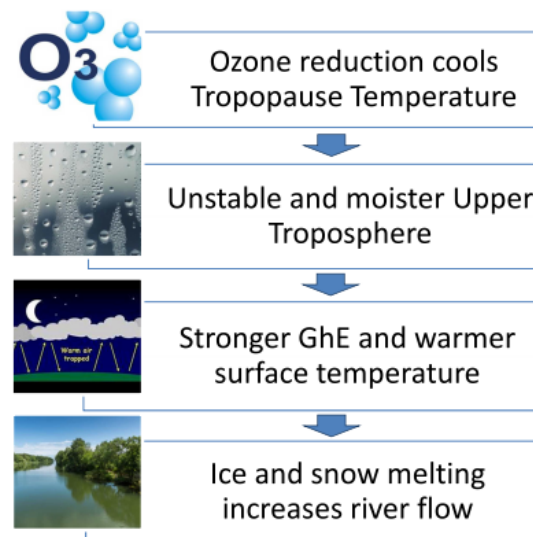


Figure 6. Schematic diagram of the effect of ozone on surface temperature and late winter/early spring river discharge; GhE stands for greenhouse effect.

The mechanism of remote ozone influence on river discharge appears to be valid in the presence of ice and snow in the river basins. This may explain the lack of a convincing relationship between surface runoff and ozone at 70 hPa in the season of lowest river discharge.

A clear indication of the existing relationship between ozone at 70 hPa and near-surface temperature can be seen in Figures 5 and 7, which show the maps of temperature and ozone dynamic anomalies. Note that the positive anomalies in ozone at 70 hPa correspond very well to the negative anomalies in near-surface temperature and vice versa. This covariance is quite well explained by our mechanism for ozone influence on the near-surface temperature (refer to Figure 6).

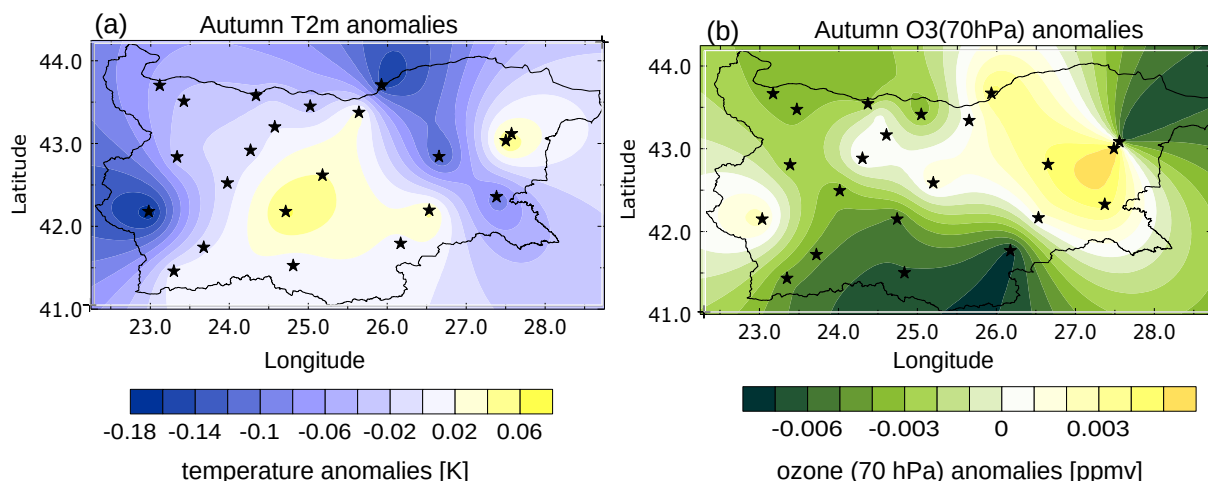


Figure 7. Maps of the autumn near-surface temperature (a) and ozone at 70 hPa (b) dynamic anomalies, calculated for the period 1993–2022 (coloured shading). Stars indicate the location of hydrological stations.

Graphical analysis of the full time series—of ozone at 70 hPa and river discharge—shows a visual synchronisation between them at many monitoring sites. An example of the hydrological station “Plovdiv” is shown in Figure 8. The cross-correlation coefficients, calculated in each station, are significantly positive (at $\alpha = 0.05$). However, a time lag of 1–2 months for the river response is found in most of the hydrological stations.

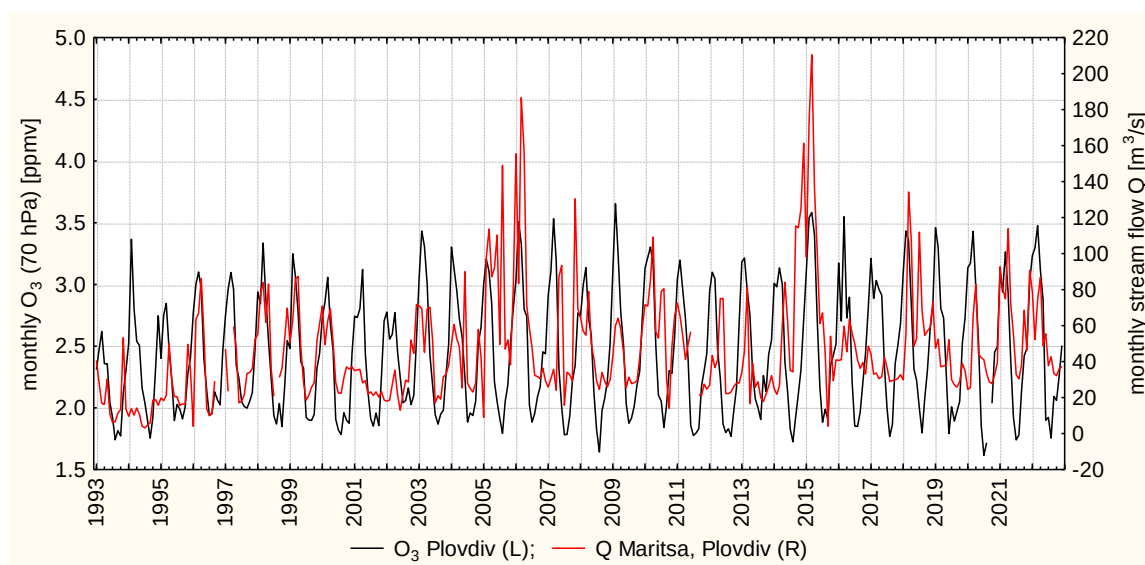


Figure 8. Time series of the monthly discharge of the Maritsa River, measured in Plovdiv, and the ozone values at 70 hPa, over Plovdiv, for the period 1993–2022.

The degree of similarity between the temporal evolution of ozone at 70 hPa and river discharge (using the whole time series) was estimated by the artificial neural network approach. A model of runoff variability based on the corresponding ozone data was constructed for each hydrological station. The degree of similarity between the modelled and measured streamflow is given by a correlation coefficient—the stronger the correlation, the greater the influence of ozone on streamflow. These correlation coefficients (calculated for each station) were used to generate a map of the similarity between ozone and river discharge over time (see Figure 9).

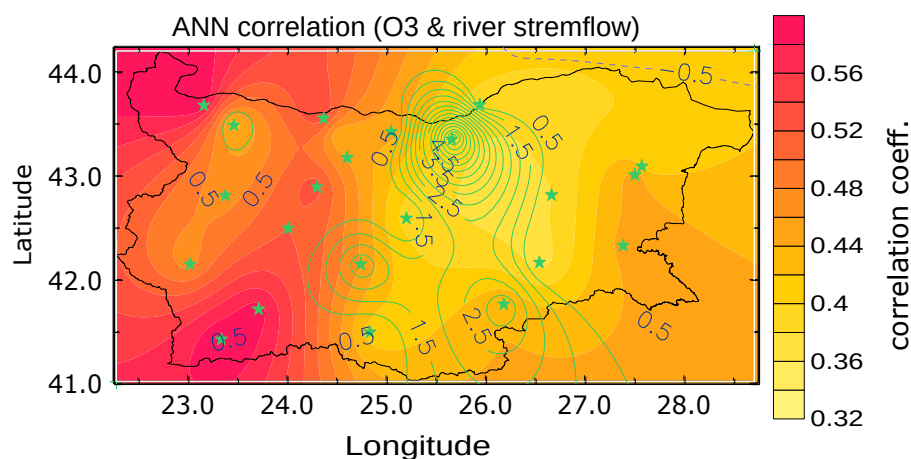


Figure 9. Projection of the influence of ozone at 70 hPa on the rivers discharge, determined by an artificial neural network (colour shading). The green contours indicate the statistically significant trend in river discharge (shown in Figure 2). Stars indicate the location of hydrological stations.

Figure 9 shows that the temporal covariance of ozone density near the tropopause and river discharge is irregularly distributed over the territory of Bulgaria. Note that stations with higher positive trends are located in regions with a weaker ozone impact on river discharge (the correlation coefficients are in the order of 0.3–0.4). Referring to Figure 5, these regions are mainly characterised by positive ozone anomalies at 70 hPa and negative surface air temperature anomalies. Thus, Figure 5 supports our idea that higher ozone densities lower the near-surface temperature by stabilising the upper troposphere and

reducing the lifting of moist air masses from the middle troposphere. This is followed by drying of the upper troposphere and suppression of the greenhouse effect.

However, Figure 5 shows the mean spatial distribution of ozone and temperature anomalies. In fact, ozone density varies from year to year due to the influence of many factors, and its variations are also projected onto the surface air temperature. Thus, a sudden drop in ozone at 70 hPa causes the near-surface temperature to rise. In a cold season, this would favour the melting of ice and snow and an increase in river discharge. Conversely, an increase in ozone density at 70 hPa, as mentioned above, cools the surface and reduces river flow.

To summarise: The results of this study suggest that variations in lower stratospheric ozone exert a regional/local control on surface temperature, which is further projected onto river hydrology, particularly effective during the snow and ice melt season.

4. Discussion

Understanding the variability of river discharge and its causes is the basis for sustainable management and planning of water resources in the recent period of climate change. For Bulgaria, we found a gap in knowledge related to the spatial distribution of river discharge, as most of the studies are based on aggregated data for the country or for two to three large regions. On the other hand, estimates based on climate models suggest a decrease in river discharge, at least on an annual basis [22–25].

The analysis of the monthly values of river discharge measured in 22 hydrological stations located on 19 of the largest Bulgarian rivers shows that for a limited period (1993–2022), no trend was detected in the period of lowest river discharge in all the analysed measuring points. On the other hand, the trend of the highest spring discharge is significantly positive ($\alpha = 0.05$) in half of the river basins. The analysis of the spatial distribution of the trend shows that the stations with a positive trend are not randomly distributed but grouped, forming a pattern that crosses the country from northwest to southeast (see Figure 2). This result raises at least three questions related to (i) different tendencies of maximum and minimum streamflow, (ii) the factor(s) responsible for the observed positive trend, and (iii) the mechanism(s) of influence on the river discharge.

The spatial attention to the seasonal variations of climatic and anthropogenic impacts affecting the river flow allows us to conclude that the positive trend of the maximum discharge could be attributed to regional peculiarities of climate forcing due to the significant reduction of human activities during the period Feb–Apr. In addition, the neutral trend of the minimum discharge indicates that neither climate change nor anthropogenic forcing has a significant influence on its temporal evolution.

Among the climatic variables, precipitation and surface temperature are the most important factors influencing river discharge. However, the analysis of the covariance between precipitation and river discharge shows that the regions with the highest correlation do not coincide with the regions with the maximum positive trend existing in spring discharge (see Figure 3a). This result is quite reasonable since the months with the highest streamflow are also the months with the lowest precipitation [12]. In addition, the trend analysis of the precipitation shows that a negative trend has been detected in most of the stations, although it is not statistically significant.

The influence of the near-surface temperature, at least during the maximum spring runoff, appeared to be more important. The good spatial coincidence of the temperature-runoff covariance and the positive trend of the runoff maxima is clearly visible in Figure 3b.

In addition, we found that the temperature variations are significantly correlated with the ozone density at 70 hPa—the correlation coefficients in the area of positive runoff trend are within the range of 0.55–0.79 (see Figure 3c). Further analysis of the synchronicity between ozone and river discharge—based on the analysis of (i) the spatial distribution of ozone and temperature

anomalies and (ii) the covariance of ozone and runoff full time series (consisting of monthly values)—confirms the existence of a relationship between ozone at 70 hPa and river discharge.

We propose a mechanism to explain the remote influence of near-tropopause ozone on surface temperature and river discharge. It takes into account a well-established relationship between lowermost stratospheric ozone and tropopause temperature. For example, the reduced ozone density cools the tropopause, which in turn destabilises and wets the upper troposphere. At the same time, the excess water vapour strengthens the atmospheric greenhouse effect and warms the planetary surface. During the cold season, such warming episodes can influence river discharge and have been detected in the raw data analysis. This mechanism also explains the absence of a relationship between ozone and river discharge during periods of lowest river flow. The missing link in the causal chain, in this case, is the absence of surface ice and snow in autumn.

5. Conclusions

This study shows that for the period 1993–2022, the model predictions for river discharge on the territory of Bulgaria are not confirmed by measurements at 22 hydrological stations located on 19 of the largest rivers. Contrary to the predicted negative trend, we found no trend in the lowest autumn river discharge in all hydrological stations and a positive trend in the highest spring river discharge in half of the measuring points.

The hydrological stations with a positive trend are not randomly distributed in space. The pattern they form is slightly elongated from northwest to southeast. This configuration made us curious about the factors responsible for the positive trend pattern. Further investigations show that the positive trend observed in the maximum spring runoff could be attributed to ozone variations at 70 hPa, which force the appearance of temperature anomalies near the surface, altering the melting of snow and ice in the spring season. The absence of any trend in autumn river discharge is also explained by our mechanism for the remote ozone influence, and the explanation is related to the absence of snow and ice in this season.

Author Contributions: Conceptualization, N.A.K. and G.I.M.; methodology, N.A.K.; software, N.A.K.; validation, G.I.M. and A.C.M.; formal analysis, G.I.M. and A.C.M.; investigation, N.A.K.; resources, G.I.M. and A.C.M.; data curation, G.I.M.; writing—original draft preparation, N.A.K.; writing—review and editing, N.A.K.; visualization, N.A.K. and G.I.M.; supervision, N.A.K.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Access to ERA 5 reanalysis data is available after registration at <https://cds.climate.copernicus.eu/datasets> (accessed on 15 December 2023, 29 January 2024 and 7 February 2024). Data for air surface temperature, total precipitation and ozone at 70 hPa with a resolution of 0.25 deg are retrieved from ERA 5. Hydrological data consisting of monthly values of river discharge are freely available at <https://bulletins.cfd.meteo.bg> (accessed on 30 March 2023), provided by the National Institute of Meteorology and Hydrology of Bulgaria. The commercial software STATISTICA (licence of StatSoft) has been used to estimate trends and correlations. Maps are produced using the SURFER program, licensed by Golden Software.

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

References

1. Stancalie, G.; Nert, A. Possibilities of Deriving Crop Evapotranspiration from Satellite Data with the Integration with Other Sources of Information. In *Evapotranspiration—Remote Sensing and Modeling*, Irmak, A., Ed.; IntechOpen: London, UK, 2012; pp. 437–466. [CrossRef]
2. Burba, G. Evapotranspiration. 2013. Available online: <http://editors.eol.org/eoearth/wiki/Evapotranspiration> (accessed on 15 September 2024).
3. Kilifarska, N.A. Mechanism of lower stratospheric ozone influence on climate. *Int. Rev. Phys.* **2012**, *6*, 279–290.

4. Kilifarska, N.A. Hemispherical asymmetry of the lower stratospheric O₃ response to galactic cosmic rays forcing. *ACS Earth Space Chem.* **2017**, *1*, 80–88. [CrossRef]
5. IPCC. *Climate Change 2021: The Physical Science Basis*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., Eds.; Cambridge University Press: Cambridge, UK, 2021; pp. 147–286. [CrossRef]
6. Guo, A.; Huang, Q.; Wang, Y. Quantitative study of impacts of climate change and human activities on runoff in Beiluohe River basin. *Proc. IAHS* **2015**, *368*, 263–268. [CrossRef]
7. Kirilova, S. Annual and monthly outflow of the Dospatska river in the conditions of anthropogenic impacts and climate change. *Annu. Univ. Archit. Civ. Eng. Geod. Sofia* **2022**, *55*, 155–167.
8. Hristova, N.; Orehova, T.; Nicheva, O. Stability and predictability of the streamflow of Demjanitsa river at Bansko. *Annu. Sofia Univ. “St. Kliment Ohridski”* **2022**, *113*, 161–176.
9. Georgiev, S.; Genev, M.; Bojilova, E.; Orehova, T. *Water Resources During the Drought Period 1892–1994. Likely Scenarios for Future Development*; Heron Press: Sofia, Bulgaria, 2004; pp. 17–79. (In Bulgarian)
10. Hristova, N.; Penkov, I.; Seymenov, K. Fluctuation and climate elasticity of annual streamflow in Bulgaria. *Annu. Book Sofia Univ.* **2018**, *111*, 63–73.
11. Bishop, C.M. Neural networks and their applications. *Rev. Sci. Instrum.* **1994**, *65*, 1803–1832. [CrossRef]
12. Nikolov, D.; Dimitrov, C. Analysis of The Variability of the Winter Precipitations and Temperatures in two Mountain Regions of Bulgaria. In Proceedings of the 22nd International Multidisciplinary Scientific GeoConference SGEM 2022, Albena, Bulgaria, 2–11 July 2022. [CrossRef]
13. Milošević, D.; Savić, D. Analysis of precipitation quantities and trends from Pannonian and Peripanno-nian parts of Serbia. *Dela* **2013**, *39*, 125–139. [CrossRef]
14. Climate Change Knowledge Portal, For Development Practitioners and Policy Makers. Available online: <https://climateknowledgeportal.worldbank.org/country/bulgaria/climate-data-historical#:~:text=Monthly%20mean%20precipitation%20ranges%20from,the%20lowest%20levels%20of%20precipitation> (accessed on 13 December 2024).
15. Kilifarska, N.A. Bi-decadal solar influence on climate, mediated by near tropopause ozone. *J. Atmos. Sol.-Terr. Phys.* **2015**, *136*, 216–230. [CrossRef]
16. North, G.R.; Eruhimova, T.L. *Atmospheric Thermodynamics: Elementary Physics and Chemistry*; Cambridge University Press: New York, NY, USA, 2009; p. 267.
17. Young, J.A. Static stability. In *Encyclopaedia of Atmospheric Sciences* Holton, 2nd ed.; Holton, J.R., Curry, J.A., Pyle, J.A., Eds.; Academic Press: Cambridge, MA, USA, 2003; Volume 2, pp. 423–430.
18. Sinha, A.; Harries, J.E. Water vapour and greenhouse trapping: The role of far infrared absorption. *Geophys. Res. Lett.* **1995**, *22*, 2147–2150. [CrossRef]
19. Spencer, R.W.; Braswell, W.D. How dry is the tropical free troposphere? Implications for global warming theory. *Bull. Am. Meteorol. Soc.* **1997**, *78*, 1097–1106. [CrossRef]
20. Inamdar, A.K.; Ramanathan, V.; Loeb, N.G. Satellite observations of the water vapor greenhouse effect and column longwave cooling rates: Relative roles of the continuum and vibration-rotation to pure rotation bands. *J. Geophys. Res. Atmos.* **2004**, *109*, D06104. [CrossRef]
21. Kilifarska, N.; Velichkova, T.; Mokreva, A. Multiannual Variability of the North Atlantic Pressure and Temperature Imposed by the Lower-Stratospheric Ozone. *Earth Interact.* **2023**, *27*, e230007. [CrossRef]
22. Andrea, C.R.; MacKenzie, D. *Climate Risk Country Profile: Bulgaria*; World Bank Group: Washington, DC, USA, 2021; pp. 17–19.
23. Marinova, T.; Bocheva, L. (Eds.) *The Changing Climate of Bulgaria—Data and Analyses*; National Institute of Meteorology and Hydrology: Sofia, Bulgaria, 2023; 106p, ISBN 978-954-90537-3-9. Available online: <https://www.meteo.bg> (accessed on 12 November 2024).
24. Alexandrov, V.; Genev, M. Climate variability and change impact on water resources in Bulgaria. *Eur. Water* **2003**, *1*, 25–30.
25. Stanev, K. The climate change impact on the Mesta river basin runoff. In Proceedings of the XXIV-th Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management, Bled, Slovenia, 2–4 June 2008.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.