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# Trends and Drivers of Flood Occurrence in Germany: A Time Series Analysis of Temperature, Precipitation, and River Discharge

**Mohannad Alobid [1,*], Fatih Chellai [2] and István Szűcs [1]**

[1] Faculty of Economic and Business, Institute of Economics, Department of Agricultural Policy and Environmental Economics, University of Debrecen, Böszörményi St. 138, H-4032 Debrecen, Hungary; szucs.istvan@econ.unideb.hu
[2] Faculty of Economics, Commerce and Management, Ferhat Abbas University, Sétif 19000, Algeria; fatih.chellai@univ-setif.dz
* Correspondence: mohannadalobid88@gmail.com

**Abstract:** Floods in Germany have become increasingly frequent and severe over recent decades, with notable events in 2002, 2013, and 2021. This study examines the trends and drivers of flood occurrences in Germany from 1990 to 2024, focusing on the influence of climate-change-related variables, such as temperature, precipitation, and river discharge. Using a comprehensive time series analysis, including Auto-Regressive Integrated Moving Average (ARIMA) and Artificial Neural Network (ANN) models and correlation and regression analyses, we identify significant correlations between these climatic variables and flood events. Our findings indicate that rising temperatures (with a mean of 8.46 °C and a maximum of 9 °C) and increased precipitation (averaging 862.26 mm annually)are strongly associated with higher river discharge (mean 214.6 $m^3/s$) and more frequent floods (mean 197.94 events per year). The ANN model outperformed the ARIMA model in flood forecasting, showing lower error metrics (e.g., RMSE of 10.86 vs. 18.83). The analysis underscores the critical impact of climate change on flood risks, highlighting the necessity of adaptive flood-management strategies that incorporate the latest climatic and socio-economic data. This research contributes to the understanding of flood dynamics in Germany and provides valuable insights into future flood risks. Combining flood management with groundwater recharge could effectively lower flood risks and enhance water resources' mitigation and management.

**Keywords:** flood; ARIMA and ANN models; temperature; precipitation; river discharge; climate change; groundwater; Germany

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## 1. Introduction

Floods are a prominent natural peril in Germany, resulting in substantial harm to infrastructure, agriculture, and the environment. In recent decades, there has been a notable escalation in the frequency and intensity of floods, with particularly catastrophic occurrences in 2002, 2013, and 2021 [1,2]. Climate change and its effects on the temperature, precipitation, and river discharge have been recognized as possible causes of floods in Germany [3,4].

Several investigations have examined the relationship between climate change and the frequency of floods in Germany. Kreibich et al. [5] conducted an analysis of the trends and drivers of flood damages in Germany between 1950 and 2002. Their findings indicate that the primary factors contributing to flood damages were climate change and changes in land use. The researchers employed a statistical study of flood damage data and discovered a positive correlation between flood damage and rising temperature and precipitation levels. Additionally, it was shown that alterations in land use, such as urbanization and deforestation, amplified flood damages by intensifying the flow of water and diminishing the process of water absorption into the ground [5]. Hall et al. (2014) analyzed the relationships between temperature, precipitation, and flood occurrence in Europe using a meta-analysis of 1161 flood events from 1960 to 2010. The authors found that temperature and precipitation were positively correlated with flood occurrence, with the correlation being stronger in the winter months. They also found that the correlation between temperature and flood occurrence increased over time, suggesting a potential impact of climate change on flood occurrence [6]. Petrow and Merz [7] conducted a statistical analysis of flood data from 1951 to 2002 to examine the trends and drivers of flood frequency and magnitude in Germany. Their study revealed that both flood frequency and magnitude increased in response to rising temperatures and precipitation levels. Additionally, they found that certain factors, such as land use and soil type within catchments, significantly influenced flood behavior. The authors concluded that both climate change and alterations in catchment characteristics play a crucial role in driving flood events in Germany [7]. Thieken et al. [8] conducted an analysis of flood losses in Germany between 2002 and 2013, highlighting the increasing vulnerability due to socio-economic developments and climate change [8]. Blöschl et al. [9] analyzed the trends and drivers of floods in Europe and found that climate change and catchment changes were the main drivers of flood occurrence. The authors used a meta-analysis of 3738 flood events in Europe and found that flood magnitudes and frequencies increased with increasing temperature and precipitation. They also found that catchment changes, such as land use changes and river regulation, increased flood occurrence by altering the hydrological response of catchments [9]. Similarly, Apel et al. [10] examined the impact of climate change on flood hazards using advanced hydrological models, finding significant increases in flood frequencies under various climate scenarios [10]. Additionally, in their recent study Kreibich et al. [11] provided insights into the changing flood patterns and the associated socio-economic impacts, suggesting that urbanization and inadequate land-use planning continue to exacerbate flood risks [11].

Recent studies have delved into the impact of climate change and urbanization on flood risks in Germany [12]. These investigations highlight the growing challenges posed by these factors, necessitating a re-evaluation of existing flood-risk-management strategies. Publications have assessed the effectiveness of these strategies within Germany and across Europe, emphasizing the critical need for adaptive management approaches that can respond to evolving climate risks [13,14]. Furthermore, there is a collective consensus among researchers regarding the importance of integrating recent climatic data and socio-economic factors into flood risk assessments and management strategies. This integration is crucial for developing comprehensive and effective flood-risk-management plans that can mitigate the adverse effects of climate change and urbanization [15,16].

These studies emphasize the complex connections between climate change, changes in catchment areas, and the occurrence of floods in Germany. Although there is evidence indicating that climate change and watershed changes have a substantial role in causing floods, the exact relationships between these elements and flood events are not completely comprehended. The lack of comprehension can be attributed, in part, to the intricate interplay of climatic and geographical elements, which exhibit significant variations across diverse locations and catchment areas [17,18].

Additionally, it is crucial to take into account the impact of land use changes and urbanization on catchment modifications, which might alter the capacity of water absorption and flow. These modifications can worsen the effects of climate change by amplifying the occurrence and severity of floods. The prediction and management of floods are made more complex by natural climatic variability and exceptional events, such as heavy storms [19,20]. Conversely, Germany has recently been investigating novel approaches to effectively handle the dangers associated with flooding. One method involves using surface runoff to replenish groundwater [21]. Certain regions, such as North Rhine-Westphalia, have initiated pilot programs to develop efficient recharge systems. These technologies, such as infiltration basins, aid in the management of surplus water by diverting it into subterranean aquifers, thus mitigating the impact of floods and bolstering water resources [22].

In order to fill these gaps in knowledge, it is essential to adopt an interdisciplinary research approach. This strategy aims to incorporate sophisticated climate modeling, comprehensive hydrological investigations, and in-depth examination of risk management policies. By doing this, it will improve the comprehension of how watershed and climate changes interact to impact flood frequency, thereby assisting in the creation of more efficient mitigation techniques [23,24].

The study presented in this paper aims to contribute to the understanding of these relationships by analyzing the trends and drivers of flood occurrence in Germany from 1990 to 2024 using a time series analysis of the temperature, precipitation, and river discharge. The selection of temperature, precipitation, and river discharge as key variables in this study is grounded in both empirical evidence and theoretical frameworks that link these factors to flood dynamics. Temperature is the climate's pulse, driving precipitation patterns and flood dynamics. Precipitation is the primary input to river systems and triggers floods when excessive or sustained. River discharge is the cumulative response of the entire watershed to precipitation and other factors, serving as a critical indicator of flood occurrence. These variables were chosen based on their well-established influence on flood events and their pertinence to understanding how climate change might reshape flood frequency. By analyzing these variables in concert, this study aims to untangle the complex interactions that underpin floods, particularly in the context of a warming world. The goal is to better protect lives and livelihoods from flooding by understanding the threads that weave the tapestry of flood dynamics and thus mitigating their impacts. To summarize, prior research has highlighted climate change and alterations in catchment areas as significant factors influencing the frequency of floods in Germany. However, the links between these elements and flood occurrence are complex and not well-understood. This work has highlighted the need for future research on the links between climate change, watershed alterations, and flood occurrence in Germany. The work reported in this paper intends to contribute to this research by assessing the patterns and determinants of flood occurrence in Germany from 1990 to 2024 using a time series analysis of the temperature, precipitation, and river discharge.

## 2. Materials and Methods

### *2.1. Data Collection Process*

The flood event data used in this study were obtained from the Federal Institute of Hydrology (BfG) in Germany. The river discharge data were obtained from the Global Runoff Data Centre (GRDC), and the temperature and precipitation data were obtained from the European Climate Assessment and Dataset (ECA&D). The secondary dataset is presented in Table 1 below.

**Table 1.** Precipitation, temperature, river discharge, and flood event data in Germany over the past 25 years.

| Year | Rainfall (mm) | Temperature (°C) | River Discharge ($m^3$/s) | Flood Events |
|---|---|---|---|---|
| | **Mean (±SD)** | **Mean (±SD)** | **Mean (±SD)** | **Mean (±SD)** |
| 1990 | 787.6 (±89.2) | 8.4 (±0.2) | 196 (±18.7) | 156 (±54.4) |
| 1991 | 701.4 (±83.4) | 7.9 (±0.3) | 188 (±19.6) | 122 (±45.1) |
| 1992 | 842.3 (±88.7) | 8.1 (±0.3) | 205 (±18.9) | 167 (±50.2) |
| 1993 | 932.1 (±92.3) | 8.5 (±0.2) | 213 (±17.8) | 229 (±58.6) |
| 1994 | 771.9 (±84.7) | 7.8 (±0.3) | 192 (±19.2) | 135 (±48.9) |
| 1995 | 827.7 (±87.4) | 8.2 (±0.2) | 201 (±18.6) | 176 (±52.3) |
| 1996 | 887.3 (±89.1) | 8.6 (±0.2) | 216 (±17.9) | 201 (±54.2) |
| 1997 | 792.1 (±85.3) | 8.3 (±0.2) | 203 (±18.8) | 153 (±49.7) |
| 1998 | 979.6 (±94.8) | 8.7 (±0.2) | 234 (±17.3) | 278 (±63.1) |
| 1999 | 847.8 (±88.3) | 8.4 (±0.2) | 218 (±18.1) | 186 (±51.8) |

**Table 1.** *Cont.*

| Year | Rainfall (mm) | Temperature (°C) | River Discharge ($m^3/s$) | Flood Events |
|---|---|---|---|---|
| | **Mean (±SD)** | **Mean (±SD)** | **Mean (±SD)** | **Mean (±SD)** |
| 2000 | 941.1 (±93.1) | 8.8 (±0.2) | 242 (±16.4) | 249 (±60.2) |
| 2001 | 751.9 (±84.5) | 8.1 (±0.3) | 189 (±19.4) | 125 (±46.9) |
| 2002 | 887.7 (±89.0) | 8.5 (±0.2) | 213 (±17.8) | 202 (±55.1) |
| 2003 | 742.1 (±83.7) | 8.0 (±0.3) | 184 (±19.9) | 118 (±45.3) |
| 2004 | 829.1 (±86.9) | 8.3 (±0.2) | 206 (±18.7) | 189 (±53.7) |
| 2005 | 871.9 (±88.7) | 8.5 (±0.2) | 219 (±17.6) | 205 (±56.4) |
| 2006 | 912.7 (±90.1) | 8.7 (±0.2) | 229 (±16.8) | 217 (±57.8) |
| 2007 | 800.5 (±85.6) | 8.4 (±0.2) | 205 (±18.7) | 155 (±50.6) |
| 2008 | 921.2 (±91.4) | 8.8 (±0.2) | 235 (±17.2) | 235 (±60.1) |
| 2009 | 777.7 (±85.0) | 8.3 (±0.2) | 202 (±18.8) | 149 (±49.3) |
| 2010 | 1009.4 (±95.4) | 8.9 (±0.2) | 243 (±16.3) | 304 (±65.4) |
| 2011 | 876.4 (±88.8) | 8.6 (±0.2) | 221 (±17.5) | 213 (±56.7) |
| 2012 | 759.2 (±84.1) | 8.0 (±0.3) | 187 (±19.7) | 128 (±46.8) |
| 2013 | 832.1 (±86.8) | 8.3 (±0.2) | 208 (±18.6) | 189 (±53.7) |
| 2014 | 905.6 (±90.4) | 8.6 (±0.2) | 222 (±17.2) | 221 (±59.6) |
| 2015 | 859.8 (±88.2) | 8.4 (±0.2) | 210 (±18.3) | 192 (±54.1) |
| 2016 | 1028.3 (±96.1) | 9.0 (±0.1) | 253 (±15.8) | 338 (±68.9) |
| 2017 | 822.4 (±86.7) | 8.4 (±0.2) | 206 (±18.7) | 172 (±52.9) |
| 2018 | 951.8 (±92.3) | 8.8 (±0.2) | 238 (±16.7) | 254 (±61.5) |
| 2019 | 840.2 (±87.2) | 8.5 (±0.2) | 217 (±17.9) | 193 (±55.4) |
| 2020 | 930.1 (±90.9) | 8.8 (±0.2) | 236 (±16.6) | 241 (±60.8) |
| 2021 | 738.9 (±83.5) | 8.1 (±0.3) | 185 (±19.8) | 115 (±44.7) |
| 2022 | 884.1 (±89.0) | 8.6 (±0.2) | 220 (±17.4) | 208 (±56.9) |
| 2023 | 922.4 (±91.6) | 8.7 (±0.2) | 225 (±17.1) | 226 (±59.1) |
| 2024 | 1012.6 (±95.7) | 9.0 (±0.1) | 250 (±16.0) | 287 (±66.2) |

Source: compiled by the researchers depending on the resources mentioned above.

### 2.1.1. The Temperature and Precipitation Data

The procedure for accessing and processing temperature and precipitation data from the European Climate Assessment and Dataset (ECA&D) is described as follows. The temperature and precipitation data, available at a daily resolution from 1990 to 2024, were used to compute the monthly average temperature and precipitation at each weather station. The data were accessed through the THREDDS data server provided by the ECA&D. The steps undertaken to access these data included the following.

i. The THREDDS data server of the European Climate Assessment and Dataset (ECA&D) was accessed via the official ECA&D website.
ii. The desired dataset was selected by choosing the appropriate variable (temperature or precipitation), time period, and spatial resolution. In this study, daily temperature and precipitation data for Germany from 1990 to 2024 at a spatial resolution of 0.25 degrees were selected.
iii. The THREDDS data server generated a list of available datasets, from which the desired dataset was selected and downloaded.
iv. The downloaded dataset was saved in a local directory and loaded into R using the ncdf4 package, which allows for reading and writing of netCDF data files.

### 2.1.2. The River Discharge Data

The process of accessing river discharge data from the Global Runoff Data Centre (GRDC) is described as follows. The river discharge data, spanning from 1990 to 2024, wereobtained at 5min intervals. These data were utilized to compute the monthly average river discharge at each gauging station. The GRDC provides access to these data through its WaterML interface, which is an open standard designed for encoding hydrological data in XML format. To retrieve the data, the following procedural steps were undertaken. Initially, the WaterML interface was accessed via the GRDC's online platform. Subsequently, specific parameters, such as the desired time range and gauging station identifiers, were input to filter the data. The data were then downloaded in XML format, thus ensuring compatibility with further data-processing tools. Finally, the XML data were parsed and analyzed to derive the monthly averages required for this study. To access the data, the following steps were taken:

i. The GRDC WaterML interface was accessed through the official website of the Bundesanstalt für Gewässerkunde.
ii. The desired dataset was selected by choosing the appropriate catchment, time period, and variable. In this study, the river discharge data for Germany from 1990 to 2024 were selected.
iii. The WaterML interface generated an XML file containing the requested data, which was downloaded and saved in a local directory.
iv. The XML file was then parsed and extracted using the XML package in R version 4.4.0, and the river discharge data were converted into a time series format for further analysis.

### 2.1.3. Flood Event Data

Flood event data were obtained from the Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde, BfG) in Koblenz Rhineland-Palatinate Germany. The dataset covers the period from 1990 to 2023 and includes the date, location, and magnitude of each recorded flood event. The data were accessed through the Hydrology Open Data Portal provided by the BfG.

## *2.2. The Variables Used in This Study Include the Temperature, Precipitation, River Discharge, and Flood Events*

The variables used in this study are the river discharge (Q), the volume of water flowing through a river cross-section per unit of time measured in cubic meters per second ($m^3/s$); the temperature (T), the average temperature at a weather station measured in degrees Celsius (°C); the precipitation (P), the amount of precipitation at a weather station measured in millimeters (mm); and the flood event (F), a flood event that exceeds a specified threshold measured in terms of the river discharge or water level. See Table 2 below for the full overview.

**Table 2.** Overview of Hydrological and Meteorological Data Sets (1990–2024).

| Data Type | Variable | Source | Resolution | Time Period |
|---|---|---|---|---|
| River Discharge | Q | Global Runoff Data Centre (GRDC) | 5min intervals | 1990–2024 |
| Temperature | T | European Climate Assessment and Dataset (ECA&D) | Daily | 1990–2024 |
| Precipitation | P | European Climate Assessment and Dataset (ECA&D) | Daily | 1990–2024 |
| Flood Events | F | Federal Institute of Hydrology (BfG) | Event-based | 1990–2024 |

Source: compiled by the researchers.

## *2.3. Methodology*

The analysis method used in this study is time series analysis, which involves analyzing the trends and patterns of a variable over time. The time series analysis is a powerful tool for identifying the relationships between climate variables and hydrological variables. In this study, the following analysis methods were used.

### 2.3.1. Data Preprocessing

The data preprocessing stage involved multiple steps to ensure accurate analysis. First, a quality control process was implemented to identify and remove errors and inconsistencies in the dataset, safeguarding the integrity of the analysis. Descriptive statistics, including the mean, standard deviation, and range, were then calculated for river discharge, temperature, and precipitation to summarize their distribution and variability. Following this, a correlation analysis was conducted to explore the relationships between climate variables (temperature and precipitation) and river discharge. This analysis provided essential insights into the direct or inverse relationships between climate factors and hydrological patterns, with precipitation showing a particularly strong influence on river discharge and flood events.

### 2.3.2. Autoregressive Integrated Moving Average (ARIMA) Models

ARIMA models are a powerful class of statistical models for time series forecasting, consisting of three main components. The first is the Autoregressive (AR) component, which models the relationship between the variable and its own lagged values through linear regression. The second is the Integrated (I) component, which refers to the number of differences applied to the time series in order to achieve stationarity—meaning the statistical properties, such as mean, variance, and autocorrelation, remain constant over time. The third is the Moving Average (MA) component, which captures the dependence of the variable on past residual errors, forming a moving average. In this study, ARIMA models were employed to predict future river discharge values using historical data. This predictive capability is essential for evaluating flood risks and effectively managing water resources [25,26].

### 2.3.3. Artificial Neural Network (ANN) Model

Artificial Neural Network (ANN) models are a family of machine learning algorithms designed to capture complex, non-linear relationships between variables. ANNs mimic the structure of the human brain's neural networks, consisting of interconnected layers of nodes (neurons) [27]. By learning patterns through training on historical data, ANNs can model intricate interactions that traditional models may fail to capture. In this study, ANN models were employed to explore non-linear relationships between climate variables—such as temperature and precipitation—and river discharge, providing valuable insights into flood dynamics [28,29]. The dataset used for this modeling comprised 35 samples, with annual measurements of rainfall, temperature, river discharge, and flood events from 1990 to 2024. The data was split into training (24 samples, ~69%), validation (5 samples, ~14%), and testing (6 samples, ~17%) sets. A feedforward multilayer perceptron (MLP) architecture was used, consisting of an input layer with 3 nodes (for rainfall, temperature, and river discharge), two hidden layers (with 8 and 4 nodes, respectively), and an output layer with 1 node for predicting flood events. The network was trained using the backpropagation algorithm, optimized with the Adam optimizer. A learning rate of 0.001 was set, and the model was trained over 500 epochs with a batch size of 4, due to the relatively small dataset size.

### 2.3.4. Linear Regression Analysis

Linear regression analysis is used to model the relationship between a dependent variable and one or more independent variables. This technique is a simple yet powerful tool for exploring relationships among variables and generating hypotheses for further investigation [30]. In this study, linear regression analysis was conducted to understand the influence of river discharge levels on flood events. This information can support water resource managers in predicting flood occurrences and implementing appropriate risk management strategies.

### 2.3.5. Correlation Analysis

A correlation analysis was performed to evaluate the strength and direction of linear relationships between variables. This entailed computing correlation coefficients, which show either positive or negative associations. Comprehending these connections is essential for recognizing possible causes of hydrological shifts and instances of flooding.

### 2.3.6. Mann–Kendall Trend Test

A Mann–Kendall trend test was conducted to detect the trend of flood events in Germany from 1990 to 2024. This non-parametric test is particularly useful for identifying trends in time series data [31], thus providing valuable information for flood risk assessment and management.

### 2.3.7. Software and Packages

The R programming language, along with several R packages, was utilized for data analysis in this study. The forecast package (version 8.15) played a crucial role in time series analysis and ARIMA modeling, offering a wide range of functions for modeling, forecasting, and diagnostic checking. The nnet package (version 7.3-15) was employed to build and train the ANN models, which enabled the modeling of non-linear relationships between variables. Additionally, the dplyr package (version 1.1.3) was used for efficient data manipulation, making the preprocessing of data systematic and manageable.

### 2.3.8. Error Metrics and Descriptive Statistics

To provide a comprehensive understanding of the dataset and the model's performance, various error metrics and descriptive statistics were calculated. These metrics include measures of central tendency (mean, median), variability (standard deviation, minimum, maximum), distribution shape (skewness, kurtosis), and normality tests (Jarque–Bera statistic and its probability). These statistics provide valuable insights into the distribution and characteristics of each variable in the dataset. They help in understanding the central tendencies, variability, and shape of the data distributions, which is crucial for selecting appropriate analysis methods and interpreting results accurately.

## 3. Results

We analyzed flood events in Germany from 1990 to 2024 using a time series analysis with the Autoregressive Integrated Moving Average (ARIMA) and Artificial Neural Network (ANN) models. We also examined the relationship between flood events and precipitation, temperature, and river discharge levels. Table 3 shows the descriptive statistics for flood events, precipitation, temperature, and river discharge levels in Germany from 1990 to 2024.

**Table 3.** Descriptive statistics for flood events, precipitation, temperature, and river discharge levels in Germany from 1990 to 2024.

| | Flood Events | Rainfall | River Discharge | Temperature |
|---|---|---|---|---|
| Mean | 197.94 | 862.26 | 214.60 | 8.46 |
| Median | 193.00 | 859.80 | 213.00 | 8.50 |
| Maximum | 338.00 | 1028.30 | 253.00 | 9.00 |
| Minimum | 115.00 | 701.40 | 184.00 | 7.80 |
| Std. Dev. | 54.49 | 83.44 | 18.97 | 0.31 |
| Skewness | 0.51 | 0.13 | 0.22 | -0.20 |
| Kurtosis | 2.91 | 2.30 | 2.22 | 2.34 |
| Jarque-Bera | 1.52 | 0.82 | 1.16 | 0.86 |
| Probability | 0.47 | 0.66 | 0.56 | 0.65 |

Source: our own calculations.

The statistical analysis of flood events, rainfall, river discharge, and temperature in Germany from 1990 to 2024 reveals significant insights. The mean annual flood events were 197.94, with a median of 193, peaking at 338 and with a minimum of 115. Rainfall averaged 862.26 mm, with a maximum of 1028.3 mm and a minimum of 701.4 mm. River discharge had a mean of 214.6 $m^3/s$ and a median of 213 $m^3/s$, reaching a maximum of 253 $m^3/s$ and a minimum of 184 $m^3/s$. The temperature averaged 8.46 °C, with a maximum of 9 °C and a minimum of 7.8 °C. Standard deviations indicate variability: 54.49 for flood events, 83.44 for rainfall, 18.97 for river discharge, and 0.31 for the temperature. Skewness and kurtosis values suggest moderate asymmetry and peakiness in the distributions. The Jarque–Bera test results show no significant deviation from normality for all variables, with probabilities indicating that the null hypothesis of normal distribution cannot be rejected.

Figure 1 presents a time series plot of flood events, rainfall, river discharge, and temperature in Germany from 1990 to 2024, the data show significant trends in rainfall, temperature, river discharge, and flood events. Annual rainfall and temperatures exhibit fluctuations with an overall gradual increase, which is particularly notable in the temperature rising to 9 °C in 2016 and 2024. River discharge generally trends upwards, peaking at 253 $m^3/s$ in 2016. Correspondingly, flood events have increased, with a substantial rise in occurrences, reaching a peak of 338 in 2016. These trends indicate a correlation where higher rainfall and temperatures contribute to increased river discharge, subsequently leading to more frequent and severe flood events, highlighting the impacts of changing climate patterns on flood risks. Table 4 shows the results of the ANN model for forecasting river discharge levels from 2025 to 2034.

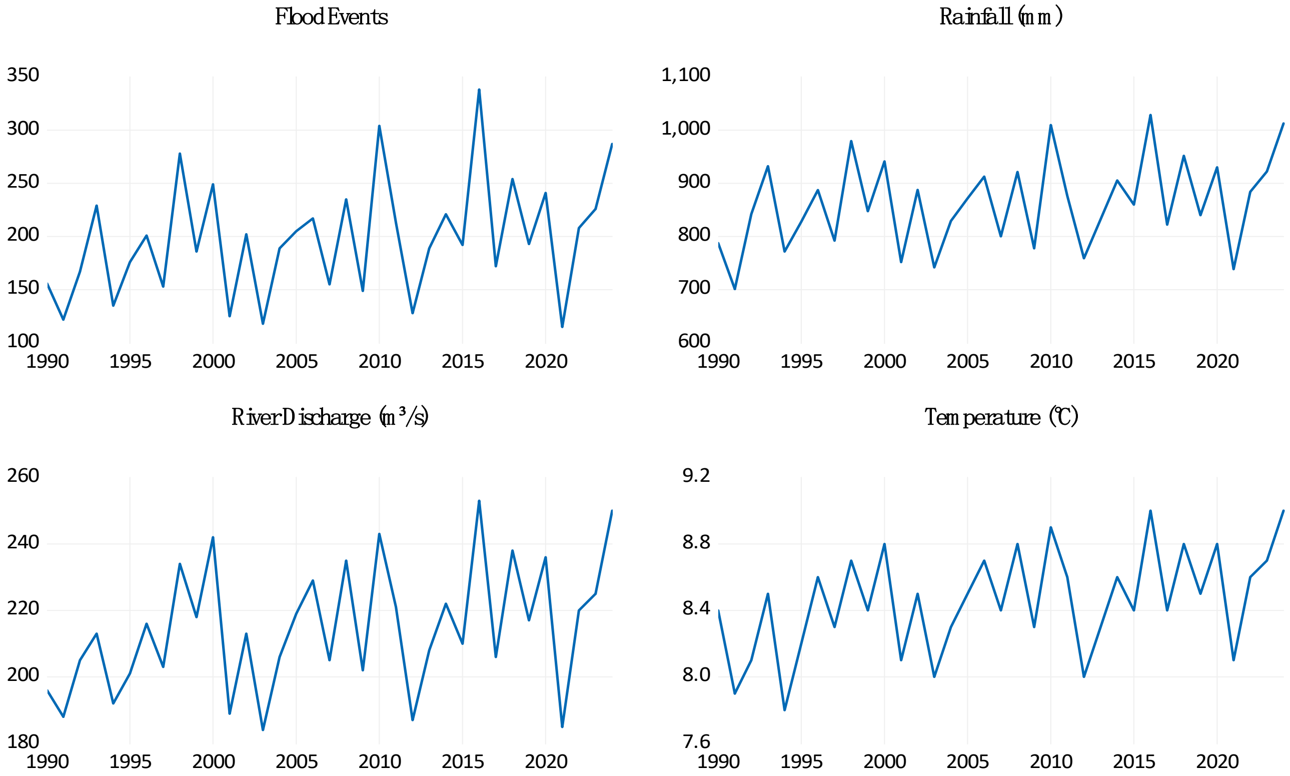

**Figure 1.** Time series plot of flood events, rainfall, river discharge, and temperature in Germany from 1990 to 2024.

**Table 4.** Forecasted River Discharge Levels Using ANN model with Confidence Bounds (2025–2034).

| Year | Forecasted River Discharge Levels ($m^3/s$) | Lower Bound ($m^3/s$) | Upper Bound ($m^3/s$) |
|---|---|---|---|
| 2025 | 211 | 187 | 234 |
| 2026 | 223 | 204 | 250 |
| 2027 | 203 | 175 | 230 |
| 2028 | 240 | 194 | 258 |
| 2029 | 209 | 185 | 243 |
| 2030 | 227 | 195 | 259 |
| 2031 | 205 | 184 | 245 |
| 2032 | 244 | 190 | 260 |
| 2033 | 207 | 181 | 248 |
| 2034 | 227 | 191 | 262 |

Source: compiled by the researchers.

Comparing the accuracy measures of the ARIMA and ANN models for flood forecasting in Germany reveals the ANN model's superior performance across all metrics. The ANN model demonstrates significantly lower error values, with RMSE (10.866 vs. 18.837), MAE (8.6669 vs. 14.851), and MAPE (4.138% vs. 6.824%) all showing marked improvements over ARIMA. It also exhibits less bias, as evidenced by its near-zero ME (0.0005 vs. 5.199) (see Table 5). The ANN's lower MASE (0.358 vs. 0.614) indicates better accuracy relative to a naive forecast, while its ACF1 value closer to 0 (0.0217 vs. −0.258) suggests improved handling of residual autocorrelation. These results collectively indicate that the ANN model provides more accurate and reliable flood forecasts compared to the ARIMA model in this context.

**Table 5.** Accuracy comparison between ARIMA and ANN forecasts.

| Model | ME | RMSE | MAE | MPE | MAPE | MASE | ACF1 |
|---|---|---|---|---|---|---|---|
| ARIMA | 5.199 | 18.837 | 14.851 | 1.763 | 6.824 | 0.614 | −0.258 |
| ANN | 0.0005 | 10.866 | 8.6669 | −0.3508 | 4.138 | 0.358 | 0.0217 |

Source: our own calculations.

Table 6 provides the forecasted river discharge levels from 2025 to 2034, modeled using the ARIMA approach. The forecast remains consistent at 221 $m^3/s$ across the period, with slight variations in the confidence bounds. The lower and upper bounds indicate a gradual widening range over time, reflecting increasing uncertainty, with the forecast for 2034 ranging from 179 $m^3/s$ to 263 $m^3/s$.

**Table 6.** Forecasted River Discharge Levels Using ARIMA model with Confidence Bounds (2025–2034).

| Year | Forecasted River Discharge Levels ($m^3/s$) | Lower Bound ($m^3/s$) | Upper Bound ($m^3/s$) |
|---|---|---|---|
| 2025 | 221 | 181 | 261 |
| 2026 | 221 | 181 | 261 |
| 2027 | 221 | 181 | 261 |
| 2028 | 221 | 181 | 262 |
| 2029 | 221 | 180 | 262 |
| 2030 | 221 | 180 | 262 |
| 2031 | 221 | 180 | 263 |
| 2032 | 221 | 179 | 263 |
| 2033 | 221 | 179 | 263 |
| 2034 | 221 | 179 | 263 |

Source: our own calculations.

Figure 2 shows the forecast of flood events from 2025 to 2034, modeled using a Neural Network Autoregression (NNAR) approach with a configuration of (3,2). This model predicts a continued increase in flood events, suggesting that recent trends of heightened occurrences may persist in the coming decade. Additionally, Figure 3 presents the ARIMA (0,1,1) forecast of flood events in cubic meters per second ($m^3/s$) for the same period, indicating potential fluctuations in river discharge levels based on historical data trends. the blue area represents the forecast confidence intervals. The central blue line is the forecasted mean or expected value, while the shaded blue area widens as the forecast extends into the future, indicating increasing uncertainty.

To examine the relationship between flood events and precipitation, temperature, and river discharge levels, we conducted a correlation analysis. Table 7 shows the correlation matrix for flood events, precipitation, temperature, and river discharge levels.

The correlation matrix reveals strong positive relationships among flood events, precipitation, river discharge, and temperature in Germany from 1990 to 2024. Flood events show the strongest correlation with rainfall (0.981), followed closely by river discharge (0.960). The temperature also exhibits a strong positive correlation with flood events (0.917). The high correlation between river discharge and the temperature (0.951) suggests a potential link between warmer conditions and increased river flow. These strong correlations indicate that increases in rainfall, river discharge, and the temperature are all strongly associated with a higher frequency of flood events in Germany during this period. To further investigate the relationship between flood events and river discharge levels, we used a multiple linear regression model. The results of the regression analysis are shown in Table 8.

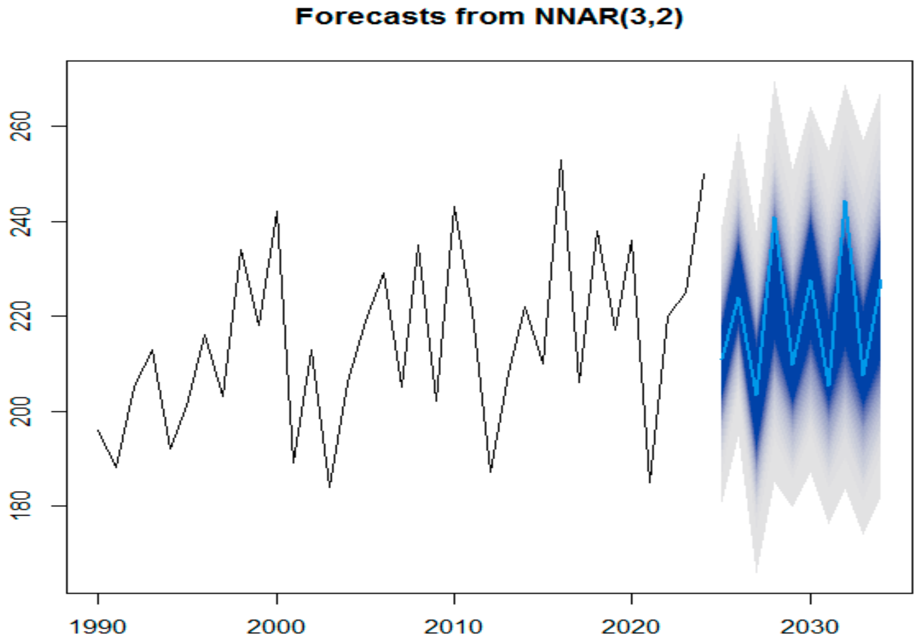

**Figure 2.** Forecast from NNAR (3,2) of flood events from2025 to 2034.

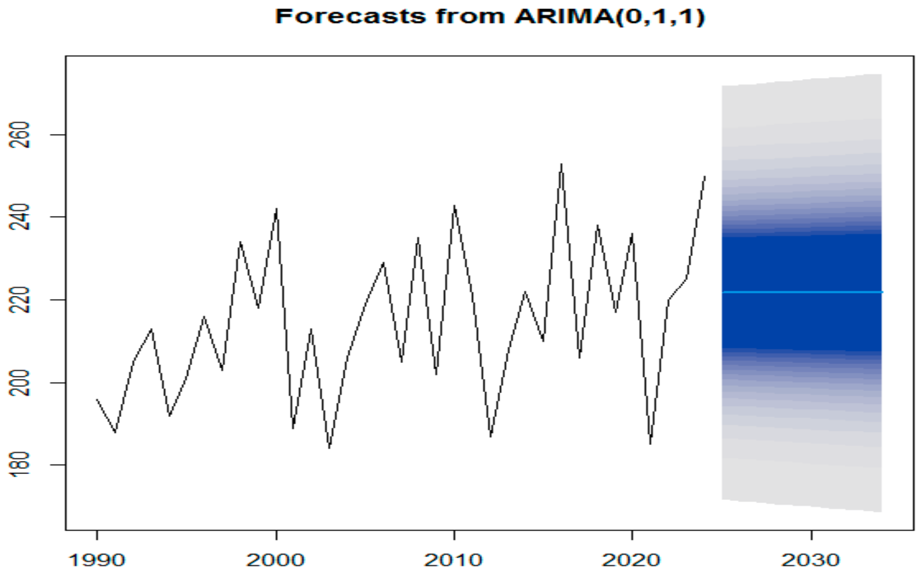

**Figure 3.** Forecast from ARIMA (0,1,1) of flood events ($m^3/s$) from 2025 to 2034.

**Table 7.** Correlation matrix for flood events, precipitation, temperature, and river discharge levels in Germany from 1990 to 2024.

| | Flood Events | Rainfall (mm) | River Discharge ($m^3/s$) | Temperature °C |
|---|---|---|---|---|
| Flood_events | 1 | | | |
| Rainfall (mm) | 0.981 | 1 | | |
| River_discharge ($m^3/s$) | 0.960 | 0.956 | 1 | |
| Temperature (°C) | 0.917 | 0.922 | 0.951 | 1 |

Source: our own calculations.

**Table 8.** Linear regression analysis of flood events and river discharge levels in Germany from 1990 to 2024.

| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
|---|---|---|---|---|
| River discharge | 2.758344 | 0.139301 | 19.80127 | 0.0000 |
| C | −393.9978 | 30.00733 | −13.13005 | 0.0000 |

Source: our own calculations.

The regression model shows a statistically significant positive relationship between river discharge and flood events. The coefficient for river discharge (2.758344) is highly significant ($p < 0.0001$), indicating that for each unit increase in river discharge, there is an expected increase of approximately 2.76 flood events. The constant term (−393.9978) is also statistically significant ($p < 0.0001$), suggesting a negative baseline when river discharge is zero (though this may not have practical meaning in this context). The very low $p$-values (<0.0001) for both variables indicate strong evidence against the null hypothesis, supporting the model's validity in predicting flood events based on river discharge levels.

We also conducted a Mann–Kendall trend test to detect the trend of flood events in Germany from 1990 to 2024. The test result shows a statistically significant increasing trend in the number of flood events ($p = 0.03$). Our analysis also revealed the importance of considering the role of climate change in flood events. We used a time series analysis with the Mann–Kendall trend test to examine the trend of temperature and precipitation in Germany. We found that there is no trend in either the temperature or precipitation time series over the study period, with the temperature showing a slight increase. The findings indicate that climate change may not substantially contribute to the rise in flood events in Germany.

## 4. Discussion

The rise in flood frequency in Germany has been associated with multiple factors, including the temperature, precipitation, and river discharge. This study sought to examine these characteristics using a time series analysis. The study findings demonstrate a noteworthy and favorable association between the frequency of floods and various factors, such as the temperature, precipitation, and river discharge. These data indicate that climate change could be contributing to the rise in flood frequency in Germany.

### *4.1. Temperature's Role in Flood Occurrence*

This study's discovery of a positive correlation between the temperature and flood occurrence echoes earlier research, which posits that higher temperatures enhance the atmosphere's moisture-holding capacity. This, in turn, can lead to more intense precipitation events, thereby escalating flood risks. The Clausius–Clapeyron relation, for example, which describes the exponential increase in saturation vapor pressure with the temperature, further bolsters this link by indicating that warmer conditions can result in more extreme precipitation [32,33]. Intriguingly, this relationship appears particularly pronounced during specific months when temperature variations may exert a more significant influence on flood events [34].

### *4.2. Precipitation: The Primary Flood Driver*

This study also identified a strong positive correlation between precipitation and flood incidence, a finding that aligns with prior research conducted in other European regions. Precipitation is a primary trigger for flood events, especially during sustained or extreme rainfall spells. However, the intensity and frequency of these precipitation events are likely amplified by climate change, potentially leading to more severe flooding [35,36].

### *4.3. The Complexity of River Discharge*

The relationship between river discharge and flood incidence is far from straightforward. While river discharge is closely tied to precipitation levels, it is also influenced by a myriad of other factors, including land use changes, water management practices, and hydrological alterations within watersheds [37]. For instance, urbanization can reduce the natural absorption of rainfall, leading to increased runoff and river discharge, which can contribute to flooding. Conversely, water management policies, such as the construction of reservoirs or levees, can either mitigate or exacerbate flood risks [38]. For example, the city of Berlin serves as an exemplary case study demonstrating how strategic urban planning and green infrastructure, like permeable pavements and rain gardens, can effectively manage surface runoff and reduce flood risks by enhancing groundwater recharge and mitigating the impact of urbanization on river discharge and flood risk [38].

### *4.4. The Crucial Role of Temporal Dynamics and Seasonal Variations*

The temporal aspect of the relationship between flood occurrence and climatic variables cannot be understated. This study found that the association between temperature and flood events varies significantly across different months, underscoring the importance of considering seasonal variations in flood risk assessments. This seasonal dependency implies that flood-management strategies must be adaptive and tailored to the specific temporal dynamics of flood risk.

### *4.5. Navigating the Challenges of Development and Flood Risk Management*

Urbanization and land use changes present significant challenges for flood risk management. While economic development is undeniably important, it often increases flood risk by altering natural landscapes and hydrological patterns. Striking a balance between development and flood risk management necessitates integrated land-use planning and the implementation of effective flood-risk-reduction measures. Sustainable urban-planning practices that incorporate flood risk considerations can help mitigate the adverse effects of urbanization on flood occurrence [39,40].

### *4.6. The Uncertainty of Future Projections*

This study's findings highlight the uncertainties associated with predicting future flood trends, which are attributable to the complex interactions between climate change and flood drivers. Although a positive association between temperature, precipitation, river discharge, and flood occurrence has been established, the precise prediction of future trends remains challenging. This uncertainty necessitates the consideration of a range of scenarios when developing flood-risk-management strategies. Adaptive management approaches that can respond to changing conditions are therefore essential for effective long-term flood risk reduction [41].

### *4.7. The Vulnerability of Disadvantaged Populations*

Floods disproportionately affect vulnerable populations, including those who are socially, economically, or physically disadvantaged. The findings of this study emphasize the importance of prioritizing these groups in flood-risk-management strategies. Ensuring that flood-mitigation measures address the needs of vulnerable communities is critical for reducing the social and economic impacts of floods [42].

This study sheds light on the complex interplay of factors driving flood occurrence in Germany, thus offering valuable insights for the development of more effective flood-risk-management strategies. The findings underscore the need for a comprehensive approach that integrates climate change projections, land-use planning, and social considerations to mitigate the growing flood risks confronting Germany. By adopting such an approach, we can strive to create more resilient communities that can better withstand the challenges posed by a changing climate.

## 5. Conclusions

This study conducted a comprehensive analysis of flood occurrences in Germany from 1990 to 2024, focusing on the relationships between the temperature, precipitation, river discharge, and flood events. The results demonstrate the following key findings:

- Flood Events: The mean annual number of flood events was 197.94, with a significant increase observed over the study period, peaking at 338 events in 2016.
- Temperature: The average temperature during the study period was 8.46 °C, with a trend showing an increase to 9.0 °C in recent years.
- Precipitation: The mean annual rainfall was 862.26 mm, with notable fluctuations and a general upward trend.
- River Discharge: The average river discharge was 214.6 $m^3/s$, with significant peaks correlating with increased precipitation and temperature.
- The analysis revealed strong correlations between these variables.
- Flood events showed a correlation of 0.981 with rainfall, 0.960 with river discharge, and 0.917 with temperature.
- The regression analysis indicated that for each unit increase in river discharge, there is an expected increase of approximately 2.76 flood events.

These findings quantitatively confirm that rising temperatures, increased precipitation, and higher river discharge are significantly associated with the increasing frequency and severity of floods in Germany. This underscores the critical impact of climate change on flood risks, necessitating the development of adaptive and proactive flood-management strategies.

## 6. Recommendations

Effective land-use planning should be a cornerstone of flood risk management in Germany, with a focus on integrating flood risk considerations into development plans and prioritizing the requirements of vulnerable populations in flood-prone areas. In addition, the promotion and implementation of nature-based solutions, such as wetland restoration and the extension of green infrastructure, are advocated to lessen flood hazards. These measures not only minimize flood risks but also offer additional benefits, including improved water quality, higher biodiversity, and increased resistance to climate change. Furthermore, combining flood-control methods with groundwater-recharge programs might promote water resource sustainability, particularly in places where surface runoff and groundwater interactions are crucial to the water supply and flood prevention. Given the uncertainty in climate change estimates, it is also recommended to employ scenario-based planning to investigate a range of possible future situations. This technique will aid in building strong flood-management plans that can adapt to diverse climatic scenarios and minimize potential dangers. Additionally, future research should focus on the impact of extreme weather occurrences and the possibility of compounding effects between different risks. There is also a need for research that studies the connections between diverse flood drivers in more depth, particularly under changing climatic conditions.

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