Non-stationary approach in the spatio-temporal analysis of precipitation time series

LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al Magnifico Rettore
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Non-stationary approach in the spatio - temporal analysis of precipitation time series

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Doctorate in Risk And Environmental, Territorial And Building Development

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POLITECNICO DI BARI

04
2024

DICATECh
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Approccio non stazionario nell'analisi spazio-temporale di serie storiche di precipitazione

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EXTENDED ABSTRACT (eng)

An increasing perception of climate change both on a global and local scale, on the one hand confirmed by the increase in average surface temperature of the oceans, and on the other one by the random extreme events occurring in different territories, creates the necessity of developing and use of hydrological tools and models in the framework of non-stationarity. In most official national guidelines for risk assessment the traditional stationary approach to hydrological modelling is still widely recommended. This thesis aims to strengthen the change of this paradigm in the statistical treatment of hydrological data, by enhancing methods for detection of non-stationarity in hydrological processes.

In these analyses I focus on the extreme hydrological events, especially on floods, mainly triggered by rainfall. In particular, my research concentrates on the analysis of the daily and hourly rainfalls recorded in Puglia (Southern Italy). These datasets are published in the Annals part I by Puglia Region Civil Protection Section. The thesis begins with a qualitative analysis, focused on identifying the number of consecutive missing data, to select the annual maxima precipitation time series that guarantee good quality, necessary to provide best interpretation of the results of the statistical tools used.

The non-stationarity in hydrology takes different forms, including abrupt change in datasets, trends, cyclicality, seasonality or combination of all or some of them. In accordance with the Italian Institute for Environmental Protection and Research (ISPRA), the search for change points for the time series is recommended to be conducted by the non-parametric Pettitt test which allows to identify abrupt and sudden changes in the series considered. Furthermore, in scientific literature the widely used non-parametric test, Mann-Kendall (MK) test is suggested to identify monotonic trends, then followed by the application of a further non-parametric measure of trend, the Sen's Slope. Indeed, in parametric methods the non-stationary character is exercised with the addition of the temporal variable

t in the probability distribution, thus increasing the number of parameters and making the process of estimating more onerous.

In this framework the Two-Stage (TS) method allows to tackle this problem by associating the temporal dependence directly to the mean and standard deviation of the observed data. Usually, the non-stationary character of the process is introduced by the addition of the temporal dependence *of the probability distribution's parameters, thus increasing the total* number of distribution parameters and thus making the computational process of inference more demanding. The TS incorporates time covariate directly to the first two moments, namely: mean and standard deviation, usually in the form of a linear trend in both the mean and variance, or just in the first or the latter.

Such an incorporation of the time in the moments tends to model the processes that concern the Earth sciences in a linear way, which is commonly accepted by the hydrological scientists and practitioners as a simple and parsimonious choice. However, in this work, I exploit the versatility and adaptability of the TS method, to investigate also non-linear trends, suggested by the temporal variability of datasets whose behavior resamples oscillations.

The aim of this thesis is to contribute to the complex interpretation of the hydrological processes that are nowadays in the center of the scientific debate. The acceptance of a more general approach, including feasibility and testing of non-stationarity of the extreme events, is undoubtedly the first step to enhance the design practice and, consequently, the natural hazards management, such as flood risk.

Keywords: Climate Change, Precipitation, Non-stationarity, Flood risk, Two-Stage, Trend

EXTENDED ABSTRACT (ita)

La crescente percezione del cambiamento climatico sia a scala globale che locale, confermata da un lato dall'aumento della temperatura media superficiale degli oceani e dall'altro dagli eventi estremi che in cui si imbattono diversi territori, induce nella comunità scientifica idrologica la necessità di utilizzare e sviluppare metodologie statistiche che contemplino l'ipotesi di non-stazionarietà dei processi. Tuttavia, negli strumenti attualmente utilizzati a livello tecnico ed istituzionale per la previsione degli eventi estremi l'approccio classico stazionario è ancora largamente applicato. Questa tesi mira a rafforzare il cambio di prospettiva nella trattazione statistica del dato idrologico, analizzando e rafforzando l'uso di tecniche per la individuazione della non stazionarietà dei processi idrologici. Tra gli eventi estremi annoveriamo le alluvioni la cui causa principale sono le precipitazioni che rappresentano, in questa analisi, il dato osservato. In particolare, sono analizzate le piogge giornaliere ed orarie facendo riferimento ai dati raccolti e pubblicati negli Annali parte I della Protezione Civile della Regione Puglia. Il lavoro di tesi si avvia con un'analisi qualitativa, incentrata sull'individuazione del numero di dati mancanti consecutivi, per selezionare le serie storiche dei massimi annuali di precipitazione che godono di buona qualità, necessaria per interpretare al meglio i risultati degli strumenti statistici utilizzati.

La non stazionarietà può essere individuata in diverse forme, tra cui change point, trend, ciclicità, stagionalità. In accordo con quanto proposto dall'ISPRA, la ricerca di change point per le serie storiche è stata condotta utilizzando il test non-parametrico di Pettitt che consente di individuare i cambiamenti bruschi e repentini delle serie considerate. Ampiamente diffuso in letteratura scientifica tra i test non parametrici, il test di Mann-Kendall (MK) è stato utilizzato per individuare trend monotoni, seguito poi dall'applicazione di una misura non parametrica del trend, la Sen's Slope. Al contrario, nei metodi parametrici il carattere non stazionario viene esercitato con l'aggiunta della variabile temporale t nella distribuzione di probabilità, rendendo più oneroso il processo di stima dei parametri.

Il metodo Two-Stage (TS), applicato in questa tesi, consente di superare tale ostacolo analizzando la dipendenza temporale direttamente sulla media e sulla deviazione standard del campione osservato. Si propongono i risultati ottenuti considerando il trend lineare nella media e nella varianza, o solo nella prima o nella seconda.

In genere, per semplicità si tende a ipotizzare che i trend osservabili siano di tipo lineare. In questa trattazione, grazie alla versatilità ed adattabilità del metodo TS, è stato possibile indagare su trend non lineari, il cui comportamento è assimilabile ad un'oscillazione.

L'obiettivo di questa tesi è quello di dare un contributo nell'interpretazione complessa dei processi idrologici che sono al centro del dibattito scientifico. La valutazione del carattere non stazionario degli eventi estremi è senza dubbio il primo passo affinché questo venga considerato nella pratica progettuale e, di conseguenza, nella gestione dei rischi naturali, come il rischio alluvione.

Keywords: Cambiamento climatico, Non-stazionarietà, Rischio alluvioni, Two-Stage, Trend

INDEX

1 INTRODUCTION

Changes in the rainfall regime and river flows lead hydrologists to develop methods for detection of non-stationarity for the frequency analysis of extreme events. On the other hand, in the engineering practice the stationary hypothesis is still considered the most robust approach, assuming that the natural systems are invariable over time and considering that a different hypothesis may lead to uncontrolled uncertainty in risk assessment. Milly et al. (2008) stated that “stationarity is dead” in the framework of water management, starting and stimulating scientific debate at an international level. In probabilistic terms, this results in removing the assumption of time-invariant parameters of probability density functions, whose estimates are based on recorded data (for example rainfall, hydrometric levels or discharge).

In the Article 1 of the United Nations Framework Convention on Climate Change climate change is defined as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.”

The observed climate change effects may be additionally accelerated by natural internal processes or external forces such as solar cycles modulation, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. In this sense, the acceptance of non-stationarity in hydrological cycle therefore has a significant impact on the management and mitigation of the risk of infrastructures that are part of an increasingly complex dynamic system.

Consequently, the management of water resources also requires in-depth analysis and thorough examination by scientists, who are expected to give an answer with a medium-long perspective. In fact, human activities are strongly influenced by the climate, especially agriculture which is doomed to modify its processes by adapting to new climatic conditions. For instance, between 2022 and the first five months of 2023, 432 severe extreme climatic events were recorded in Italy, which resulted in the estimates of the economic damage in the last 43 years to over 100 billion euros and more than 22 thousand deaths in total. Official data records provide that there were 310 extreme climatic events on Italian territory in 2022 (hailstorms, storms, tornadoes, etc.) which also caused 29 deaths, according to the Italian Society of Environmental Medicine (SIMA). In the first 5 months of 2023 there was a 135% increase in adverse phenomena compared to the same period in 2022: 122 extreme weather events between January and May. The flood in Emilia Romagna in May 2023 caused 17 deaths and damages of around 10 billion euros.

The urgent necessity to provide responses to the different communities has naturally been acknowledged by global and European institutions, which are gradually accelerating the intervention plans and strategies to be undertaken to diminish the negative results climate change and to limit the human impact on environment. The National Recovery and Resilience Plan (PNRR) is placed in this context, which in turn is part of the Next Generation EU (NGEU) programme, a 750 billion euro package, approximately half of which is made up of grants, agreed by the European Union in response to the pandemic crisis.

The PNRR investment projects are divided into 6 missions, including mission 2 called "Green revolution and ecological transition". This mission includes a sub-mission dedicated to the protection of the territory and water resources. In particular, there is a need to strengthen the forecasting capabilities of the effects of climate change through the creation of advanced and integrated monitoring and forecasting systems and a simplification and acceleration of the procedures for the implementation of interventions against hydrogeological instability and measures for the flood risk management. Ultimately, the PNRR wants to contribute to strengthening key skills, technological and knowledge transfer, and involvement of the Italian governance in disaster risk management, a better understanding of environmental, natural and anthropogenic risks as well as their interrelationship with the effects of climate change, the development of new monitoring methodologies/technologies through the strengthening of basic knowledge towards the application and exploitation of technologies, with the involvement of public administrations, stakeholders and private companies.

Indeed, every year in Italy the Institute for Environmental Protection and Research (ISPRA) processes the estimate of the components of the hydrological balance using the BIGBANG model, i.e. the GIS-Based Hydrological Balance at a national scale on a regular raster (Braca et al., 2021); the components analyzed are total precipitation, evapotranspiration, runoff and aquifer recharge. The update of the 2023 report on precipitation data from the regional hydro-meteorological offices alarms that in 2022 a minimum precipitation since 1951 with 719.1 mm of precipitation was noted. The average value for the period 1951-2022 is 949.9 mm, therefore there is a reduction or deficit in precipitation of approximately 24%. During 2023 this precipitation deficit on Italian territory occurred in a very diversified way, the most affected area was in the North-West Italy. While in the territory of the Southern Apennines District the deficit was smaller, equal to 9%.

Although, floods and droughts are opposite phenomena, they may have a common origin and interactions; long periods of drought drastically reduce the absorption capacity of the soil and, together with intense rainfall, increase the risk of floods and river overflows. In addition, the change in land use and cover is also one of the determining factors of the variability of the hydrological cycle. The growing waterproofed areas limit infiltration into the soil, consequently increasing surface runoff. This aspect is of crucial importance in the management and mitigation of hydrogeological and hydraulic risk in urbanized centres.

1.1 Objective of the thesis

The aim of this thesis is to contribute to the complex interpretation of the hydrological processes that are nowadays at the core of scientific debate. Methods for detecting and assessing a non-stationary nature of extreme events is undoubtedly the first step to enhance the design practice and, consequently, the natural hazards mitigation and management of flood risk. Furthermore, this thesis aims to give scientific support to decision makers in the context of the Regional Climate Change Adaptation Strategy for the Puglia Region (Italy).

The results of this thesis are part of an increasingly heated and current international debate (Raczyński and Dyer, 2023; Wubneh et al., 2023; Taylan et al., 2023; Amognehegn et al., 2023). The methodologies usually applied in this field, however, often refer exclusively to the use of non-parametric test, which do not provide a complete picture for the analysis and interpretation of the results.

The novelty of this work comes, on one hand, from the combination of parametric tests with non-parametric tests and, on the other hand, from the effort of modelling trends by means of cutting-edge statistical techniques based on parametric methods. The aspect of fundamental importance and novelty consist on the possibility of the visual, qualitative and quantitative analysis of results to identify a trend behaviour (parabolic, oscillatory and in general non-linear) in hydrological datasets. The proposed methodology allows to assume any type of trend function, making it adaptable and versatile and to translate it analytically into the system of equations to be solved to obtain the parameters of the fitted function. Results obtained with different methodologies do not always converge towards the same behaviour, but different forms of non-stationarity can be certainly detected.

1.2 Thesis outline

Chapter 2 describes a state of the art of the frequency analysis of extreme events, highlighting the notable aspects of both the classic and the more innovative approaches with a particular focus on the Return Period which represents the essential variable in the design of infrastructures or in soil conservation works.

Chapter 3 describes the study area. Starting from an orographic and hydrographic description of the Apulian territory, we move on to an examination of the datasets and of the data collection methods from the beginning in 1917 until today. The annual daily and hourly precipitation maxima represent the dataset of the analysis of this dissertation. In this chapter I will report the history of the various state and/or regional offices with the expertise in monitoring, collection and control of data with a focus on the quality of the data, necessary to select the historical series to analyse.

Chapter 4 illustrates the methodologies used in the search for forms of non-stationarity, in particular change points and trends. For detecting change point the Pettitt test was applied, while Mann-Kendall, Sen's Slope and Two-Stage methods for trend assessment. The Two-Stage method is applied, in a form of the 3 cases of linear trend (linear mean and constant standard deviation, constant mean and linear standard deviation, linear mean and standard deviation) and a non-linear one using a third polynomial degree.

Chapter 5 shows the results and critical discussions of the forms of non-stationarity investigated and their further developments, highlighting what are the salient aspects of the results obtained and outline what is still necessary to be deepened and continued in further research.

2 FREQUENCY ANALYSIS

The frequency analysis of extreme events (FA) aims to establish relationship between the magnitude of the event with its return period (TR), by means of the use of probability distributions. In this sense, time series which are mainly discharge and rainfall in hydrology, represent directly observed and measured values.

Hydrological processes are studied as stochastic processes, i.e. series of random variables having an assigned probability distribution whose observed data are represented by time series. In this specific discussion we will refer to time series of annual maxima precipitation (Annual Maxima, AM).

Cunanne et al. (1987) proposed a review of the methods commonly employed in Flood Frequency Analysis in which the relationship between the estimate of flood quantiles and the decision-making process to be undertaken is addressed. Regional flood frequency analysis (RFFA) is discussed in the context of regional smoothing of hydrological data, the concept of regional homogeneity is explained and the effect of inter-site dependence of flood data is discussed in Cunanne et al. (1988). Often, in order to enable practioners direct use for hydrologic modelling, the simplest distribution is used which correlates extreme rainfall or peak discharge with their frequency.

However, most FFA methods require certain properties of the datasets to be fulfilled. The first one is to consider the time series data as independent and identically distributed (iid). In the case of river flows, these are understood to be not subject to natural or anthropic changes in the hydrological regime and governed by a single probability distribution even in the case of large basins. Therefore, this means that the true probability distribution is unknown. The performance of distributions is evaluated by using different statistical tests.

All these assumptions have been widely discussed and debated in the scientific literature: Dalila et al. (2002), Yevjevich et al. (1968), Klemes et al. (l983a), Chow (1964), Yevjevich (1972), Haan (1977), Kite (1977), Singh (1987), Potter (1987), Duckstein et al., (1991), McCuen (1993), and Castellarin et al. (2001).

Later, Iacobellis et al. (2010) discussed the theoretically flood-derived frequency distributions in order to select the best model based on different runoff generation mechanism. In case of lack of peak discharge data, Eagleson (1972) allows to simulate the floods frequency based on reconstructed data. Allamano et al. (2009) examine the effect of temperature on Flood Frequency Analysis on mountains basins. Sivapalan et al. (2005) use the derived flood frequency model to analyze how to change the flood frequency curve due to climate change and land use. Laio et al. (2009) use the Akaike Information Criterion and the Bayesian Information Criterion to identify the probability distribution of hydrological extremes when the data sample is small and the probability distribution is asymmetric.

In this context, is essential to understand that the time series represent the starting point for estimating the relationship between peak discharge or extreme rainfall and the return period. Cunanne (1989) identifies three models of time series to analyze in Frequency Analysis:

- The annual maxima series (AM);
- The partial duration series (PD) or peaks over threshold (POT);
- The time series model (TS).

The use of the AM-based model may result in the information loss and this is discussed in Kite (1977) and Chow et al. (1988). This problem can be overcome by using the POT model where only the peaks above a certain threshold are considered, not excluding those that could be decisive for understanding how a flood event occurred; but in this case the observations may not be independent. So, in accordance to Cunanne (1989) the AM model is statistically more efficient than POT model.

Definitely, the data independence is ensured by the treatment of only maximum values, which excludes the possibility of treating two data points that belong to the same precipitation of flood event.

2.1 The concept of Return Period

Traditionally, extreme hydrological events have been treated in a stationary way in the field of probabilistic methods used in the design of hydraulic infrastructures, despite that much scientific literature has verified the presence of forms of non-stationarity in the recorded data (Olsen,1998; ISPRA, 2013). Therefore, here, in other words, I would like to give greater support to the hypothesis of non-stationarity in the definition of boundary conditions in the planning and management of water resources and related hydraulic infrastructures.

The forms of non-stationarity can be of different types: trend, sudden change (aka change point), cyclicality, seasonality. It is, therefore, appropriate to consider the non-stationary regime of events in the definition of the project variables that govern the infrastructures present in the area.

Cunanne (1989) defines the return period as the average time between flood events. It represents the reference quantity in the design of hydraulic structures and infrastructures. However, the relationship between probability of occurrence of an extreme event and its return period can be formulated as:

$$F(Q_T) = F(Q_T \leq q) = 1 - P(Q_T > q) \\ = 1 - \frac{1}{T} \qquad (1)$$

Where T is the return period, $P(Q_T > q)$ is the probability of exceedance and $F(Q_T)$ is the cumulative probability of non-exceedence.

Salas et al. (2014) widely discussed, treated and revisited the classical conception of the return period. The time series analyzed are both flood peaks and sea levels. The concept of non-stationarity is introduced in the definition of the return period by evaluating its entity in the case of events with increasing, decreasing or shifting trends. What emerges from the analytical treatment of the return period is that under the same value of project life (n) of the structure the risk of breakage (%) R increases considering the non-stationary type return period (Fig. 1).

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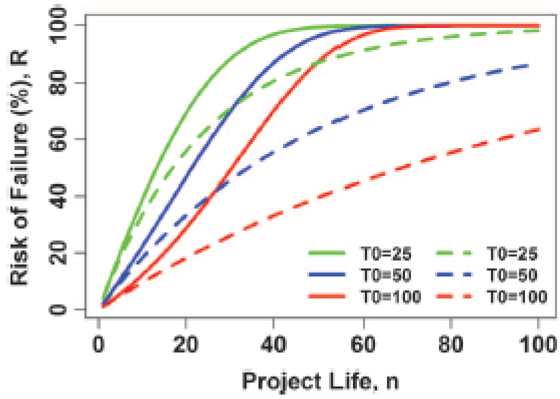


Fig. 1 – The dashed lines show the risk for the stationary condition, while the solid lines show the risk for nonstationary conditions assuming Return Period equal to 25, 50 and 100 years (Salas et Al.,2014)

3 STUDY AREA

Puglia is the region of peninsular Italy with the greatest coastal development and its territory is covered in 1.5% by mountains, 45.2% by hills and 53.3% by plains (Fig. 2). The study area coincides with the entire regional territory (Southern Italy) and, moving from South-West to North-East, is constituted by the Daunian Apennine, the Tavoliere plain and the Gargano promontory. The highest peak of the Daunian Mountains is Monte Cornacchia (1151 m a.s.l.) and is located on the border with the region, followed by the 1055 m high Monte Calvo in the Gargano promontory.

Going South, we find the Murgia, a rectangular plateau of karst origin which lies in the Bari area and in the province of Barletta-Andria-Trani and extends towards the provinces of Brindisi and Taranto, also extending towards the neighboring region of Basilicata.

The "heel" of Italy is represented by Salento which extends into the portion of territory between the Adriatic Sea and the Ionian Sea between the provinces of Brindisi, Lecce and Taranto. Salento has undergone phases of total and partial submersion and emergence, which have determined independent geomorphological evolutionary stages. However, the set of rock formations has physical characteristics that can essentially be traced back to two: the older karstifiable rocks, which allow the water to travel underground within the aquifers, and the more recent non-karstified and poorly permeable covering rocks, on whose surface they flow networks of short watercourses.

Fig. 2 – Geographical map of Puglia Region (www.regionepuglia.it)

The most important rivers inside and surrounding the study area are the Rivers Fortore, Candelaro, Carapelle, Cervaro and Ofanto, whose main streams cross or delimit the Tavoliere plain (Fig. 3). Due to the significant change in slope, from mountains to the plain, the regime of rivers in the area is torrential, and urban areas are prone to flash floods that may be triggered by frontal events, convective storms or Mediterranean cyclones.

Moreover, low-lying coastal areas are often affected by inundation phenomena due to the combined effect of heavy rainfalls and severe storm surges.

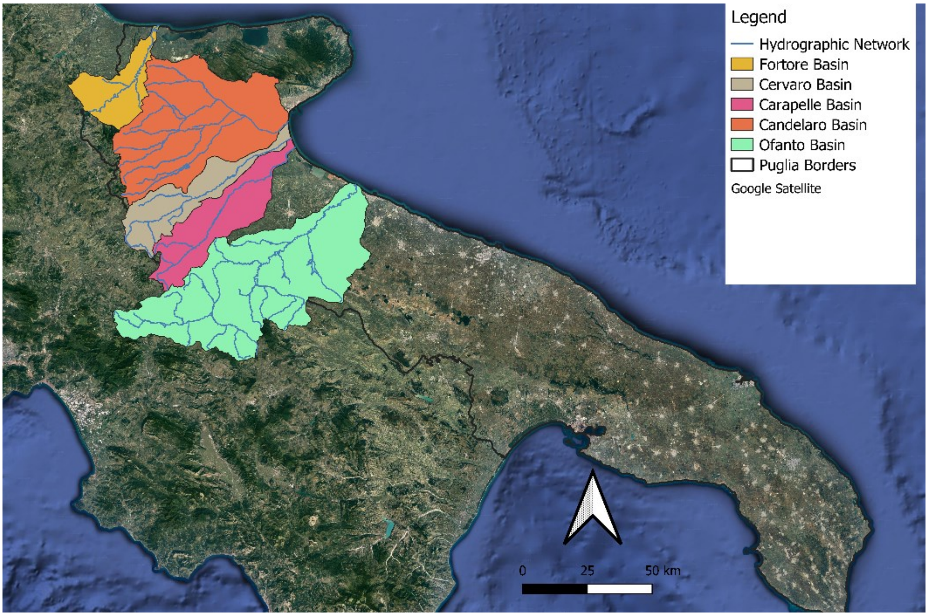


Fig. 3 - Apulian rivers, streams and basins

3.1 The climatology on study area

The climate of the Apulian region varies according to the geographical position and the shares on the average sea level of its areas. Overall, it is a Mediterranean climate characterized by warm and moderatily rainy summers and not excessively cold and medium rainy winters, with increased intensity of rainfall during the autumn season. The average temperatures are about 15-16 ^{o}C, with average values higher in the Ionic-Salentine area and lower in the Daunian and Gargano sub-Apennines. Summers are quite hot, with average summer temperatures ranging from 25 ^{o}C to 30 ^{o}C and peaks of over 40 ^{o}C on warmer days. On the Ionic side, during the summer period, particularly high temperatures can be reached, even above 30-35 ^{o}C for a long time. Winters are relatively temperate and temperatures rarely drop below 0 ^{o}C, except at the highest altitudes of the Daunian Sub-Apennines and Gargano. in most parts of the region the average winter temperature is higher than 5 C. The snow is rare, with exception of the high altitude areas of the Gargano and the Sub-Apennines (Cotecchia, 2014). Several consequent years can be snowless, especially in the southern Murgia and in the Salento . Precipitation is largely concentrated in the autumn (November-

December) and winter period, while summers are relatively dry, with zero rainfall even for long intervals of time or very concentrated heavy rain winds, but of short duration, especially in the Salento area.

3.2 Dataset

Currently, the Decentralized Functional Center (CFD) of the Civil Protection of the Puglia Region manages 300 hydro-meteorological stations located within the area of competence capable of acquiring the data in real time and with a frequency of one minute of:

- precipitation
- temperature
- air humidity
- atmospheric pressure
- speed and direction wind
- air humidity
- solar radiation
- river levels.

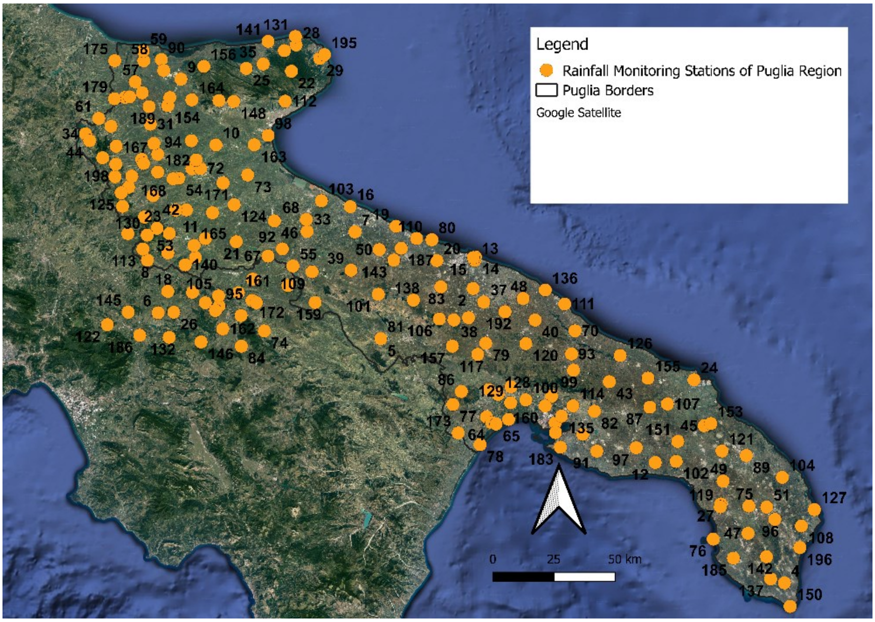


Fig. 4 - Hydro-metereological network of Decentralized Functional Center (CFD) of Puglia Region

The recorded data are collected, processed and published in the Hydrological Annals (https://protezionecivile.puglia.it/annali-e-dati-idrologici-elaborati). The Part I of the Annals contains data relating to thermometry, pluviometry, snow cover, atmospheric pressure and relative humidity, wind on the ground; the Hydrological Annals Part II contain annual data relating to meteoric inflows, hydrometry, flow rates and hydrological balances. The Hydrological Annals are available in paper format until 1996 and in digital format from 1997 to 2022.

The offices responsible for collecting and processing meteorological-hydro data throughout history have undergone several changes which are described in more detail in the next subparagraph.

3.2.1 Historical framework: since 1917 to today

The Italian Hydrographic Agency was established with Decreto Luogotenenziale of 17° June and 5° October 1917 at the “Genio Civile” Offices of the Ministry of Public Works with the aim of standardizing, organizing and making available pluviometric, hydrometric and tidal measurements in Italy. Before, such measurements were performed in an uncoordinated manner by individual facilities that had performed this task in pre-unification states (1861). The Hydrographic Service also proceeded, until its decommissioning, with the publication of the so-called “Hydrological Annals”, relating to the various compartments into which the territory had been divided. The compartmental division roughly followed the hydrographic basins of the main Italian rivers and took into account the particular administrative nature of the various territories, more precisely the 14 compartments were (Fig. 5):

- Po hydrographic office - Parma (Ministry of Public Works)
- Hydrographic office of the Water Magistrate - Venice (Ministry of Public Works)
- Genoa Section (Ministry of Public Works)
- Bologna Section (Ministry of Public Works)
- Pisa Section (Ministry of Public Works)
- Section of Rome (Ministry of Public Works)
- Pescara Section (Ministry of Public Works)
- Naples Section (Ministry of Public Works)
- Bari Section (Ministry of Public Works)
- Catanzaro Section (Ministry of Public Works)
- Palermo Section (Sicilian Region)
- Section of Cagliari (Sardinia Region)
- Section of Trento (Autonomous Province of Trento)
- Section of Bolzano (Autonomous Province of Bolzano)

Fig. 5 - Hydrographic compartment (retrieved from www.isprambiente.gov.it)

Subsequently, with Law 183/1989, it was established that the Hydrographic and Mareographic Services (the latter established with Law n. 1460 of 10/18/1942), unified in the National Hydrographic and Mareographic Service (SIMN), merged together to other technical services (seismic, dams and geological), already existing in the Ministries of Public Works and the Environment, in the National Technical Services of the Presidency of the Council of Ministers.

With the Presidential Decree 85/1991 (art. 22) new and broader tasks attributed to the SIMN were identified and described, including that of having to provide the survey, validation, archiving and publication of climatic, hydrological and hydrographic quantities affecting the surface and underground hydrographic network, lagoons, maritime climate, sea levels and coastlines. Furthermore, the same

Presidential Decree (art. 23) describes the organization of the SIMN, confirming its structure as it had evolved over time consisting of a central management (based in Rome), ten compartmental offices (Venice, Parma, Bologna, Pescara, Bari, Catanzaro, Naples, Rome, Pisa and Genoa), seven detached sections (Udine, Padua, Milan, Turin, Sondrio, Potenza and Florence) and the Strà workshop.

Furthermore, the SIMN is entrusted with the task of providing addresses for the Hydrographic Offices of Bolzano, Trento, Cagliari and Palermo in order to ensure coordination between the activity of the National Service and the aforementioned Offices. With Legislative Decree no. 112 of 31 March 1998 “Conferral of administrative functions and tasks of the State to the regions and local authorities, in implementation of chapter I of law 15 March 1997, n. 59” (Bassanini Law) it was ordered that the peripheral offices of the Department of National Technical Services be transferred to the regions (art. 92, paragraph 4).

The transfer was definitively sanctioned with the Prime Ministerial Decree of 07/24/2002, in which it was stated that from 1 October 2002 the compartmental offices were transferred to the regions where they were based to be incorporated into the regional operational structures responsible for the subjects. It was also established (art. 7) that to guarantee unity at the hydrographic basin scale and the coordinated management of compartmental functions, agreements were stipulated between the territorially interested regions, capable to guarantee the functioning of the detection networks on the basis of the standards set by SIMN, in agreement with the regions, as well as the continuity of the survey of SIMN's historical stations and the analysis, validation and publication of hydrological data at the river basin scale.

The Decentralized Functional Center (CFD), based in the Civil Protection Section of the Puglia Region, was established with DGR n. 2217 of 12/23/2003 and was declared active with DGR n. 2181 of 26/11/2013, transposing the PCM Directive of 27/02/2004 and Law no. 100 of 12 July 2012 containing "Urgent provisions for the reorganization of Civil Protection". With DGR n. 1571 of 03/10/2017, the Puglia

Region has updated the alert procedures of the regional civil protection system, defining the tasks and roles of each component.

The CFD of Puglia Region carries out its hydrogeological and hydraulic assessment activity autonomously, following the weather assessments developed by the Central Functional Centre, and is organized into three functional areas:

- Data collection and validation: area of collection, concentration, processing, archiving and validation of data collected on the regional territory through the meteorological-hydro-pluviometric monitoring network, also in real time;
- Data interpretation: area of interpretation and integrated use of the real-time data collected by the meteorological-hydro-pluviometric network and the information produced by the forecast models;
- Management of the information system: exchange of instrumental data, forecasting of ground effects, management of messaging and/or information from the territory, also in graphic form, between the Decentralized Functional Centre (CFD), the Regional Integrated Operations Room (SOIR) and the Central Functional Center (CFC).

3.2.2 Data Quality check

The highest quality of the data is guarateed by the regular submission of the time series to rigorous checks that ensure the absence of errors in the phases of observation, transcription and archiving of the data.

The ISPRA has proposed a procedure for automatic control of hydrological data based on the recommendations of the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) (Durre et al., 2010; Arquez et al., 2012). This procedure, which will be referred to below under the heading "the ISPRA protocol", is based on the implementation of a series of tests, statistical and otherwise, which have the objective of identifying different types of errors, such as impossible values, duplicate values, outliers, internal or temporal inconsistencies.

The National Oceanic and Atmospheric Administration (NOAA) checks ensure the good quality of the daily temperature, precipitation and snow depth series.

The ISPRA protocol divides the procedures for the quality control of hydrological series on the basis of the tests used. Based on this approach, the tests are divided into (i) basic integrity tests, (ii) tests for the identification of outliers, (iii) internal and temporal consistency tests and (iv) spatial consistency tests.

The basic integrity test can check for repeated values, data gaps, duplicate years and months, and unlikely values for both temperature and precipitation. The check identifies sequences of 20 or more identical consecutive values that are reported with a bad data flag.

The test for identifying anomalous values uses two different approaches, the first is the gap check while the second is a climatological check. The gap check is able to identify the tail values of the distributions that are very distant from the main probability mass of the distribution.

Climate control is based on the normalization of data and identifies those that exceed a certain threshold; this type of test is applicable only to long series.

Internal consistency tests check temperature jumps or inconsistencies between maximum and minimum temperatures, whereas temporal control occurs by evaluating the temperature differences between two subsequent days.

Finally, spatial consistency tests identify anomalous values missed in previous tests by comparing the data with neighboring measurement stations using statistical tools such as regression for estimating the variable.

The World Meteorological Organization proposes to combine automated procedures with the manual evaluation of lists of suspicious data to possibly maintain data correction. This last work was carried out as the first step of all the analyzes to follow. More precisely, in order to carry out as exhaustive a validation as possible of the annual maxima daily and hourly precipitation data, three different sources were compared:

- the Hydrological Annals, compiled by the Decentralized Functional Center of the Puglia Region and available, from 1921 to 2019, at the web address https://protezionecivile.puglia.it/centro-nazionale-decentrato/rete-di-monitoraggio/annali -e-processed-hydrological-data/hydrological-annals-part-i-download/;

- the elaborate Hydrological Annals, also drawn up by the Decentralized Functional Center of the Puglia Region: it is a series of Excel sheets in which the annual maxima hourly and daily rainfall up to 2013 have already been extracted; such data can be found at the web address https://protezionecivile.puglia.it/centro-nazionale-decentrato/rete-di-monitoraggio/annali-e-dati-idrologico-elaborati/annali-idrologico-parte-i-dati- historical/;
- the rainfall data contained in the report Evaluation of floods in Puglia.

From this qualitative analysis, it is important to establish robust methodology of correct management of hydrological data even in common hydrological applications, since the transmission of data containing typos can present a disturbing element in the analysis of time series, especially if aimed at evaluating climate trends. From this point of view, the availability of IT supporting tools opens the way not only to the digitization of data still present in paper format and/or not susceptible to IT processing, but also to the validation of those databases already transferred to electronic media.

Before tackling a quantitative study, it is advisable to carry out an exploratory or visual analysis using graphs which allow you to visually highlight missing data, seasonality and trends in the time series precipitation managed by CFD of Puglia Region.

The first graph useful for exploratory or visual analysis is the "Time Plot" or the chronological diagram through which the pattern of the variable with respect to time is highlighted. The time series can be represented as a line graph or histogram (Fig. 6**Errore. L'origine riferimento non è stata trovata.**). The latter is preferable when precipitation is the quantity to be evaluated.

The annual daily maxima precipitation time series of Bovino (FG) station is considered as an example, as it is one of the first stations to be installed; the years starting from the year of first recording are shown on the abscissa while the rainfall depth in millimeters is represented on the ordinate.

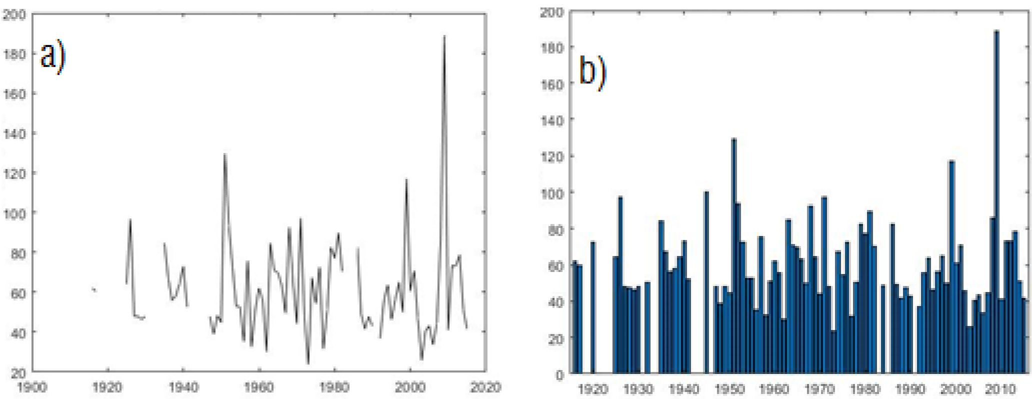


Fig. 6 – a) Line graph for Bovino rain gauge, b) Histogram for Bovino rain gauge

Fig. 6 indicates that the missing data are more frequent until the end of the 1940; furthermore, the presence of an extreme daily annual maxima in the year 2012 is noted with a sudden change compared to the temporal trend which could indicate the presence of an anomaly or suspicious data, e.g. due to the change of the measuring methodology.

Fig. 7 shows the Box Plot relating to the time series of the Bovino station of annual daily maxima; this graph is to describe how the sample is distributed through the position and dispersion indices and was obtained in the Matlab environment. In particular, boxplot allows to display five values of dataset (see Fig. 7): minimum value (first horizontal black line), first quantile 25% (first horizontal blue line), second quantile 50% or median (horizontal red line), third quantile 75% (second horizontal black line), maximum value (second horizontal black line); red crosses represent outliers.

To sum up, graphic or visual analysis allows to carry out a quick check on the time series of data which must then necessarily be supported by automated and systematic control procedures that allow incorrect or suspicious data to be identified in a short time.

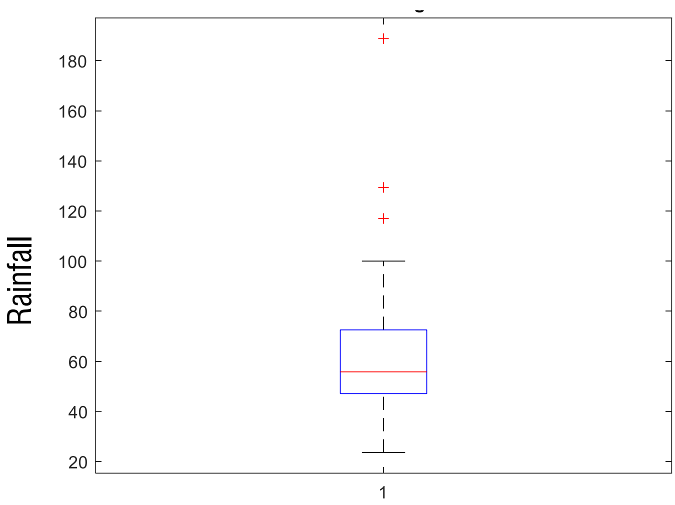


Fig. 7 - Boxplot for Bovino rain gauge

Missing values pose a problem in the analysis of time series and may be due to recording interruption due to instrument malfunction or maintenance. It is therefore necessary to quantify the presence of missing data to understand the reliability of the precipitation data in relation to the hourly, daily, monthly or annual time scale and evaluate its effects on the analysis and prediction. In this regard, we proceeded with an analysis of the missing data on the time series of daily and hourly annual maxima lasting 1, 3, 6, 12 and 24 hours of precipitation.

For each rain gauge station, the years of start and end of recording were retrieved, the length of the sample was determined, valid data and missing data were counted and the percentage of valid data for each station was highlighted as significant data (Fig. 8-Fig. 13).

In this sense, an analysis was conducted which reports the percentage of functioning stations and the number for both daily and hourly maxima precipitation, the numerical details are reported in Appendix B.

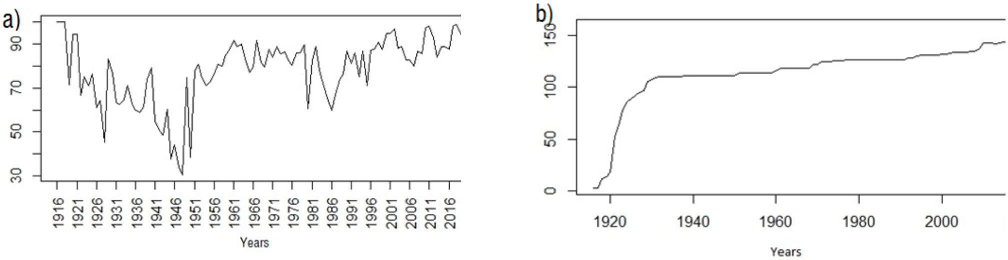


Fig. 8 - **a)** Percentage of working rain gauges on Y-axis (Annual maxima daily precipitation), **b)** Number of working rain gauges on Y-axis (Annual maxima daily precipitation)

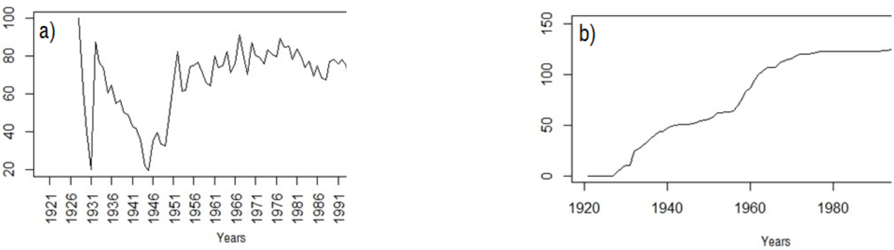


Fig. 9 - **a)** Percentage of working rain gauges on Y-axis (Annual maxima hourly precipitation - 1h), **b)** Number of working rain gauges on Y-axis (Annual maxima hourly precipitation - 1h)

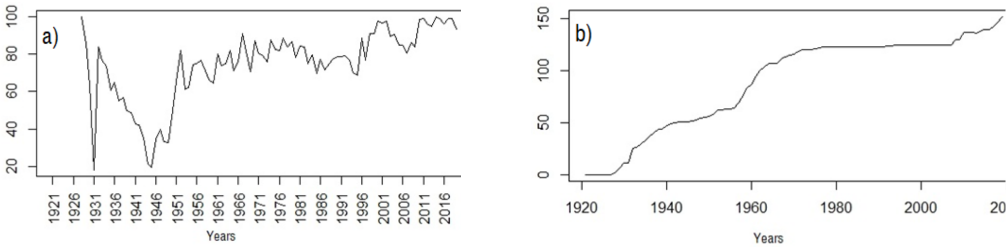


Fig. 10 – **a)** Percentage of working rain gauges on Y-axis (Annual maxima hourly precipitation - 3h), **b)** Number of working rain gauges on Y-axis (Annual maxima hourly precipitation - 3h)

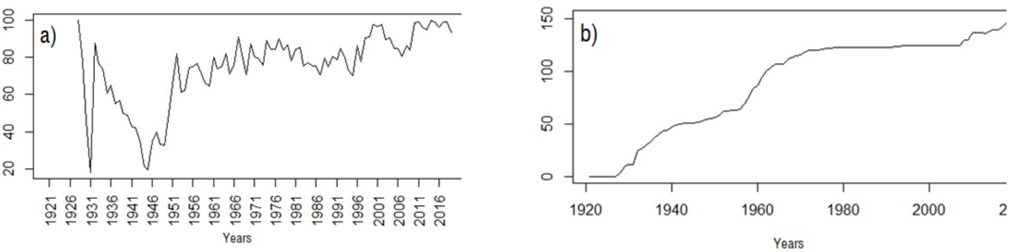


Fig. 11– **a)** Percentage of working rain gauges on Y-axis (Annual maxima hourly precipitation - 6h), **b)** Number of working rain gauges on Y-axis (Annual maxima hourly precipitation - 6h)

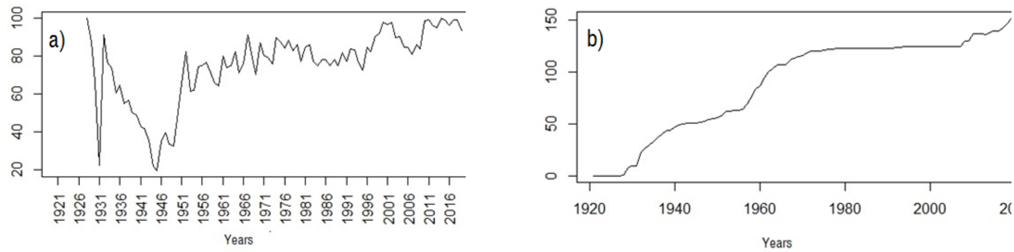


Fig. 12 – **a)** Percentage of working rain gauges on Y-axis (Annual maxima hourly precipitation - 12h), **b)** Number of working rain gauges on Y-axis (Annual maxima hourly precipitation - 12h)

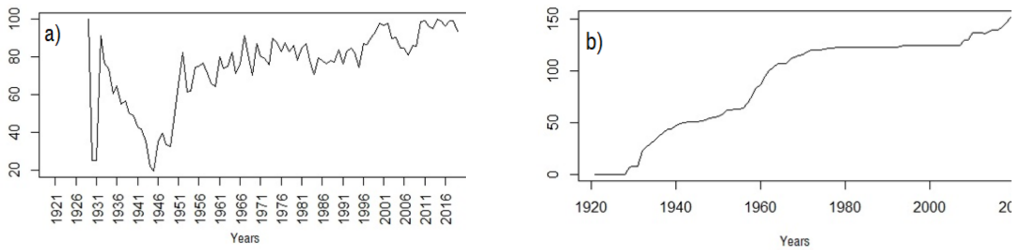


Fig. 13 – **a)** Percentage of working rain gauges on Y-axis (Annual maxima hourly precipitation - 24h), **b)** Number of working rain gauges on Y-axis (Annual maxima hourly precipitation - 24h)

3.2.3 The selection of time series in literature

The number of works in the literature relating to the selection of time series for an analysis of annual maxima trends is still modest and yet insufficient. Brunetti et al. (2001) studied daily precipitation in Italy for the period 1951-1996 and to estimate missing data they used the procedure proposed by Karl and Knigt (1998). Singh et al. (1997) manage missing value with entropy-based model. Bonaccorso et al. (2005), in analyzing series of annual precipitation maximums lasting 1, 3, 6, 12, 24 hours in the period 1921-2000 recorded in 16 Sicilian monitoring stations, chose to use those series with at least 50 years of observations. Cannarozzo et al. (2006) analyzed cumulative precipitation at annual, seasonal and monthly scales and found an amount of missing data equal to 16% (with a peak of 72% during the World War

2), reconstructed according to the scheme proposed by Bono et al. (2005). Arnone et al. (2013) in defining the stations to be analyzed in the interval 1929-2009 followed a two-step procedure: first, a time window was identified which corresponded to a number of functioning stations of no less than 60; finally, they analyzed stations with at least 40 years of valid data. Fioravanti et al. (2013), following the procedure proposed by Desiato et al. (2012), when analyzing data since 1961 (in order to guarantee a greater number of time series) they chose only those time series with:

- at least 86% valid data in the entire time series;
- no more than 4 consecutive years of missing data;
- end after 2007.

This last requirement is due to the need to put greater weight to the most recent data.

This type of approach, capable of combining missing data both in relation to their total number and their consecutive arrangement, was considered more similar to our analysis. In order to obtain a graphical evaluation of the quantity of stations that can be used for the analysis, a parametric analysis was conducted using different combinations of the maximum consecutive number of missing data and the maximum percentage threshold of valid data. Moving from a more liberal to a more restrictive hypothesis on the consecutive number of missing data, the number of stations that can be analyzed decreases significantly; this means that few stations have good data quality.

In the case of hourly durations, the discontinuity of time series is considerably higher than that of daily ones, which effectively makes an analysis of change points inapplicable for these durations. Therefore, it was decided to limit the analysis of change points only to the annual maxima daily precipitation.

The absence of continuous time series should theoretically prevent any type of analysis; however, setting a more restrictive criterion than that proposed by Fioravanti et al. (2013) seems reasonable to obtain a rough indication of missing data.

3.2.3.1 Case study: the time series selected in Puglia Region

In this sense, we chose to conduct the analysis by setting a maximum consecutive number of missing data equal to 1 and a percentage of valid data equal to 95%. This criterion is applied to the annual maxima daily precipitation time series and the rain gauge identified are shown in Fig. 14.

The need to use such a stringent requirement is motivated by the following consideration: from the visual analysis of the annual maxima precipitation time series, it emerged that the only trend that can be assimilated to a 4-5 year minimum located approximately close to the beginning of the 1980s: since this is an extremely narrow interval, it is estimated that increasing the consecutive number of missing data, especially if located in this time band, could reduce the power of the test to unacceptable values.

Given the need to also conduct a trend analysis for hourly durations, it was decided to conduct it exclusively for the same stations chosen for the daily precipitation.

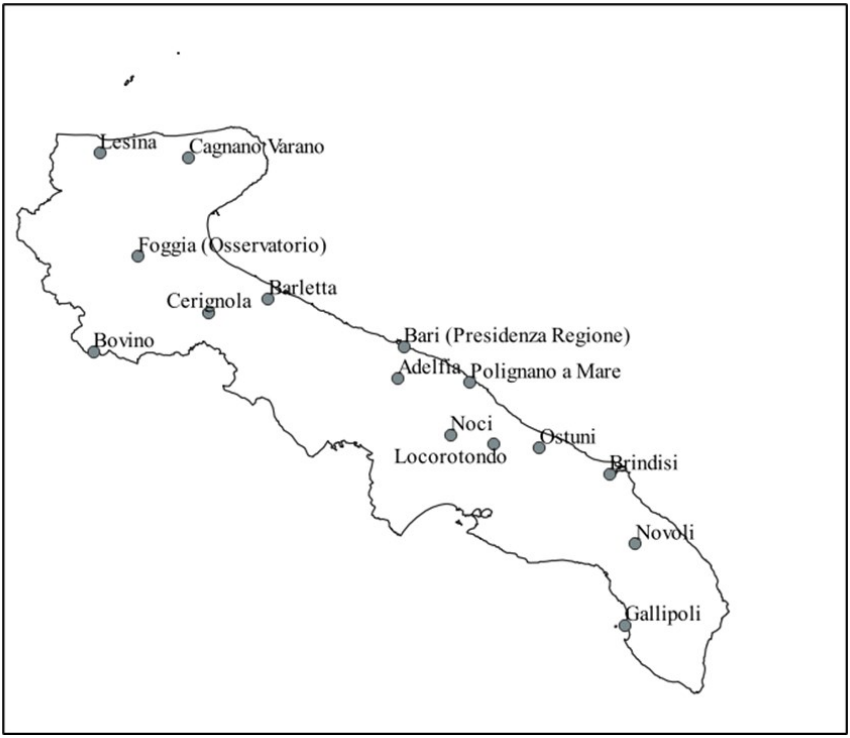


Fig. 14 – Rain Gauges Selected

3.3 *On importance of metadata in statistical analysis*

Reliable metadata are necessary to ensure the user has no doubts about the conditions under which the data was recorded, collected and transmitted, to obtain accurate assessments from their analysis. The length of the series and its quality for assessments also on climate change are of fundamental importance.

According to the "Guidance on Metadata and Homogenization" (Aguilar et al., 2003) each station must be identified by name and code and must be geolocalised, furthermore, information on the start and end date of recording constitute minimum requirements.

Tab. 1 - Rain Gauge Metadata

ID	Rain gauges	X (LON)	Y (LAN)	Elevation	First recording year
1	Adelfia	41.0040	16.8508	153	1922
2	Bari Presidenza Regione	41.1197	16.8819	17	1938
3	Barletta	41.3006	16.2003	30	1959
4	Bovino	41.1008	15.3181	623	1917
5	Brindisi	40.6339	17.9117	22	1936
6	Cagnano Varano	41.8336	15.8003	167	1921
7	Cerignola	41.2506	15.9003	134	1921
8	Foggia (Osservatorio)	41.4617	15.5431	94	1934
9	Gallipoli	40.0544	17.9944	31	1934
10	Lesina	41.8506	15.3500	17	1928
11	Locorotondo	40.7500	17.3333	397	1964
12	Noci	40.7839	17.1167	423	1921
13	Novoli	40.3669	18.0506	51	1923
14	Ostuni	40.7339	17.5669	115	1958
15	Polignano a Mare	40.9836	17.2167	50	1927

The assessments on the length of the time series and on missing data are part of the cognitive framework necessary to interpret the results of the statistical tests to which the time series are subjected. To support this thesis, further study is appropriate on the instrumentation used over the years. In particular, it is necessary to consider the technical characteristics of the rain gauges that have been used by the competent offices as reported in Chapter 3.2.1

A survey carried out within the Civil Protection Decentrate Functional Centre (CFD) of the Puglia Region, provides information of great importance and was obtained for this study relating to the history of the instrumentation used to record and collect the data.

From the day of the establishment of the Hydrographic Office until 1984, the pluviograph was the instrument used to record rainfall data, which was a completely mechanized piece of equipment. The basic functional scheme of pluviograph is as follows: the rain water enters from a funnel and is conveyed into a cylindrical container which raises a connected float to a writing tip on a clockwork drum. The aforementioned tip traces vertical lines from top to bottom depending on the amount of rain that has fallen. Once the container is full, it is automatically emptied using a siphon system and at this moment the writing pen reaches the highest point in the diagram.

In Puglia, the tilting rain gauges are used; in this system there is a double body tray that can oscillate around a pin. The water is conveyed into one of the two bodies of the tray and as soon as this is half filled it tilts due to the moment with respect to the pin on which the tray is hinged. The capacity of the tray body is 0.2 mm. In this case the rocker is connected to the ink nib resting on a rotating drum on hich graph paper is placed. The diagram of the tipping rain gauge is shown in Fig. 15.

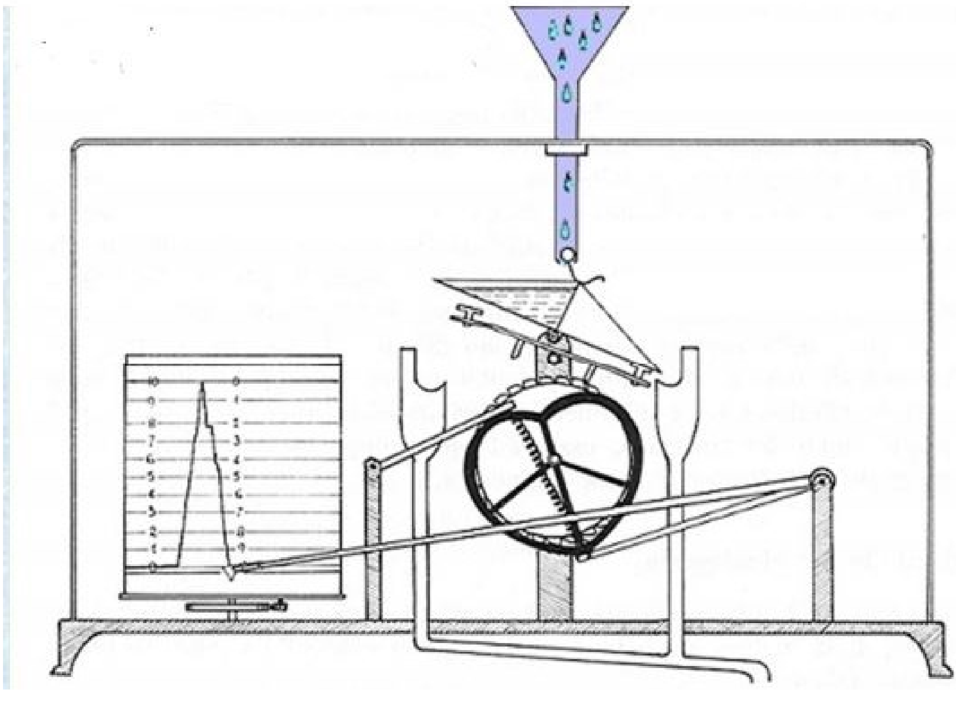


Fig. 15 – Rain gauge with bascula system (retrieved from www.protezionecivilebasilicata.it)

Starting from 1984, the rain gauge network made up entirely of mechanical equipment was gradually integrated with digital rain gauges. The advent of digital technology meant that the first rain gauges were equipped with a battery, but of short duration, which made it necessary to carry out almost daily checks on the actual functioning of the instrument. Furthermore, the data were recorded local means such as floppy disks and later read by the computer. The first digital rain gauge integrated into the current monitoring network is the SIAP SM 3810 model from 1984. Initially, the presence of mechanical and digital instrumentation, i.e. the rain gauge and the pluviograph, was necessary for the calibration of the digital instrument. Starting from the 1990s, the SIAP SM 3820 rain gauges were replaced by the SIAP SM 3810 models and added in number, this new model was characterized by having a larger memory card and longer-lasting batteries. At the same time as using the SIAP SM 3820 model, the competent office equipped itself with a new ETG model rain gauge installed first at the current station "Bari Idrografico". All ETG sensors transmitted both locally and via GSM (Global System for Mobile Communication). Between 1995 and 1998, the SIAP SM 3840 model was used, whose transmission was via radio, following which all the mechanical instruments were uninstalled, therefore it can be assumed that all rainfall measurements starting from 1999 are measured remotely.

4 METHODOLOGY

4.1 An overview on non-stationary approach

Concerning time series analysis, statistical stationary is defined as an equilibrium state in which the processes are independent of time. One of the first fundamental studies on statistical stationarity date back to early 1970s (Box et al., 2008) when linear stochastic models were studied. Over the years, authors focused in analyzing how non-stationarity manifests in hydrological time series. Most common approaches investigate the presence of linear trends or change point in records as possible indicators of changes in the hydrological regime.

Emphasizing the growing relevance of the topic in the scientific discussion, this chapter aims to critically analyze the most used techniques for identifying change point and trend detection. Among the methods used for trend detection in the scientific literature are: (i) linear regression with significance test over the adjusted slope (Alpargu and Dutilleul, 2003), (ii) Student's t test (Martìnez-Rutera et al., 2021), (iii) Mann-Whitney U test (Zhang and Lei, 2014), (iv) Spearman's rho test (Hamed, 2016; Anghileri at al., 2014), (v) Mann-Kendall test (Yue and Wang, 2004; Hamed and Rao, 2004; Hamed, 2008; De Silva at al., 2015), (vi) wavelet transform (Alpargu and Dutilleul, 2003) and Sen's Slope (Gedefaw et al., 2018).

The existing hypothesis tests fall into two categories: parametric tests and nonparametric tests. The first category includes tests in which the distribution of the data is known or assumed. Obviously, in the case of hydrological modelling the real probability distribution is unknown, but it is a matter of hypothesizing the one that comes closest to reality by making approximations. This is the reason why non-parametric tests are sometimes preferred which however lack less power as discussed in Chebana et al., 2013. The null hypothesis that governs the test must be stated at the beginning so as not to influence the researcher (Von Storch and Navarra,1999; Koutsoyiannis, 2006). Furthermore, the sample data must be independent and identically distributed (iid), as already mentioned in the previous paragraphs, this problem is overcome by choosing to analyze only the maximum annual precipitation.

Otherwise, the presence of autocorrelation can falsify the final result by providing unreal trends. Wilks (2006) proposes a technique for estimating the effective sample size by eliminating autocorrelation, while von Storch and Navarra (1999) uses prewhitening which returns a sample with zero mean and finite variance, as also widely discussed in Yue et al., 2002. Also, the autocorrelation may be removed by resampling techniques (Yue and Pilon, 2004).

Among the parametric tests widely used in the literature, one can find the Student's t which assumes data normally distributed and equates the subsamples means. It is used for instace to investigate how land use changes affected streamflow regime (Müller et al., 1998; Batista et al., 2009; Detzel et al., 2011; Fill, 2011). To analyze monotonic trends in time series, Spearman's rho (S) and Mann-Kendall (MK) tests are proposed as the most commonly used inferences. Thay are nonparametric ranked-based tests and have very similar power in detecting a trend (Yue et al., 2002), even though only the MK test is recommended by the World Meteorological Organization (Liang et al., 2011) for this task. Villarini et al. (2011) applied the MK test in maximum streamflow series for 196 North American gauges, finding few significant trends in mean.

4.1.1 Focus of the thesis

Having examined the state of the art on tests in the literature, in this work the most widespread and widely applied non-parametric tests in the literature were chosen and critically analyzed. In this dissertation, the focus is on non-stationarity form in terms of change points and trend present in annual precipitation maxima. To analyse the change points, the non-parametric Pettitt test is employed, while for trend detection the non-parametric Mann-Kendall and Sen's slope tests are applied. This type of test has the advantage of being independent of the probability distribution of the data, which makes it more reliable the result it is devoid of the hypothesis on the parent distribution to be adopted on the data; this is the first step that is done in the frequency analysis of extremes. On the other hand, parametric tests have the disadvantage of considering only the linear trend in mean of data, which may not be the best fit.

A greater contribution was made for the Two-Stage method which falls into the category of parametric tests, it represents an innovative applications over Italian territory and specially for civil protection purposes. In this sense, it was possible to consider the trend both in average and in variance. Moreover, for the first time, the Two-Stage has been applied with a non-linear approach that represents the turning point of this research. Results highlight the high versatility and adaptability of the Two-Stage that I believe can be applied and extended to the whole Italian territory to look for similarities in results, and provides an original assessment of climate change not available in literature. Often, the results relating to linear trends are heterogeneous spatially and do not allow to have a well-defined and clear view of the trend in extreme rainfall. Being of parametric type, the Two-Stage, applicable to any distributions of probability, allows to calculate and to define the quantiles of the reference hydrological quantity with a short-medium term forecast of the order of 5-10 years, both for the planning of the climate change adaptation strategy and for the management of water resources. The application to rainfall data also is feasible for application in management of artificial reservoirs, and can be used for the management of water resources to different uses thanks to the estimate obtained with TS for quantiles. The presence of non-stationary patterns supports the hypothesis of climate change. It is a scientific responsibility to identify, comprehend, and critically analyze the outcomes achieved with advanced hydrological methodologies. Answers and strategies should be given to communities that, due to frequent extreme events, are experiencing economic and asset losses. In this way, the analyses and the products obtained represent a new factor for both local stakeholders and hydrologists in the scientific discussion.

4.2 Change point detection and Pettitt Test

In accordance ISPRA's protocol, the search for change points in the time series of annual maxima precipitation was conducted using the Pettitt test (two-tailed) introduced in Pettitt, 1979.

In general, the statistical analysis for identyfing change point answers the following questions:

- are there one or more changes?
- When such changes occurred?
- are they statistically significant?

The Pettitt's test does not require any particular hypotheses on probability distribution of data. Furthermore, the null hypothesis H_0 is "there is no change point", which means that:

- When the null hypothesis H_0 cannot be rejected, the data do not present significant change point;
- When the null hypothesis H_0 is rejectable, the time series present significant change point.

This is a test that allows you to identify abrupt and sudden changes in the X_t variables at an unknown moment.

The Pettitt Test statistics is:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(X_i - X_j), \qquad \mathrm{t} = 1, \dots \mathrm{T} \qquad (1)$$

where "sgn" is the sign function. The values obtained by applying (1) allows to evaluate the K_T statistic for the test with null hypothesis "H_0: absence of a change point" against the hypothesis "H_1: presence of a change point" expressed by (2). If the direction of the sudden increase or decrease is not known, (2) changes to (3) and (4) respectively.

$$K_T = \underbrace{max}_{1 \le t < T} |U_{t,T} \quad (2)$$

$$K_T^+ = \underbrace{max}_{1 \le t < T} U_{t,T} \quad (3)$$

$$K_T^- = \underbrace{-min}_{1 \le t < T} U_{t,T} \quad (4)$$

It was demonstrated in Salas and Obeysekera (2014) that the distributions of K_T^+, K_T^- and K_T under the null hypothesis fulfill the following relations:

$$\Pr\,[K_T^+ > k^+] = exp\{-6(k^+)^2/(T^3 + T^2)\} \quad (5)$$

$$\Pr\,[K_T > k] \approx 2exp\,\{-6(k^+)^2/(T^3 + T^2)\} \quad (6)$$

For symmetry properties, Equation (5) also holds for K_T^-. k^+, k^- and k represent the values of K_T^+, K_T^- and K_T respectively. Set a significance value α, k value is calculated and Pr [K_T >k] is evaluated, if the latter is less than α then the null hypothesis H_0 can be rejected, otherwise H_0 cannot be rejected. Furthermore, equation (6) is accurate to the second decimal place for probability values less than 0.5, i.e. those of interest for detecting valid change point on the significance levels most commonly used in hydrological analyses (0.10, 0.05, 0.001). For these analyses, the significance level chosen is 5%. The results of this test for the time series of annual maxima daily precipitation, obtained using the R trend package discussed in Pohlert (2016), are reported in Chapter 5.1.1 to 5.1.6.

The test does not require the data series to be normally distributed, it can also be used with missing values in the data series and finally appears to be little dependent on the presence of outliers.

4.3 Trend Detection

The techniques to detect the trends in annual maxima precipitation series are relevant topic, as having significant implications for practitioners. There are several studies (Olsen et al., 1998; Parey et al., 2007; Totaro et al., 2020; Gioia et al., 2020; Kendall et al., 1975) which highlighted how the presence of trends (and, therefore, non-stationarity) in a time series can contribute to significantly redetermining the return period. However, the application of statistical techniques for the choice of non-stationary models is susceptible to a conscious application of these tests, especially with regard to the analysis of their power. A critical review of traditional analyzes was presented in Kendall (1975) and Mann (1945).

In this chapter we will focus on the trend analysis conducted through the Mann-Kendall test and through the Sen's slope among non-parametric and Two-Stage among parametric methods.

The Mann-Kendall test is the most widespread test in the scientific literature for trend in hydrological data, the Sen’s Slope instead allows you to quantify the trend displayed with the MK. Although the methodology chosen among the parametric tests is only applied, the area of study has so far remained unexplored and the results obtained enjoy the solidity and robustness of the method. The goal is to fill this gap in results, to obtain a homogeneous spatially mapping of the rainfall trends, first in the Apulia Region and then expand it to the rest of southern Italy.

4.3.1 Mann-Kendall Test

The Mann-Kendall test represents one of the most used non-parametric tests for the detection of monotonic trends (linear and non-linear). Here, as for the Pettitt test, the trend analysis is conducted using the R trend package (Pohlert, 2016). Given a random variable z and a data sample with length L, let:

$$z = (z_1,\dots,z_L) \quad (7)$$

The test statistic, *S,* is defined as follows in accordance with Sen (1968) and ISPRA Guide Lines:

The null hypothesis H_0 is that the time series has no significant trend.

$$S = \sum_{i=1}^{L-1} \sum_{j=i+1}^{L} sgn(z_j - z_i) \quad (8)$$

Defined *L* as sample length, if L ≥ 8, equation (8) can be rewritten considering a normal variable with mean and variance equal to 0, where *n* represents the number of groups of "tied values", i.e. groups of equal values and t_m represents the number of equal data of the group *j*:

$$V = \frac{L(L-1)(2L+5) - \sum_{m=1}^{n} t_m m(m-1)(2m+5)}{18} \quad (9)$$

The Mann-Kendall test is then applied by defining the Z-score statistic using a piecewise defined system that follows a normal distribution:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & S < 0 \end{cases} \quad (10)$$

From here it is possible to calculate the p-value, i.e. the value assumed by the Z-score, and compare it with a significance level α (related to Error type I). The symbol p indicates the “p-value”. We can come across two cases:

- $p < \alpha$, the null hypothesis must be rejected and the observed data are statistically significant;

– p ≥ α, the null hypothesis is accepted.

Also in this case, the significance level is 5%.

In this sense, a lot of analyses on detection trend are studied in Italy (Brunetti et al., 2000; Brunetti et al., 2001a; Brunetti et al., 2001b; Brunetti et al., 2002; Brunetti et al., 2006). Avino at al. (2021) apply MK test to rainfall time series with short duration and observe increasing trend in a specific portion of Campania Region (Italy). Coloiero et al. (2010) use MK for detecting trend in Calabria Region (Italy). Helsel et al. (2006) study MK for regional analyses.

4.3.2 Sen's slope Test

The Sen's slope is a non-parametric measure of trend in time series composed of N pairs of data, which is defined by the median of the pairs of points having different z coordinates. In scientific literature this method has been treated and applied in several studies (e.g. Totaro at al., 2020), while the definition of this estimator was introduced in Sen (1968) and is reported below:

$$\delta_j = \frac{z_i - z_k}{i - k}, \quad j = 1, \dots, N \tag{11}$$

With $i > k$.

Furthermore, an interesting discussion on detection trend with this method can be also found in Grubb and Robson (2020), Kundzewicz and Robson (2004), Lee (1997), Robson et al., (2000), Kundzewicz and Robson (2000), Rusticci and Renom (2008), Smadi and Zghoul (2006), Xu et al. (2003), Xiong and Guo (2004), Todaro et al. (2022).

The pros and cons of this method is widely discussed by Stefania et al. (2020) Sen's slope test represents simple non-parametric linear regression. The advantages of this test are:

- non-parametric method, the data distribution does not have to verify specific hypotheses
- is not very sensitive to the presence of outliers
- it is more efficient than the simple linear regression model when the regularity assumptions do not hold.

4.3.3 Two-Stage method

The main objective of frequency analysis (FA) is to provide the upper quantile correlated to return period. The quantiles are sensitive to the shape parameter estimated especially by Maximum Likelihood for short sample size, even in stationary case (Strupczewski at al., 2016).

In the non-stationary case, it is common to introduce the time dependence in the parameters of the probability distribution. The position and scale parameters are usually considered time-dependent, while the shape parameter is assumed to be invariant. In scientific literature there are results relating to "at-site" estimate of the time series obtained by applying a non-stationary GEV model with a linear trend in the position parameter, but what is highlighted is the uncertainty in the estimate of the GEV parameters in particular for the shape parameter (De Paola et al., 2018; Cheng et al., 2014, Condon et al., 2015; Mentaschi et al., 2016; Agilan et al., 2017). To try to overcome this obstacle dictated by greater uncertainty in the model, Kochanek et al. (2013) propose an alternative methodology, the Two-Stage (TS) method in which data are considered identically and independently distributed (i.i.d.).

The TS method can be applied both for three-parameter distributions with a lower limit parameter and for two-parameter distributions with unlimited range on both sides, such as Gumbel or Normal (Koutsoyiannis, 2003; Leese, 1973; Onen and Bagatur, 2017; Patel, 2020; Durrans, 1992, Beard, 1943). The need to divide the method into two phases also arises from the need to sort the data in ascending order for the use of L-moments (Hosking,1990; Hosking,2007). Indeed, the TS is based on Weighted Least Squares (WLS) joint to L-moments (Strupczewski and Kaczmarek, 1998; Strupczewski and Kaczmarek, 2001; Hosking et al., 1985; Hosking and Wallis, 1997).

The methodology's name obviously refers to the division into two parts which are defined below:

- First stage consists in estimation of time-dependent mean (μ_t) and standard deviation (σ_t) by means WLS for the annual maxima precipitation time series. Defined μ_t and σ_t, the time series is standardised (y_t), eliminating trend in this way:

$$y_t = \frac{(x_t - \mu_t)}{\sigma_t} \quad (11)$$

- Second stage consists in estimating by L-moments method (or any other estimation method, i.e. maximum likelihood) the parameters and quantiles of stationary sample Y(F) of a chosen cumulative distribution function (F). After that, the stationary quantiles will be re-trendend in this way:

$$X\,(F,t) = Y(F) \cdot \sigma_t + \mu_t \quad (12)$$

Where X(F,t) is the non-stationary quantiles for the Cumulative distribution function (F) chosen.

4.3.3.1 Trends in moments

To cater for the practical tradition of trend estimation in hydrological datasets, the first stage consists in estimating the parameters of the mean and standard deviation (instead of in the shared parameters) using the Weighted Least Squares (WLS) method which coincides with the Maximum Likelihood (ML) method in case of normally distributed data. Taking into account this hypothesis, in such research one studies the presence of the trend in moments in four different cases:

i. Linear mean and constant (time indifferent) standard deviation;
ii. Constant mean and linear standard deviation;
iii. Linear mean and linear standard deviation;
iv. Polynomial mean and linear standard deviation.

Normal distribution function and ML-method for estimating parameters are chosen for all the cases of the trend estimation.

The novelty of this method is that it allows us to consider linear trends also in the variance, whereas with non-parametric tests this is not possible. In this paragraph, we propose a review of the methodology by inserting the polynomial function in the mean trend, leaving the variance trend linear. This resulted in the increase in the number of system equations to be solved, rising to 6. This represents the first non-linear application of the TS method in a non-stationary approach to extreme events. Furthermore, the results seem to follow this path. The TS is a very versatile and adaptable method for these purposes, representing a strong point compared to parametric methods which limit the search only between linear trends only in the mean.

i. <u>Linear mean and constant standard deviation</u>

In the first case, the mean is assumed to be linear function of time and the standard deviation is assumed to be constant as shown in equations (13) and (14).

$$\mu_t = a \cdot t + b \tag{13}$$

$$\sigma_t = d \tag{14}$$

"a" is the slope in the trend and "b" is the intercept, both for the mean; "d" is standard deviation and "t" is the time covariate.

The parameter values have the following expressions:

$$a = -\frac{(6 \cdot \left((1+N)\right) \cdot \sum_{t=1}^{N} x_t(t) - 2 \cdot \sum_{t=1}^{N} t \cdot x_t(t)}{(N^2-1) \cdot N} \tag{15}$$

$$b = \frac{((2+4 \cdot N) \cdot \sum_{t=1}^{N} x_t(t) - 6 \cdot \sum_{t=1}^{N} t \cdot x_t(t)}{(N-1) \cdot N} \tag{16}$$

$$d = \left(\frac{(b + \sum_{t=1}^{N} a \cdot t - \sum_{t=1}^{N} x_t(t))}{N^{0.5}}\right)^2 \tag{17}$$

Where "N" is the sample length (which in annual maxima coincidates with number of years in the dataset) and "x_t" is the value in time series at time "t".

The expressions (15), (16) and (17) were derived from the application of the ML method to the Normal Distribution. ML method can be traced back, for the hypotheses taken into account, to the WLS whose mathematical steps are reported in Appendix B.

ii. Constant mean and linear standard deviation

In the second case, the presence of the trend in the standard deviation is assumed as explained below and therefore there are three parameters to estimate: "b", "c" and "d". "b" represents the mean of time series, "c" is the slope of the trend and "d" is the intercept, both for the standard deviation.

$$\mu_t = b \tag{18}$$

$$\sigma_t = c \cdot t + d \tag{19}$$

The system of three nonlinear equations (20) with three unknowns (b, c and d) is solved with R programming software using the nleqslv function (Dennis, and Schnabel, 1996).

$$\begin{cases} \sum_{t=1}^{N} \frac{(x_t(t) - b)}{(c \cdot t + d)^2} = 0 \\ \sum_{t=1}^{N} \frac{t \cdot (x_t(t) - b)^2}{(c \cdot t + d)^3} - \sum_{t=1}^{N} \frac{t}{c \cdot t + d} = 0 \\ \sum_{t=1}^{N} \frac{(x_t(t) - b)^2}{(c \cdot t + d)^3} - \sum_{t=1}^{N} \frac{1}{c \cdot t + d} = 0 \end{cases} \tag{20}$$

Where "N" is the sample length and "x_t" is the value in time series at time "t".

iii. Linear mean and standard deviation

In the third case linear trends are assumed both in the mean and in the standard deviation, therefore we will have four parameters to estimate, namely a, b, c and d.

$$\mu_t = a \cdot t + b \tag{21}$$

$$\sigma_t = c \cdot t + d \tag{22}$$

"a" is the slope in the trend in mean value and "b" is the intercept, "c" is the slope of the trend in standard deviation whereas "d" is the intercept.

The system (23) of four nonlinear equations with four unknowns is solved again with R programming software using the *nleqslv*.

$$\begin{cases} \sum_{t=1}^{N} \frac{\left(a \cdot t + b - x_t(t)\right) \cdot t}{(c \cdot t + d)^2} = 0 \\ \sum_{t=1}^{N} \frac{a \cdot t + b - x_t(t)}{(c \cdot t + d)^2} = 0 \\ \sum_{t=1}^{N} \frac{\left(a \cdot t + b - x_t(t)\right)^2 \cdot t}{(c \cdot t + d)^3} - \sum_{t=1}^{N} \frac{t}{c \cdot t + d} = 0 \\ \sum_{t=1}^{N} \frac{\left(a \cdot t + b - x_t(t)\right)^2}{(c \cdot t + d)^3} - \sum_{t=1}^{N} \frac{1}{c \cdot t + d} = 0 \end{cases} \tag{23}$$

Where "x_t" is the value in time series at time "t" and "N" is the sample length.

iv. Polynomial trend function in mean and linear in standard deviation

In the last case the trend is supposed to be non linear in the mean and the linear one in standard deviation, therefore we will have six parameters to estimate "a", "b", "c", "d", "e" and "f".

$$\mu_t = a \cdot t^3 + b \cdot t^2 + c \cdot t + d \tag{24}$$

$$\sigma_t = \mathrm{e} \cdot t + \mathrm{f} \tag{25}$$

For brevity it is reported only the expressions of mean and standard deviation in (24) and (25); the system of six nonlinear equations is solved with "optim" function in R software for solving the system (Belisle, 1992; Byrd et al., 1995; Fletcher and Reeves, 1964; Nash, 1990; Nelder and Mead, 1965; Nocedal and Wright, 1999).

In this case, after the definition of the non-linear trends in the average, in application of the second step of the TS, the quantiles at 50%, 95% and 99% were calculated at mid-series (t = ~N/2), at the end of the series (t = N) and with a view to using these data projections as future scenarios in water resources management of artificial reservoirs (t = N+). Bearing in mind the robustness of the methodology applied to future forecasts and considering the sample length, it is appropriate to project the data up to a maximum of 5 and 10 years ($t = N + 5$ and $t = N + 10$).

This approach is undisputedly novel in the non-stationary approach to data analysis in the hydrology. Unlike non-parametric tests, which do not allow the evaluation of types of trends other than linear ones, this methodology appears to be more flexible, as the results obtained evidently show that there is always a non-linearity highlighted by the parameters of the variables *t* (time) with a power greater than two and I also suggest the application of this approach throughout the Italian territory, to highlight the similarities and differences of the obtained results.

5 RESULTS AND DISCUSSION

The main results obtained from the applications of the methodology described in Section 4 are shown in this chapter. Section 5.1 discusses and analyzes the results of non-parametric test in the search of non-stationary in the extreme of precipitation (see Section 4.2, 4.3.1 and 4.3.2). The Section 5.2 is dedicated to the results obtained with the two-stage method and its application (see Section 4.3.3). Section 5.3 presents the comparison between the Sen's Slope and the TS method considering only linear trend in the mean and in standard deviation. Finally, Section 5.4 reports the analysis on the TS method considering polynomial trend in the mean and linear trend in the standard deviation.

5.1 Analysis and comparison between non-parametric tests

In this sub-section a critical analysis of results obtained with applications of Pettitt test for detecting change point, Mann-Kendall and Sen's Slope for trend detection is reported. In particular, the annual daily and hourly maxima with different duration (1h, 3h, 6h, 12h and 24h) time series selected (see Section 3.2.3.1) are studied into three different periods:

- complete time series
- 1951-2019
- 1980-2019.

All the results are reported both in the table and in GIS maps from the open-source software QGIS, this is necessary for spatial possible correlation analysis and pattern interpretation.

All results in the table are presented in this sub-chapter and have the following structure: the first column contain the name of the rainfall station analyzed, the second and third columns present the statistics (S) defined in Section 4.3.1 and the p-value related to Mann-Kendall (MK) test, respectively. The fourth column shows the trend obtained with the MK test. The fifth and sixth columns represent the value of trend (i.e. the "slope") and p-value of the Sen's slope test respectively. The seventh column emphasizes the presence of the statistically significant trend, the text "Increasing" indicates the presence of a positive trend, while the text "decresing" indicates the presence of a negative trend. The eighth column shows the p-value obtained from the Pettitt Test application for change point detection. Finally, in the last and ninth column is reported the year of the probable Change Point (CP). Green cells show a p-value for which the results are statistically significant. Cells in blue represent a decreasing trend, while cells in red indicate the presence of a growing trend. The last column shows the probable year of change point, in particular, those in green correspond to the statistically significant p-value values. “NA” in the table indicates a non-statistically significant trend or change point.

5.1.1 Results on annual maxima daily precipitation

In this sub-chapter the results on the annual maxima daily precipitation are shown. For brevity, only the most significant results were reported. From the analysis of the three above mentioned time periods, only the results considering to the complete series are more significant.

There are three statistically significant trends for the stations of Adelfia, Locorotondo and Ostuni. These trends are all decreasing, and among the statistically significant trends, they have greater validity since they have the highest p-value. For the daily time series, there is a statistically significant negative trend between the stations located in the area of Salento and Southern Murgia. As regards the analysis by application of the Pettitt test, four statistically significant change points were found for the Cagnano Varano, Gallipoli, Locorotondo and Ostuni stations (see Fig. 16). The non-significance, however, does not exclude the existence of changing points in other stations, in fact the last column reports all the possible years of change point in all stations. For the Locorotondo and Ostuni stations, we note both the presence of trends and change points statistically significant, which make the results more solid overally and these stations are also located geographically in the same area, between the southern Murgia and Salento. The other two change points highlighted are on Cagnano Varano and Gallipoli stations, recorded in the decade 1940-1950 (see Tab.

2). While more generally, we can assume that the most significant change points are found in the two decades 1940-1960 and are spread throughout Puglia.

Tab. 2 - Comparison between MK, Sen's Slope and Pettitt test on Annual maxima daily precipitation (Complete Time Series)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.01	-2.52	Decreasing	0.01	-0.17	Decreasing	0.05	1964
Bari Presidenza Regione	0.86	0.17	NA	0.86	0.03	NA	0.88	1969
Barletta	0.17	-1.37	NA	0.17	-0.10	NA	0.10	1960
Bovino	0.95	0.07	NA	0.95	0.00	NA	1.00	1983
Brindisi	0.08	-1.73	NA	0.08	-0.16	NA	0.20	1941
Cagnano Varano	0.07	1.80	NA	0.07	0.15	NA	0.03	1941
Cerignola	0.98	-0.03	NA	0.98	0.00	NA	0.72	1950
Foggia Osservatorio	0.99	0.01	NA	0.99	0.00	NA	1.00	1978
Gallipoli	0.07	-1.80	NA	0.07	-0.19	NA	0.05	1950
Lesina	0.57	0.58	NA	0.57	0.05	NA	0.53	1992
Locorotondo	0.01	-2.53	Decreasing	0.01	-0.27	Decreasing	0.01	1963
Noci	0.55	-0.59	NA	0.55	-0.06	NA	0.10	1943
Novoli	0.28	-1.07	NA	0.28	-0.11	NA	0.58	1953
Ostuni	0.02	-2.27	Decreasing	0.02	-0.21	Decreasing	0.01	1944
Polignano a Mare	0.11	-1.60	NA	0.11	-0.13	NA	0.17	1972

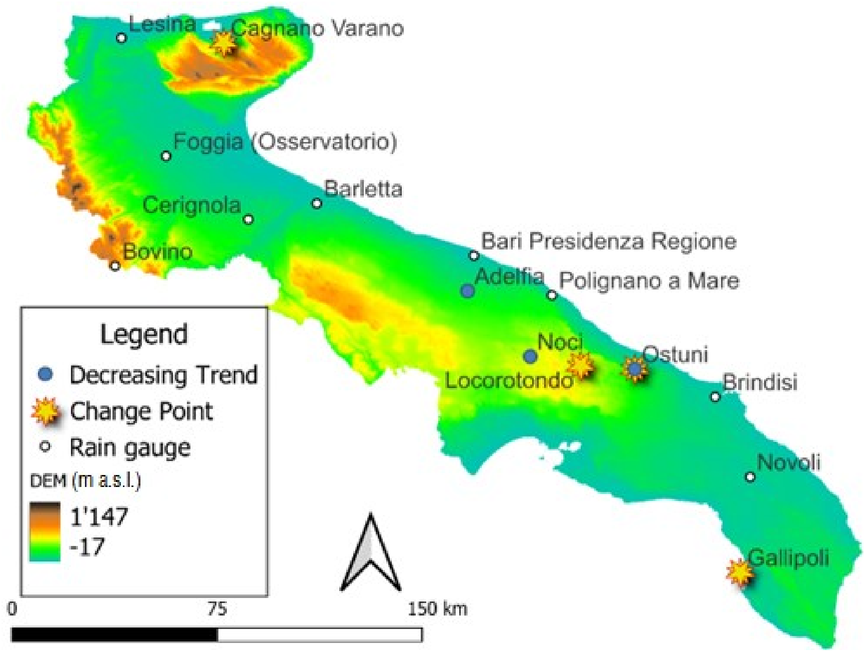


Fig. 16 - Results of MK, SEN'S SLOPE and PETTITT TEST on complete time series for annual maxima daily precipitation

5.1.2 Results on annual maxima hourly precipitation with duration of 1 hour

As for the application to the time series of the annual maxima hourly of duration (1 hour), the statistically significant results are noted both for the complete series and for the period 1980-2019. The analysis of the complete series, resulted in a single increasing trend for the station of Lesina, of 0.16mm per year having a p-very low value (0.01) which makes the results more valid (see Fig. 17). In addition, there was also a single change point in 1957 for the same station (see Tab. 3). The remaining change points, although not statistically significant, averaged around 1980. In the second part of the analysis, covering the period 1980-2019, the only statistically significant result is the growing trend for the Noci station. Although some results are non-significant, the lack of significance does not mean that the trend does not exist. In such a case it is almost always positive, increasing except the stations of

Cagnano Varano and Ostuni stations (see Tab. 4). Change points, even if non-significant, were between 1990 and 2000 (see Fig. 18)

Tab. 3 - Comparison between MK, Sen's Slope and Pettitt test on Annual maxima hourly precipitation 1h (Complete series)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.41	-0.83	NA	0.41	-0.07	NA	0.51	1982
Bari Presidenza Regione	0.66	-0.44	NA	0.66	-0.03	NA	0.96	1966
Barletta	0.39	-0.87	NA	0.39	-0.06	NA	0.14	1975
Bovino	0.63	0.48	NA	0.63	0.02	NA	1.00	1977
Brindisi	0.20	1.27	NA	0.20	0.10	NA	0.59	1947
Cagnano Varano	0.22	-1.23	NA	0.22	-0.07	NA	0.41	1973
Cerignola	0.16	1.42	NA	0.16	0.07	NA	0.51	1991
Foggia Osservatorio	0.97	0.04	NA	0.97	0.00	NA	1.00	1995
Gallipoli	0.70	-0.38	NA	0.70	-0.03	NA	0.66	1942
Lesina	0.01	2.61	Increasing	0.01	0.16	Increasing	0.03	1957
Locorotondo	0.99	-0.01	NA	0.99	0.00	NA	1.00	1970
Noci	0.90	0.12	NA	0.90	0.01	NA	0.80	1965
Novoli	0.46	-0.74	NA	0.46	-0.08	NA	0.28	1972
Ostuni	0.08	1.75	NA	0.08	0.15	NA	0.27	1979
Polignano a Mare	0.54	0.62	NA	0.54	0.05	NA	0.96	2000

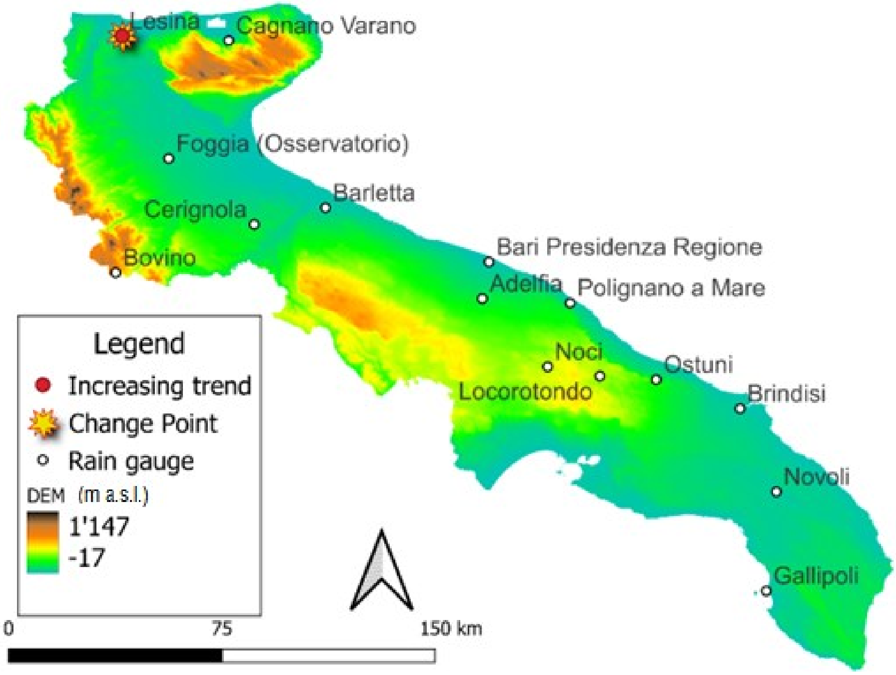


Fig. 17 - Results of MK, SEN'S SLOPE and PETTITT TEST for annual maxima hourly precipitation of 1 hour (Complete series)

Tab. 4 - Comparison between MK, Sen's Slope and Pettitt test on Annual maxima hourly precipitation 1h (1980-2019)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.19	1.32	NA	0.19	0.22	NA	0.16	2001
Bari Presidenza Regione	0.84	0.21	NA	0.84	0.02	NA	1.00	1994
Barletta	0.06	1.89	NA	0.06	0.14	NA	0.14	1994
Bovino	0.87	0.16	NA	0.87	0.01	NA	0.99	1983
Brindisi	0.88	0.16	NA	0.88	0.02	NA	1.00	2002
Cagnano Varano	0.75	-0.31	NA	0.75	-0.05	NA	0.83	1998
Cerignola	0.10	1.64	NA	0.10	0.22	NA	0.29	1998
Foggia Osservatorio	0.92	0.10	NA	0.92	0.02	NA	0.94	2018
Gallipoli	0.72	-0.36	NA	0.72	-0.08	NA	0.93	1996
Lesina	0.16	1.41	NA	0.16	0.23	NA	0.20	2001
Locorotondo	0.98	-0.02	NA	0.98	0.00	NA	1.00	1983
Noci	0.00	2.85	Increasing	0.00	0.38	Increasing	0.05	2001

Novoli	0.27	1.10	NA	0.27	0.20	NA	0.25	2006
Ostuni	0.95	-0.06	NA	0.95	-0.02	NA	1.00	2017
Polignano a Mare	0.63	0.48	NA	0.63	0.05	NA	0.90	2000

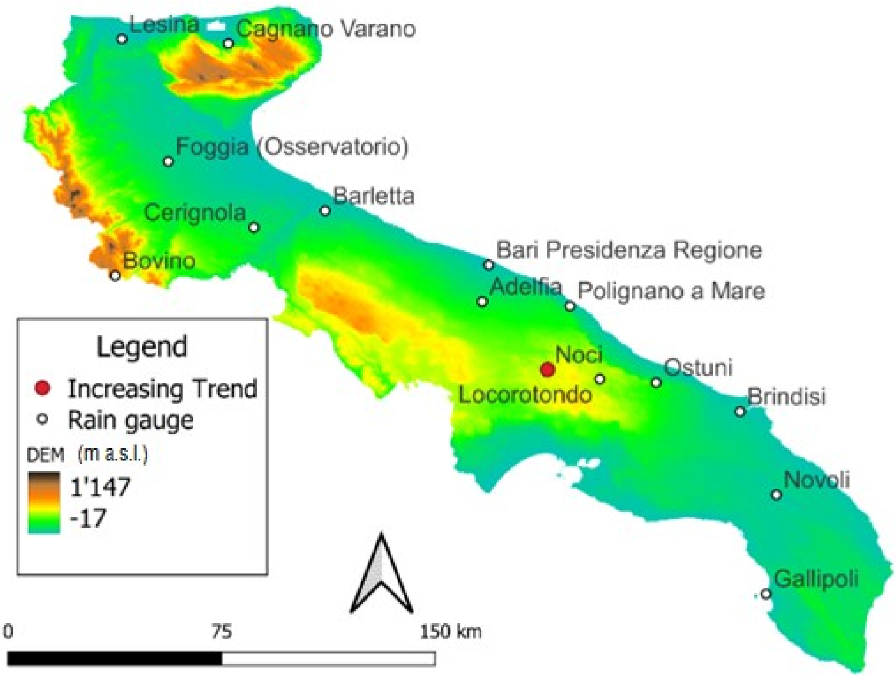


Fig. 18 - Results of MK, SEN'S SLOPE and PETTITT TEST for annual maxima hourly precipitation of 1 hour (1980-2019)

5.1.3 Results on annual maxima hourly precipitation with duration of 3 hours

The main results of this section consider the complete series and those for the period of 1980-2019. In the first case, the presence of a monotonously growing trend for the Lesina station, quite consonant, equal to 0.17 mm per year according to the estimate obtained with the Sen's Slope test, which corresponds to the p-value of 0.02; the probable year of statistically significant change point is 1961 (see Tab. 5). Among the statistically non-significant values, the change point is found around the 80s (see Fig. 19). In this regard, the study in the period 1980-2019 is significant, which effectively highlights the presence of non-stationarity in the time series. The results of the second period show two statistically significant trends, and both are increasing, for Adelfia and Noci stations (see Fig. 20).

Note that both stations are located in the same area, or in central Apulia that falls into the area of southern Murgia. For Noci station there is also a change point in 2001 which is statistically significant that reinforces the presence of non-stationary in the considered time series. It should be also considered that, in the 2000s the mechanical sensores were replaced by the digital ones in all stations. Therefore, the sudden changes do not necessarily result from the climate change indicators but may be due to a change in the measurement system. From the last column of the table, it is clear that for the period 1980-2019 change points are noticed around the year 2000 (see Tab. 6).

Tab. 5 - Comparison between MK, Sen's Slope and Pettitt test for annual maxima hourly precipitation of 3 hours (Complete series)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.62	-0.49	NA	0.62	-0.05	NA	0.55	1978
Bari Presidenza Regione	0.68	0.42	NA	0.68	0.03	NA	1.00	1979
Barletta	0.53	-0.63	NA	0.53	-0.05	NA	0.20	1974
Bovino	0.54	0.62	NA	0.54	0.04	NA	0.93	1999
Brindisi	0.27	1.11	NA	0.27	0.10	NA	0.69	1982
Cagnano Varano	0.41	-0.82	NA	0.41	-0.07	NA	0.34	1969
Cerignola	0.31	1.02	NA	0.31	0.05	NA	0.58	1946
Foggia Osservatorio	0.91	-0.11	NA	0.91	-0.01	NA	1.00	1995
Gallipoli	0.88	-0.15	NA	0.88	-0.01	NA	0.77	1942
Lesina	0.02	2.41	Increasing	0.02	0.17	Increasing	0.04	1961
Locorotondo	0.23	-1.21	NA	0.23	-0.16	NA	0.39	1978
Noci	0.37	0.89	NA	0.37	0.05	NA	0.20	1995
Novoli	0.52	-0.65	NA	0.52	-0.06	NA	0.68	1974
Ostuni	0.06	1.91	NA	0.06	0.20	NA	0.06	1980
Polignano a Mare	0.45	0.76	NA	0.45	0.10	NA	0.52	2000

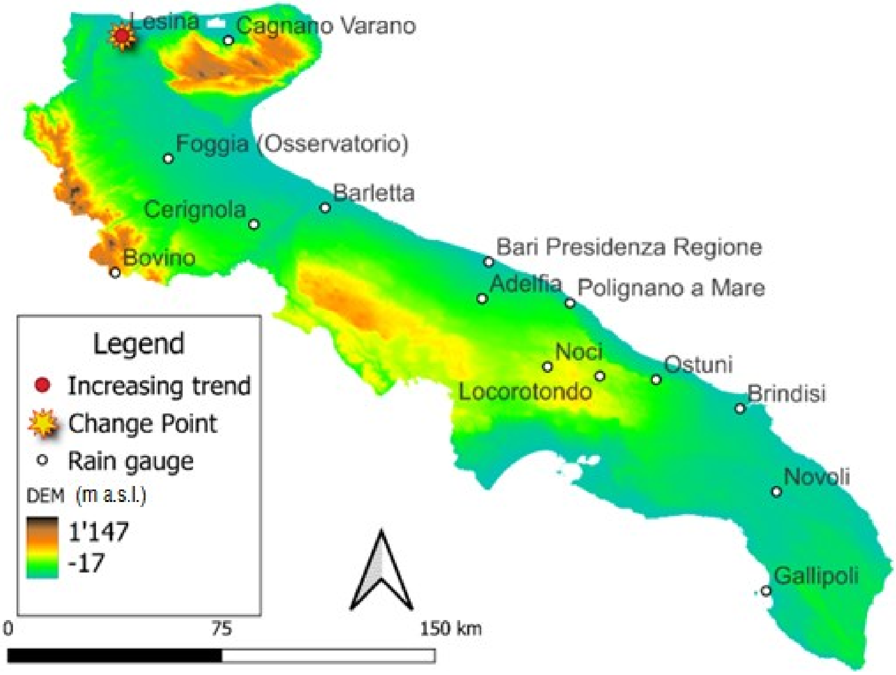


Fig. 19- Results of MK, SEN'S SLOPE and PETTITT TEST for annual maxima hourly precipitation of 3 hours (Complete series)

Tab. 6 - Comparison between MK, Sen's Slope and Pettitt test annual maxima hourly precipitation of 3 hours (1980-2019)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.05	1.98	Increasing	0.05	0.29	Increasing	0.06	1998
Bari Presidenza Regione	0.12	1.56	NA	0.12	0.20	NA	0.31	1996
Barletta	0.14	1.49	NA	0.14	0.13	NA	0.26	1994
Bovino	0.39	0.86	NA	0.39	0.18	NA	0.39	2011
Brindisi	0.49	0.69	NA	0.49	0.20	NA	0.92	1990
Cagnano Varano	0.87	-0.16	NA	0.87	-0.03	NA	1.00	2010
Cerignola	0.29	1.06	NA	0.29	0.17	NA	0.91	2009
Foggia Osservatorio	0.90	-0.12	NA	0.90	-0.04	NA	0.96	1992
Gallipoli	0.50	-0.68	NA	0.50	-0.15	NA	1.00	1997

Lesina	0.22	1.22	NA	0.22	0.23	NA	0.25	2011
Locorotondo	0.59	-0.54	NA	0.59	-0.09	NA	1.00	2012
Noci	0.02	2.35	Increasing	0.02	0.42	Increasing	0.01	2001
Novoli	0.44	0.77	NA	0.44	0.16	NA	0.47	2006
Ostuni	0.71	-0.37	NA	0.71	-0.13	NA	1.00	2017
Polignano a Mare	0.29	1.05	NA	0.29	0.22	NA	0.32	2000

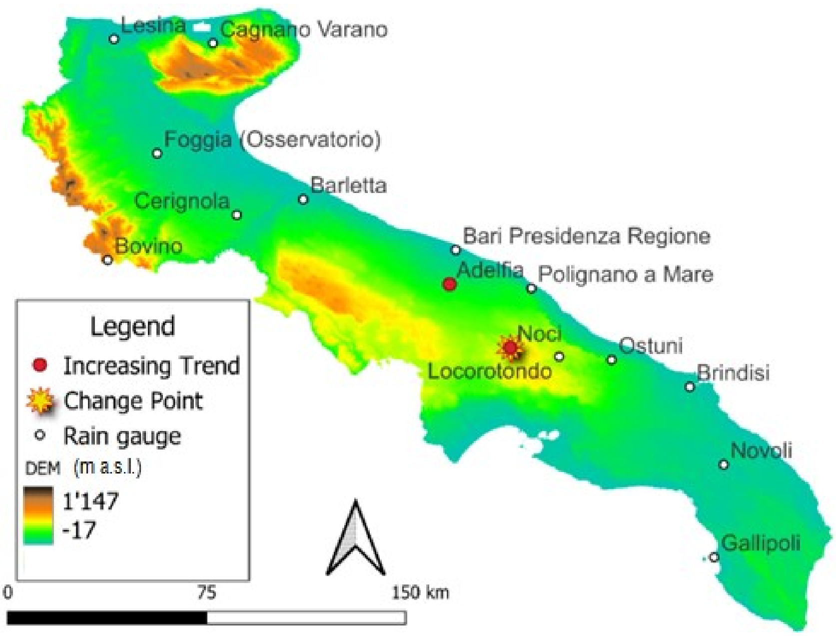


Fig. 20 - Results of MK, SEN'S SLOPE and PETTITT TEST for annual maxima hourly precipitation of 3 hours (1980-2019)

5.1.4 Results on annual maxima hourly precipitation with duration of 6 hours

All the three reference periods have statistically significant results for the duration of 6 hours of maxima annual precipitation time series. For the complete time series, the statistically significant trend is increasing with a p-value of 0.04 for the Ostuni station, which also corresponds to the change point in 1980 (see Tab. 7 and Fig. 21). In the period 1951-2019, we note the presence of a decreasing trend for the station of Barletta with a slope equal to 0.16 mm per year (see Tab. 8). At Noci station there is a fairly large increasing trend of 0.47 mm per year and with a low p-value, with the presence of a statistically significant change point found in 2002. Of the remaining probable change points, they usually revolve around year 2000 (see Fig. 22). In general, among all the stations there is almost always a positive trend, except the stations of Cagnano Varano, Gallipoli and Ostuni.

Tab. 7- Comparison between MK, Sen's Slope and Pettitt test for annual maxima hourly precipitation of 6 hours (Complete series)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.16	-1.42	NA	0.16	-0.17	NA	0.12	1983
Bari Presidenza Regione	0.65	0.45	NA	0.65	0.03	NA	0.77	1980
Barletta	0.08	-1.76	NA	0.08	-0.15	NA	0.09	1974
Bovino	0.45	0.76	NA	0.45	0.05	NA	0.97	1999
Brindisi	0.34	0.96	NA	0.34	0.11	NA	0.61	1982
Cagnano Varano	0.39	-0.86	NA	0.39	-0.07	NA	0.28	1970
Cerignola	0.73	0.35	NA	0.73	0.02	NA	0.98	1946
Foggia Osservatorio	0.94	-0.08	NA	0.94	0.00	NA	1.00	1982
Gallipoli	1.00	0.00	NA	1.00	0.00	NA	0.83	1942
Lesina	0.15	1.44	NA	0.15	0.12	NA	0.12	1963
Locorotondo	0.18	-1.34	NA	0.18	-0.26	NA	0.21	1974
Noci	0.39	0.85	NA	0.39	0.05	NA	0.30	1998
Novoli	0.69	-0.40	NA	0.69	-0.06	NA	0.88	1974
Ostuni	0.04	2.01	Increasing	0.04	0.25	Increasing	0.04	1980
Polignano a Mare	0.74	0.33	NA	0.74	0.03	NA	0.77	2000

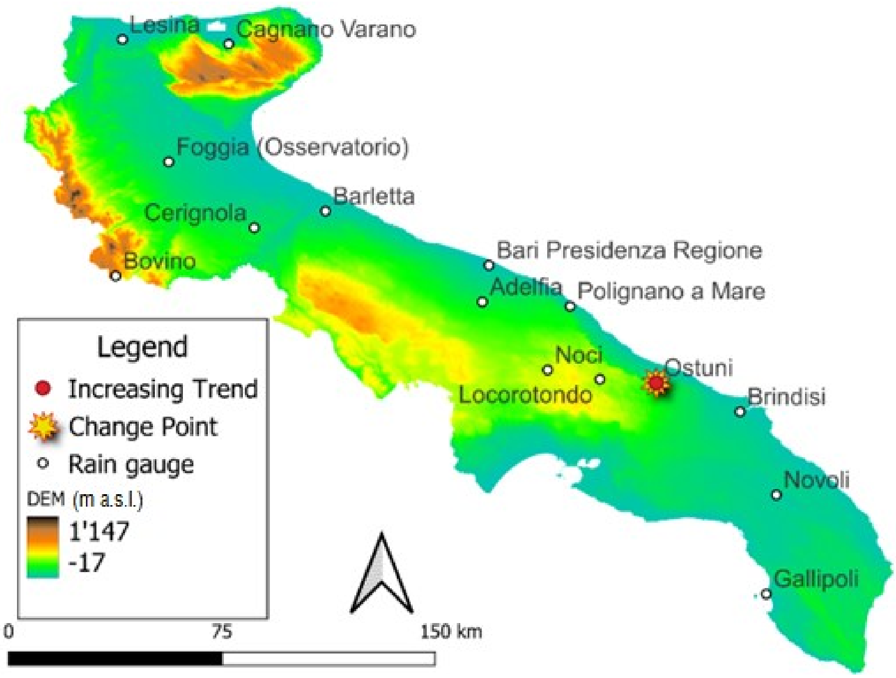


Fig. 21 - Results of MK, SEN'S SLOPE and PETTITT TEST annual maxima hourly precipitation of 6 hours (Complete series)

Tab. 8 Comparison between MK, Sen's Slope and Pettitt test on annual maxima hourly precipitation of 6 hours (1951-2019)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.32	-1.00	NA	0.32	-0.12	NA	0.20	1983
Bari Presidenza Regione	0.40	0.83	NA	0.40	0.08	NA	0.57	1988
Barletta	0.05	-1.99	Decreasing	0.05	-0.16	Decreasing	0.07	1979
Bovino	0.58	0.55	NA	0.58	0.04	NA	0.64	2010
Brindisi	0.98	0.03	NA	0.98	0.00	NA	0.94	1988
Cagnano Varano	0.29	-1.05	NA	0.29	-0.08	NA	0.21	1970
Cerignola	0.40	-0.84	NA	0.40	-0.08	NA	0.57	1956
Foggia Osservatorio	0.79	-0.26	NA	0.79	-0.01	NA	0.92	1969
Gallipoli	0.17	-1.38	NA	0.17	-0.16	NA	0.47	1963
Lesina	0.69	0.40	NA	0.69	0.05	NA	0.73	1967
Locorotondo	0.18	-1.33	NA	0.18	-0.26	NA	0.21	1974

Noci	0.98	-0.02	NA	0.98	0.00	NA	0.22	2000
Novoli	0.73	-0.35	NA	0.73	-0.05	NA	0.89	1974
Ostuni	0.10	1.66	NA	0.10	0.21	NA	0.06	1980
Polignano a Mare	0.91	0.11	NA	0.91	0.01	NA	0.97	2000

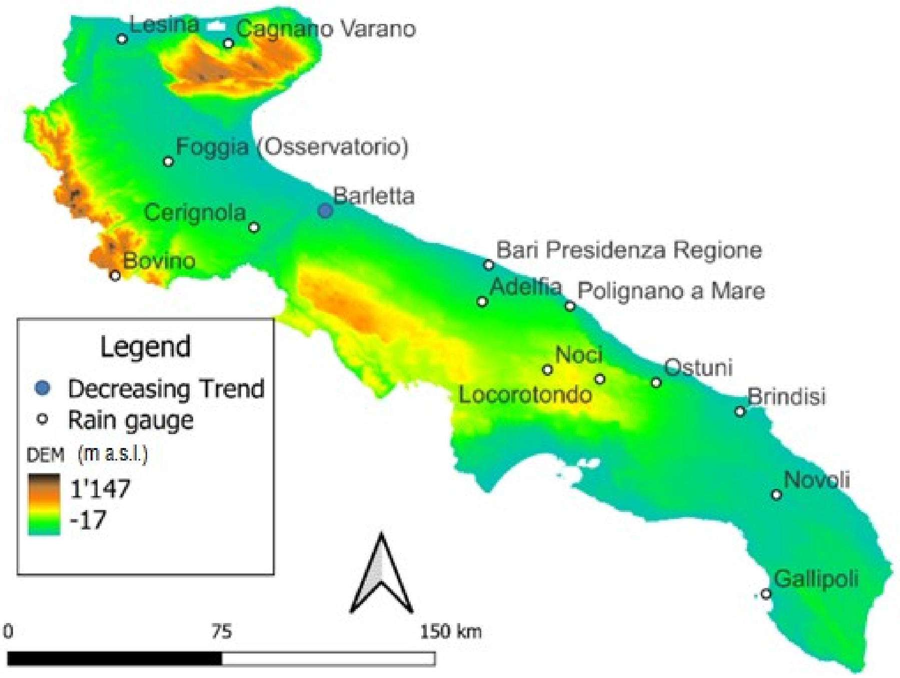


Fig. 22 - Results of MK, SEN'S SLOPE and PETTITT TEST for annual maxima hourly precipitation of 6 hours (1951-2019)

Tab. 9 - Comparison between MK, Sen's Slope and Pettitt test for annual maxima hourly precipitation of 6 hours (1980-2019)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.46	0.74	NA	0.46	0.12	NA	0.66	2001
Bari Presidenza Regione	0.12	1.54	NA	0.12	0.25	NA	0.23	1997
Barletta	0.53	0.63	NA	0.53	0.06	NA	0.70	1987
Bovino	0.63	0.48	NA	0.63	0.09	NA	0.32	2011
Brindisi	0.32	0.99	NA	0.32	0.29	NA	0.45	1990

Cagnano Varano	0.97	-0.04	NA	0.97	-0.01	NA	1.00	1998
Cerignola	0.98	0.03	NA	0.98	0.00	NA	1.00	2008
Foggia Osservatorio	0.74	0.33	NA	0.74	0.04	NA	0.91	2013
Gallipoli	0.59	-0.54	NA	0.59	-0.10	NA	1.00	2005
Lesina	0.32	1.00	NA	0.32	0.18	NA	0.32	2002
Locorotondo	0.77	0.29	NA	0.77	0.08	NA	1.00	2002
Noci	0.03	2.20	Increasing	0.03	0.47	Increasing	0.01	2002
Novoli	0.38	0.88	NA	0.38	0.21	NA	0.62	2005
Ostuni	0.67	-0.42	NA	0.67	-0.09	NA	0.97	2006
Polignano a Mare	0.28	1.09	NA	0.28	0.16	NA	0.27	2000

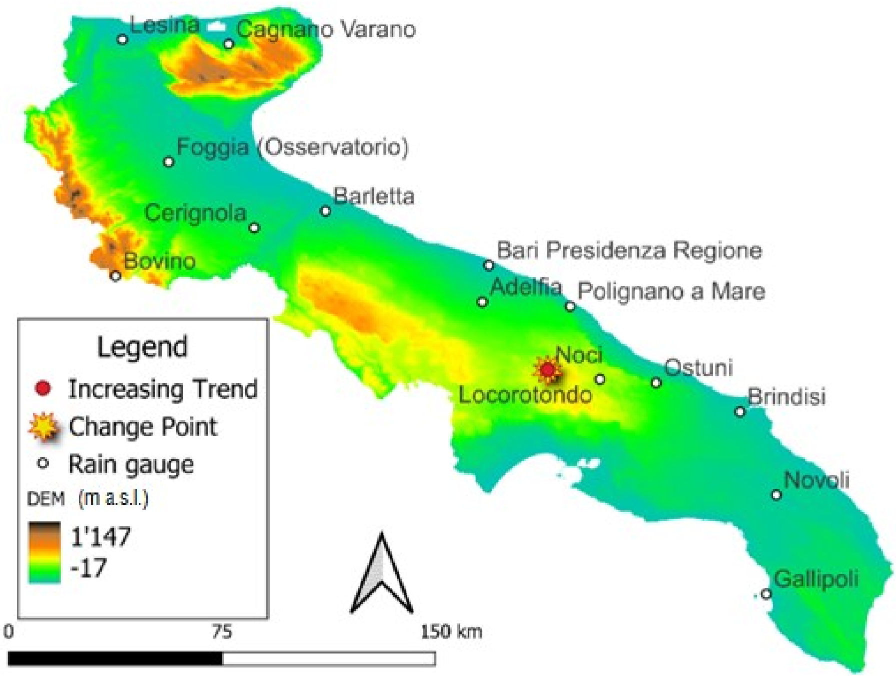


Fig. 23 - Results of MK, SEN'S SLOPE and PETTITT TEST for annual maxima hourly precipitation of 6 hours (1980-2019)

5.1.5 Results on annual maxima hourly precipitation with duration of 12 hours

For the duration of 12 hours there are neither significant trends, nor changing points. However, it is well known that lack of statistical significance does not mean that the datasets are stationary. On the contrary, the trends might be either negative or positive. There is, therefore, no general trend. On the other hand, change points are around 1980. Although this result shows that it is necessary to investigate the datasets from 1980 onwards, which for sake of brevity are not shown, from Tab. 10 it can note that there are no statistically significant results.

Tab. 10- Comparison between MK, Sen's Slope and Pettitt test for annual maxima hourly precipitation of 12 hours (Complete series)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.17	-1.37	NA	0.17	-0.18	NA	0.23	1983
Bari Presidenza Regione	0.80	0.25	NA	0.80	0.03	NA	1.00	1984
Barletta	0.19	-1.32	NA	0.19	-0.13	NA	0.14	1973
Bovino	0.56	0.59	NA	0.56	0.04	NA	1.00	1956
Brindisi	0.73	0.35	NA	0.73	0.05	NA	0.77	1946
Cagnano Varano	0.43	-0.79	NA	0.43	-0.09	NA	0.45	1969
Cerignola	0.58	0.55	NA	0.58	0.05	NA	0.99	1963
Foggia Osservatorio	0.98	-0.02	NA	0.98	0.00	NA	1.00	1982
Gallipoli	0.76	-0.31	NA	0.76	-0.04	NA	0.65	1942
Lesina	0.26	1.12	NA	0.26	0.11	NA	0.53	1996
Locorotondo	0.16	-1.41	NA	0.16	-0.33	NA	0.18	1975
Noci	0.64	0.47	NA	0.64	0.03	NA	0.54	1998
Novoli	0.41	-0.83	NA	0.41	-0.15	NA	0.90	1984
Ostuni	0.37	0.89	NA	0.37	0.15	NA	0.68	1983
Polignano a Mare	0.73	-0.35	NA	0.73	-0.07	NA	0.96	1981

5.1.6 Results on annual maxima hourly precipitation with duration of 24 hours

The final analysis, considered the maximum hourly rainfall of 24 hours for the complete set of data and presents a growing trend for the Hvar station, showing an increase in rainfalls of 0.21 mm per year (see Tab. 11 and Fig. 24). Although the trends for other stations are not statistically significant, the majority present a negative trend consistent with what was found for daily time series. For the period 1980-2019 there were monotonous growing trends for the two stations of Barletta and Noci, roughly of the same entity and located in Central Puglia (see Fig. 25). The trends for other stations are mostly increasing. In addition to these stations, significant change points are detected, which consider circa the same time (see Tab. 12).

Tab. 11 - Comparison between MK, Sen's Slope and Pettitt test on for annual maxima hourly precipitation of 24 hours (Complete series)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	SEN statistics	TREND	PETTITT p-value	CP
Adelfia	0.31	-1.01	NA	0.31	-1.01	NA	0.60	1961
Bari Presidenza Regione	0.92	-0.10	NA	0.92	-0.10	NA	1.00	1938
Barletta	0.84	-0.20	NA	0.84	-0.20	NA	0.27	1959
Bovino	0.90	0.13	NA	0.90	0.13	NA	1.00	1929
Brindisi	0.76	0.31	NA	0.76	0.31	NA	0.60	1936
Cagnano Varano	0.77	-0.29	NA	0.77	-0.29	NA	0.63	1950
Cerignola	0.95	-0.06	NA	0.95	-0.06	NA	0.96	1932
Foggia Osservatorio	0.96	-0.04	NA	0.96	-0.04	NA	0.88	1934
Gallipoli	0.71	-0.37	NA	0.71	-0.37	NA	0.92	1934
Lesina	0.05	1.96	Increasing	0.05	1.96	Increasing	0.19	1938
Locorotondo	0.11	-1.61	NA	0.11	-1.61	NA	0.21	1964
Noci	0.69	0.40	NA	0.69	0.40	NA	0.40	1929
Novoli	0.39	-0.86	NA	0.39	-0.86	NA	0.87	1959
Ostuni	0.25	1.14	NA	0.25	1.14	NA	0.43	1958
Polignano a Mare	0.97	-0.04	NA	0.97	-0.04	NA	0.77	1963

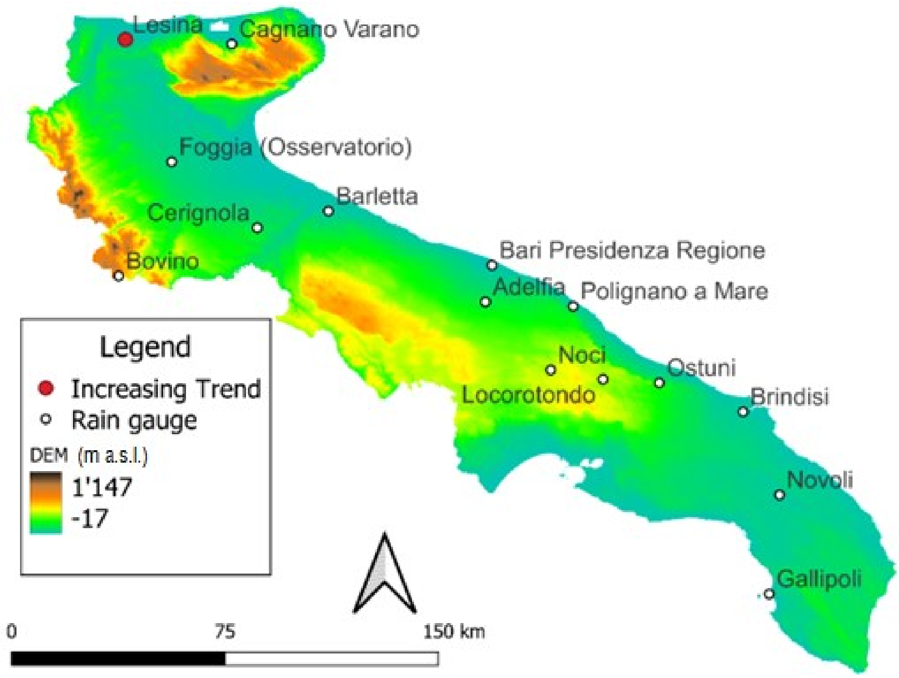


Fig. 24 - Results of MK, SEN'S SLOPE and PETTITT TEST for annual maxima hourly precipitation of 24 hours (Complete series)

Tab. 12 - Comparison between MK, Sen's Slope and Pettitt test on annual maxima hourly precipitation of 24 hours (1980-2019)

Rain gauge	MK P-value	MK statistics	TREND	SEN P-value	Slope	TREND	PETTITT p-value	CP
Adelfia	0.60	0.52	NA	0.60	0.11	NA	1.00	1994
Bari Presidenza Regione	0.26	1.12	NA	0.26	0.36	NA	0.45	1999
Barletta	0.05	2.00	Increasing	0.05	0.54	Increasing	0.01	1999
Bovino	0.62	0.50	NA	0.62	0.17	NA	1.00	2010
Brindisi	0.58	0.55	NA	0.58	0.19	NA	0.41	1986
Cagnano Varano	0.83	0.22	NA	0.83	0.06	NA	1.00	2004
Cerignola	0.40	0.84	NA	0.40	0.20	NA	0.50	2006
Foggia Osservatorio	0.18	1.33	NA	0.18	0.26	NA	0.50	2001
Gallipoli	0.45	-0.76	NA	0.45	-0.23	NA	0.73	2005

Lesina	0.07	1.82	NA	0.07	0.52	NA	0.09	2003
Locorotondo	0.80	0.25	NA	0.80	0.09	NA	1.00	1996
Noci	0.04	2.07	Increasing	0.04	0.50	Increasing	0.05	2002
Novoli	0.93	-0.09	NA	0.93	-0.03	NA	1.00	2005
Ostuni	0.66	-0.44	NA	0.66	-0.14	NA	0.89	2006
Polignano a Mare	0.26	1.13	NA	0.26	0.29	NA	0.28	1990

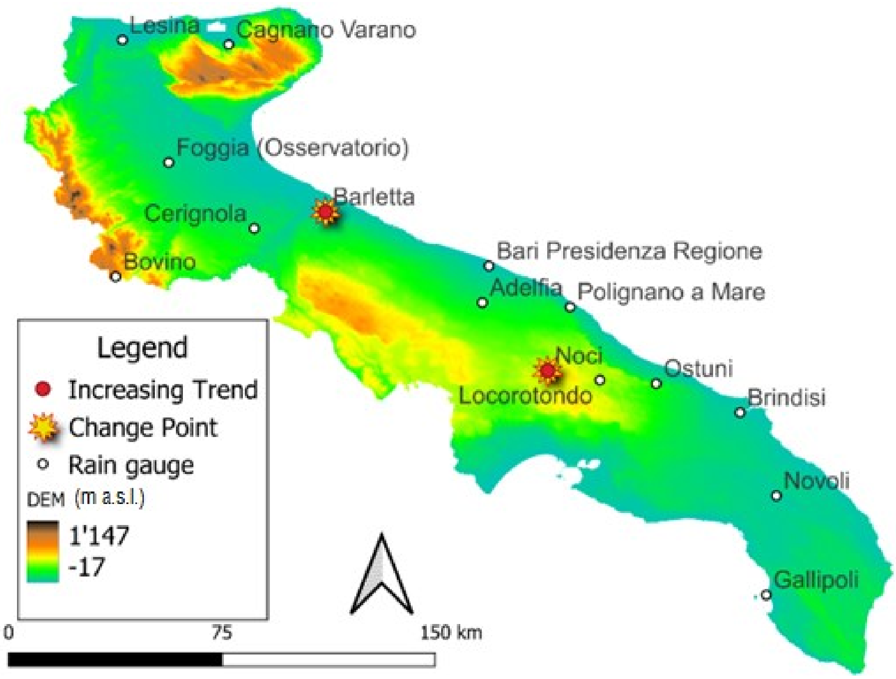


Fig. 25 - Results of MK, SEN'S SLOPE and PETTITT TEST for annual maxima hourly precipitation of 24 hours (1980-2019)

5.2 Linear trend in Two-Stage method

The results obtained by applying the Two-stage (TS) method (see Section 4.3.3) are presented in this sub-section. To analyse critically in detail the results of linear trends, only two cases (i,iii), listed in section 4.3.3.1, will be shown in this paragraph. Case iv, defined in Section 4.3.3.1, will be discussed in the next sub-section (see Section 5.3).

For the sake of clarity and significance, only the most significant results concerning the daily time series are shown. As previously, the analysis of the time series was sub-divided into three periods:

- Complete time series
- 1951-2019
- 1980-2019.

5.2.1 Case (i): Linear mean and constant standard deviation

In case (i) of application of the Two-Stage method the parameters to estimate are three: *a*, *b* and *d*. The “a” parameter represents the slope of the trend in the mean, "b" represents the intercept of the trend in the mean, while "d" for the expression (4) (defined in sub-section 4.3.3.1) is the standard deviation of the analyzed sample.

Tab. 13 shows the estimated parameters for the period 1951-2019 for the annual maxima daily time series. Note that the gradients of the trend are generally very slight, only the station of Cagnano Varano has a bolder trend. Fig. 26 and Fig. 27 show graphically the trends obtained with the TS method, marked with red line, for the case of Adelfia and Bari Presidenza Regione (*x-axis* represents the sample length expressed in a year-x, *y-axis* represents the annual daily maxima of precipitation expressed in millimeters). By decreasing the length of the sample and therefore considering the 1980 as year of starting observation, the trends turn out to be much more visible and all are positive, with the exception of Ostuni station (see Tab. 14). For the stations shown in Fig. 28 and Fig. 29 there is a significant increase of rainfalls in about 38% per year for Bari Presidenza Regione station, while Adelfia station varies from a decreasing trend to an increasing one.

Tab. 13 - Linear mean and constant standard deviation on annual maxima daily in 1951-2019

Rain gauge	**a** (Eq. 15)	**b** (Eq. 16)	**d** (Eq. 17)
Adelfia	-0.0270	54.3682	15.7250
Bari Presidenza Regione	0.1115	51.4974	21.3822

Barletta	-0.0088	52.2973	22.9110
Bovino	0.0602	59.0894	25.9454
Brindisi	0.0138	60.3466	23.8733
Cagnano Varano	-0.2146	75.4972	36.8253
Cerignola	-0.1037	53.1626	18.0499
Foggia Osservatorio	0.1148	40.0606	16.5446
Gallipoli	0.0506	58.5617	32.1396
Lesina	0.0991	52.4164	20.1609
Locorotondo	-0.1592	69.1851	24.2124
Noci	0.1090	54.1269	20.4669
Novoli	0.1545	56.6146	28.2272
Ostuni	-0.1348	71.4637	27.0980
Polignano a Mare	0.0097	54.3601	21.0887

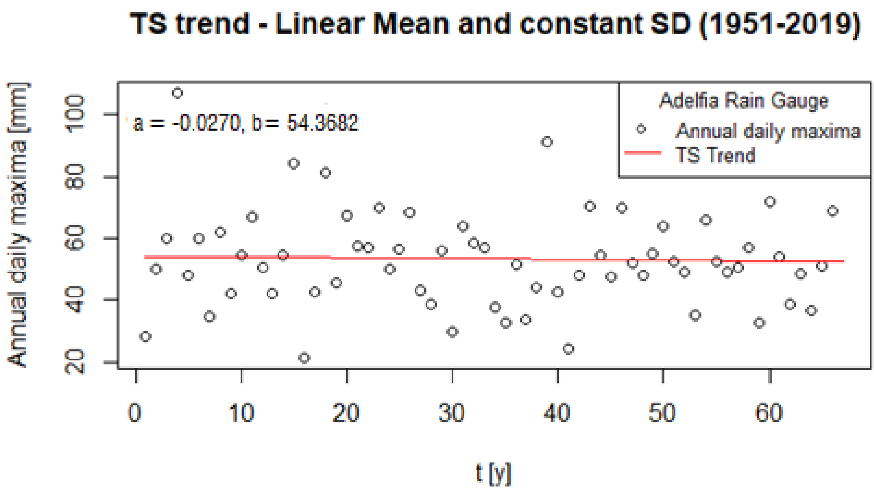


Fig. 26 – Trend detection by TS method for Adelfia station (1951-2019) considering linear mean and constant standard deviation (SD)

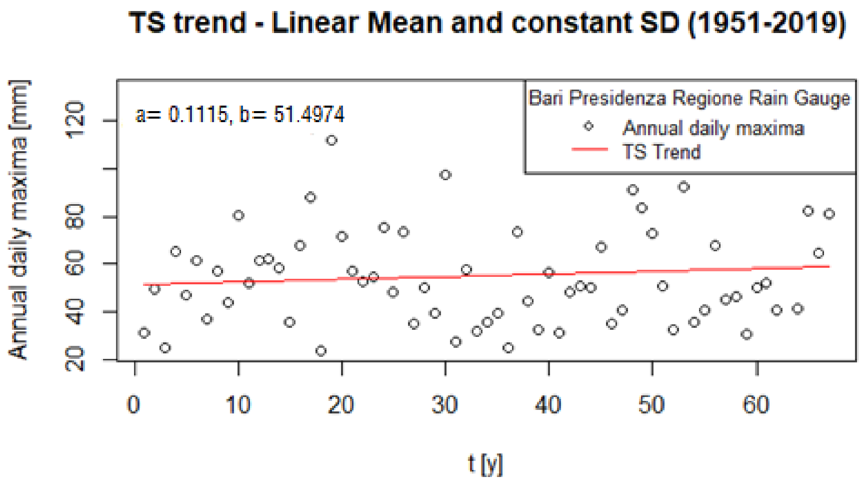


Fig. 27 - Trend detection by TS method for Bari Presidenza Regione station (1951-2019) considering linear mean and constant standard deviation (SD)

Tab. 14 - Linear mean and constant standard deviation on annual maxima daily in 1980-2019

Rain gauge	**a** (Eq. 15)	**b** (Eq. 16)	**d** (Eq. 17)
Adelfia	0.0801	49.7272	13.4339
Bari Presidenza Regione	0.4905	43.8356	21.9966
Barletta	0.7043	36.9910	21.4352
Bovino	0.1909	57.8514	28.4881
Brindisi	0.3434	54.3149	26.2633
Cagnano Varano	0.5670	54.1668	31.9976
Cerignola	0.1134	46.5486	15.7938
Foggia Osservatorio	0.1876	41.0500	16.6700
Gallipoli	0.2480	56.9212	38.3566
Lesina	0.3178	49.0046	20.0292
Locorotondo	0.2350	53.8669	21.4051
Noci	0.5285	48.0454	20.7533

Novoli	0.5380	53.0199	32.2828
Ostuni	-0.0282	67.2507	20.7247
Polignano a Mare	0.4362	44.4377	21.8066

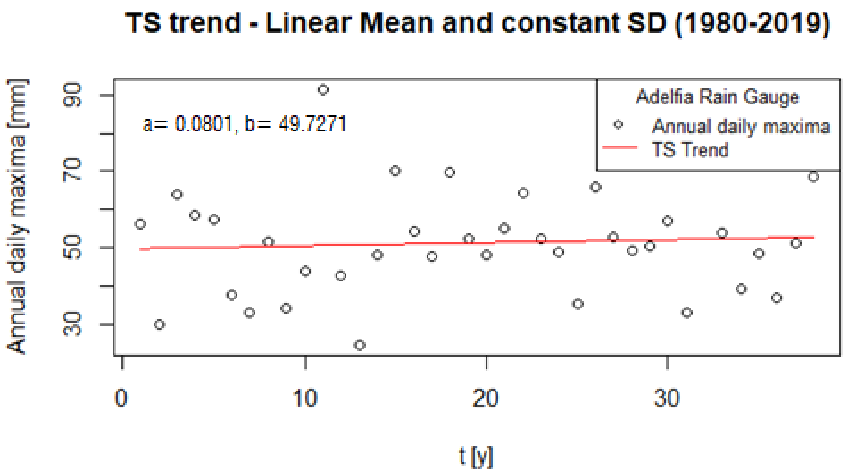


Fig. 28 – Trend detection by TS method for Adelfia station (1980-2019) considering linear mean and constant standard deviation (SD)

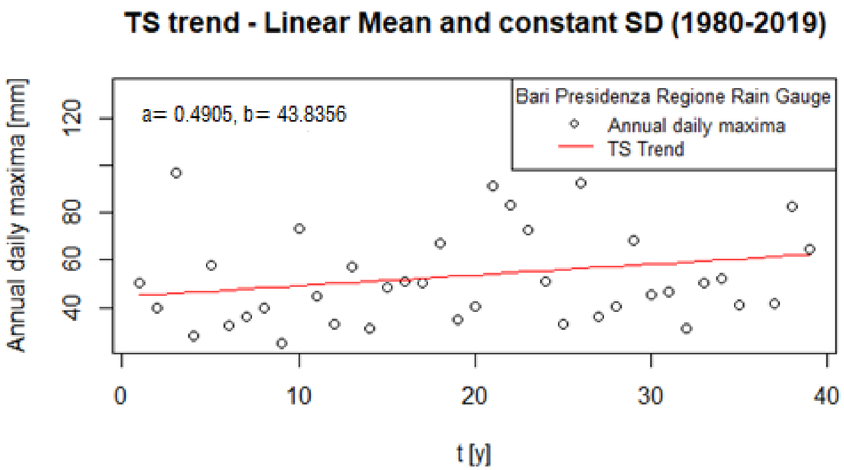


Fig. 29 - Trend detection by TS method for Bari Presidenza Regione station (1980-2019) considering linear mean and constant standard deviation (SD)

5.2.2 *Case (iii): Linear mean and linear standard deviation*

In case (iii) of application of the Two-Stage method, there are four parameters to be estimated: a, b, c and d.

The results shown in Tab. 15 for the period 1951-2019, clearly indicate that the trends do not seem to be too strong and are in line with those for the case (i) for the same reference period. Furthermore, this means that the linear trend in the standard deviation has not influenced in decisive way the linear trend in the mean. Infact, in Fig. 30 and Fig. 31 the trends are rather “flat” and similar to the case (i). The period 1980-2019 accentuates the detection of positive trends in mean compared to the previous period as shown in Tab. 16.

Tab. 15 - Linear mean and standard deviation on annual maxima daily in 1951-2019

Rain gauge	**a** (Eq. 23)	**b** (Eq. 23)	**c** (Eq. 23)	**d** (Eq. 23)
Adelfia	-0.0097	53.7645	-0.0798	18.3101
Bari Presidenza Regione	0.0997	51.8917	0.1334	16.6853
Barletta	-0.0209	52.6993	0.0774	20.2176
Bovino	0.0448	59.5957	0.1497	20.5048
Brindisi	-0.0041	60.9492	0.1028	20.2385
Cagnano Varano	-0.1565	73.5274	-0.0916	39.7473
Cerignola	-0.0700	51.9783	-0.1107	21.6405
Foggia Osservatorio	0.1036	40.4483	0.0423	15.0370
Gallipoli	-0.0520	61.6700	0.4641	15.1905
Lesina	0.0993	52.4118	-0.0012	20.2028
Locorotondo	-0.1630	69.3199	-0.0936	27.3728
Noci	0.0956	54.5917	0.0291	19.4398
Novoli	0.1554	56.6546	0.4840	10.6715

Ostuni	-0.1260	71.1702	-0.2981	36.1429
Polignano a Mare	0.0052	54.5153	0.0927	17.7836

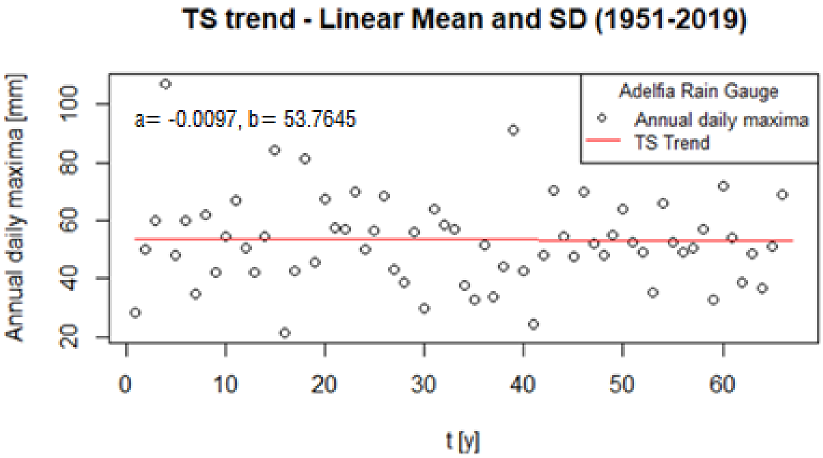


Fig. 30 - Trend detection by TS method for Adelfia station (1951-2019) considering linear mean and standard deviation

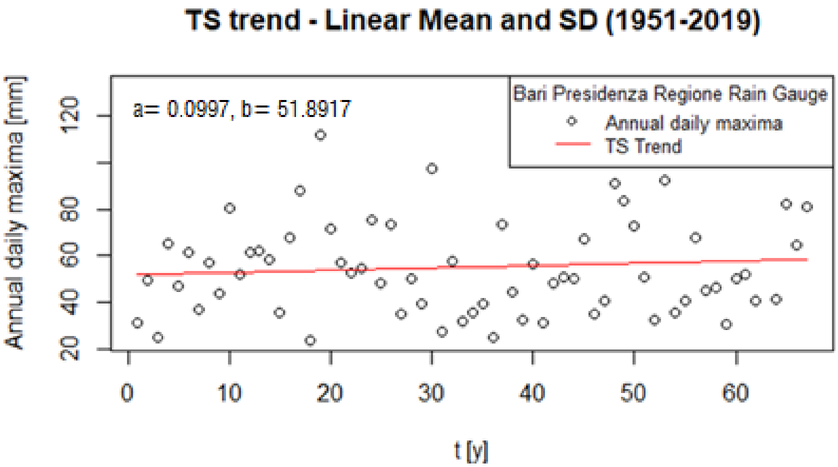


Fig. 31 - Trend detection by TS method for Bari Presidenza Regione station (1951-2019) considering linear mean and standard deviation (SD)

Tab. 16 - Linear mean and standard deviation on annual maxima daily in 1980-2019

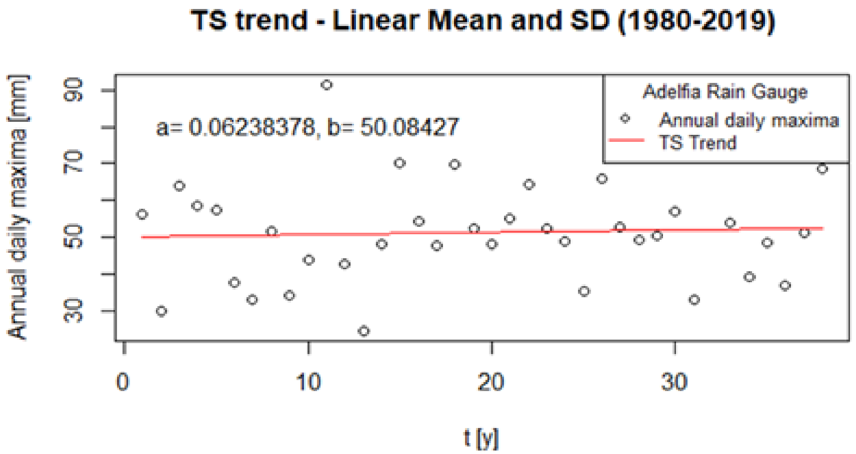


Fig. 32 - Trend detection by TS method for Adelfia station (1980-2019) considering linear mean and standard deviation (SD)

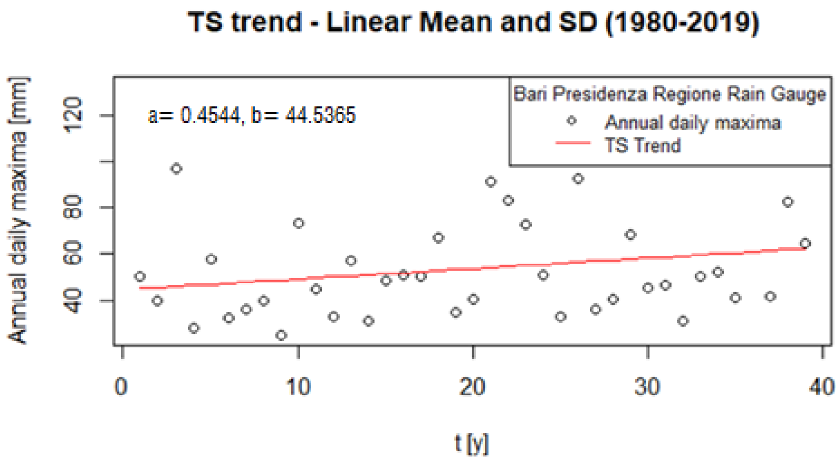


Fig. 33 - Trend detection by TS method for Bari Presidenza Regione station (1980-2019) considering linear mean and standard deviation (SD)

5.3 Polynomial trend in Two-Stage method

This chapter shows the results obtained with the Two-Stage by searching for polynomial trends in the mean and linear trends in the standard deviation. The need to investigate on the characterization of rainfall trends in the Apulian territory arises both from a visual analysis of the data (see Appendix A) which often does not lead to following the path of linear trends. The vast majority of technical applications tend to model reality in a simplistic way, gaining the advantage of obtaining results with lower computational costs, while losing the possibility of interpreting a more complex reality, whose variables that affect hydrological modelling are multiple and not always they follow linearity (economic, social, ecological, and human aspects).

In this regard, we proceeded using the same parametric methodology or the two-stage also for the search for non-linear trends. One of the greatest advantages of this method is precisely its versatility and adaptability to any form of trend, only to then consider appropriate numerical calculation tools.

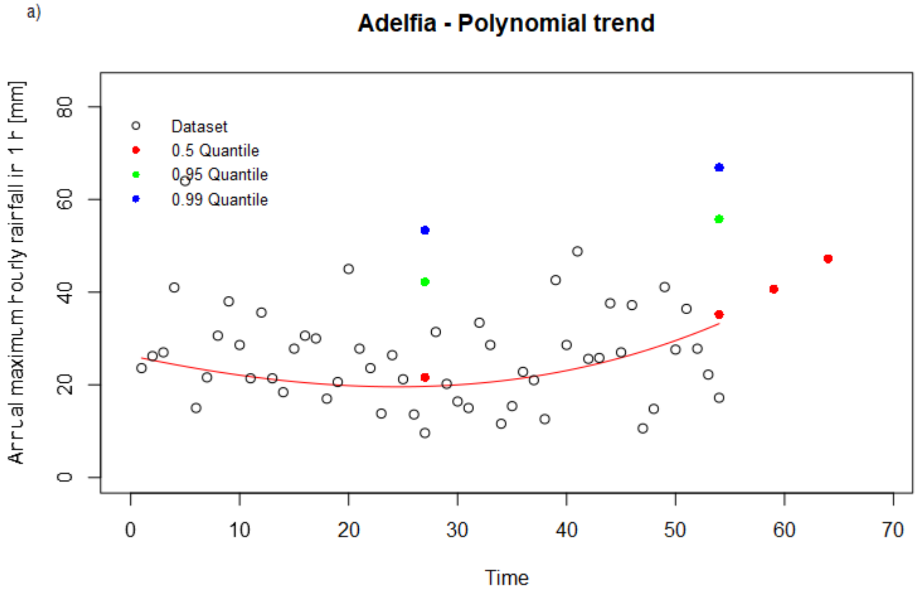
Case iv described in section 4.3.3 involves a polynomial trend and the presence of linearity in the standard deviation. The results obtained in chapters 5.1 to 5.2 do not show satisfactory results in the analysis of complete time series, which however appears to be a fundamental requirement in the validity of the result. The longer the sample, the more reliable the interpolation of the data deduced from it will be.

Therefore, in this paragraph only the results obtained considering the complete time series are shown, with particular reference to the annual maxima hourly precipitation with duration of one hour (1h). For the sake of brevity, the cases of Adelfia, Barletta, Bovino and Gallipoli are shown.

The type a) figure presents the time expressed in years on the x-axis and the precipitation value expressed in millimeters on the ordinates. From the application of the II stage of the methodology, the quantiles at 50%, 95% and 99% were calculated at the mid-length of the sample and at the end. We went into the short-term, 5 and 10 years forecast to obtain a 50% quantile value (represented by the red dots in the figure). The values thus obtained could constitute the starting point in the prediction and management of the water resource, especially for dams, which supply water for irrigation purposes with a higher percentage than other uses, thus having a notable impact on the local economy, in which the agriculture is one of the leading sectors. Figure type b) is an alternative way to show the results obtained in figure type a), in this case the Plotting Position is used.

The most interesting results are those relating to the Barletta and Bovino stations, which represent an oscillatory character in the mean trend (see Fig. 34-Fig. 37). The polynomial model seems to fit better than the simple linear model. This represents a notable result and should be explored and extended to the territory.

a)



b)

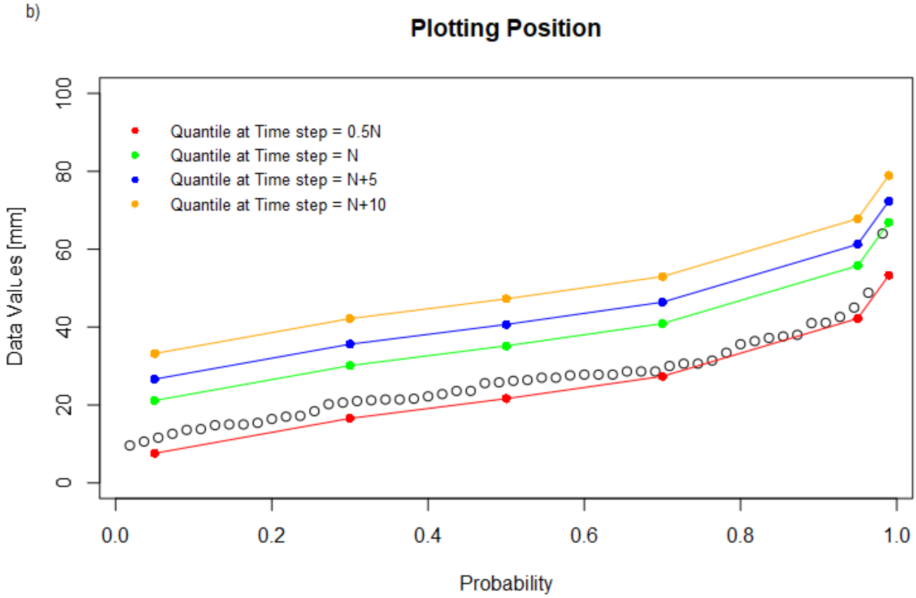
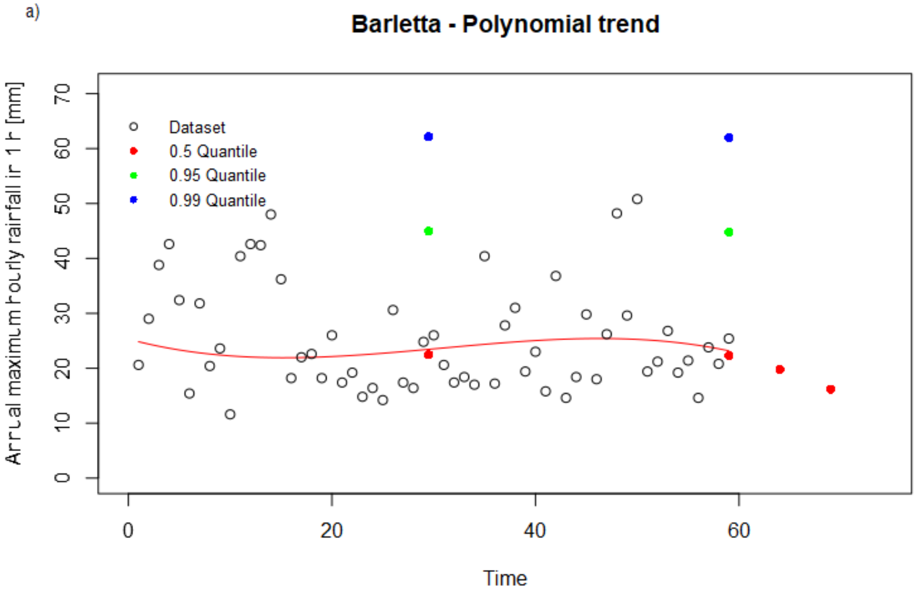


Fig. 34 - Polynomial trend by TS method for Adelfia station

a)



b)

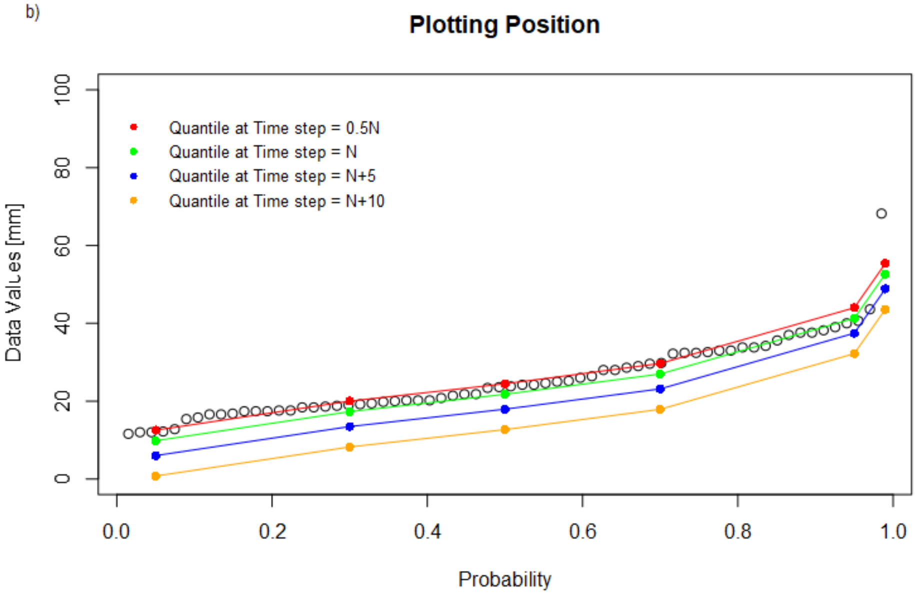


Fig. 35 - Polynomial trend by TS method for Barletta station

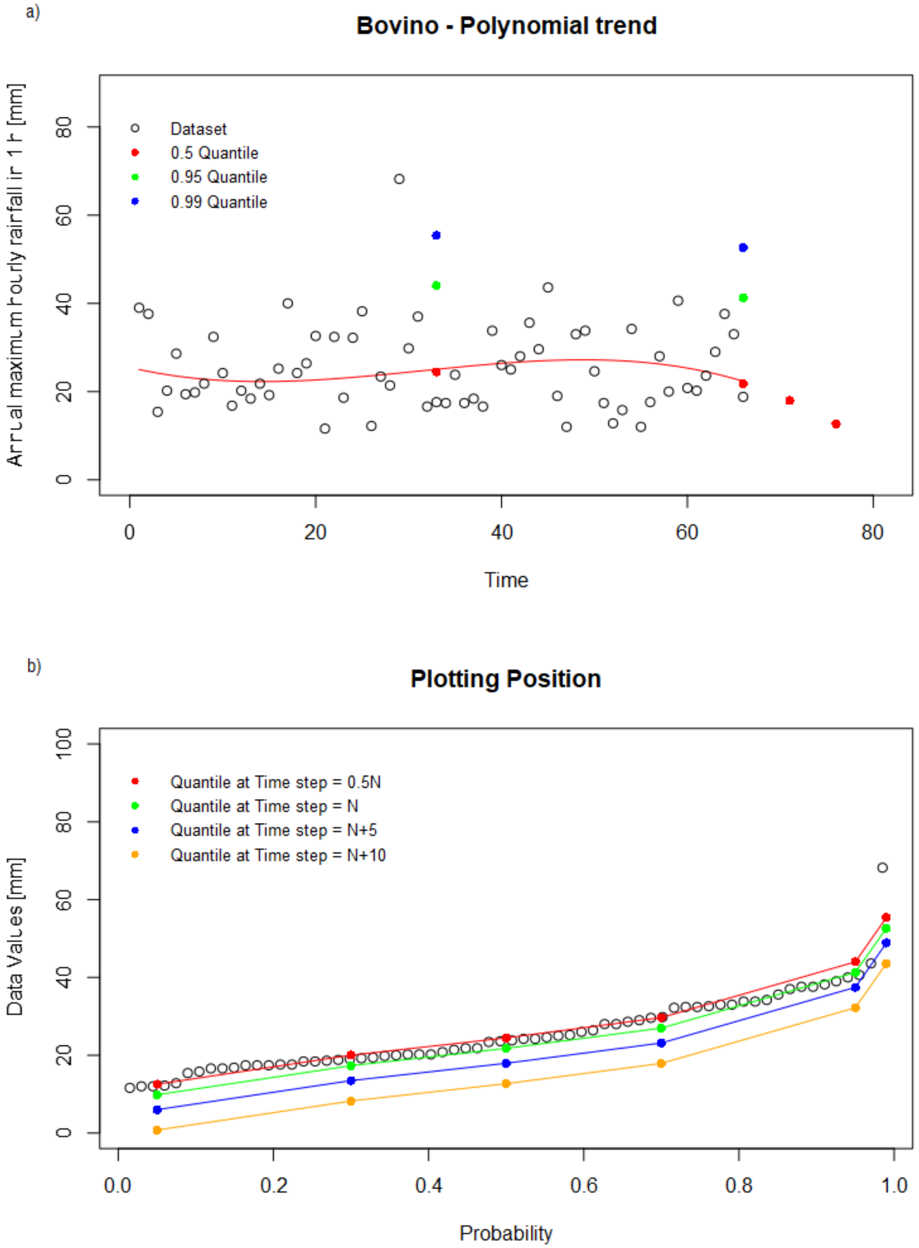
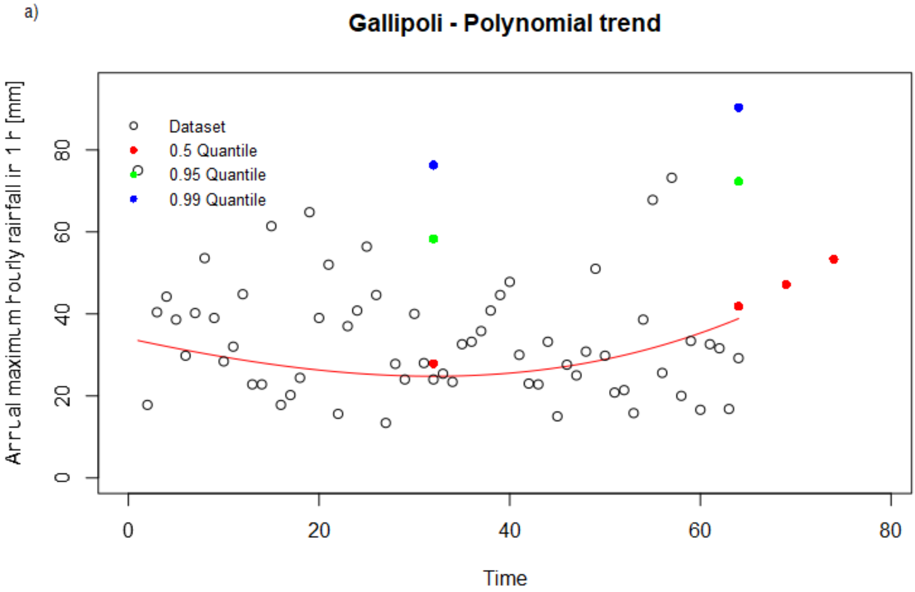


Fig. 36 - Polynomial trend by TS method for Bovino station

a)



b)

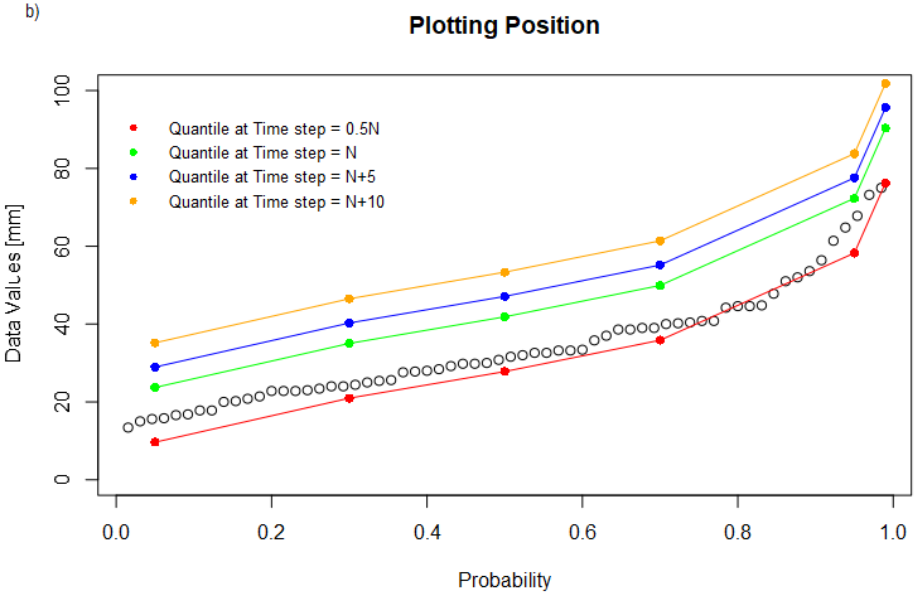


Fig. 37 - Polynomial trend by TS method for Gallipoli station

5.4 Summarising discussion

The spatial and temporal heterogeneity of extreme rainfall data makes quantifying climate change at a local level complex. However, it is known that on a global scale we have ongoing trends of increasingly frequent and intense extreme events. In this discussion, using the methods recommended in the scientific literature, an important contribution is made in the non-stationary interpretation of the observed data.

Ultimately, I can draw the following conclusions:

- trends and change points are observable and evident in the Apulian context proven by non-parametric tests;

- trends obtained by means of parametric methods include also temporal variability in the standard deviation;

- TS method allows to explore other types of trends (non-linear), such as polynomial.

Despite the evident and quite frequent non-linear behaviour of hydrological phenomena, the application of polynomial trend is the absolute novelty of this research. The confirmation of the reliability of such trend is dictated by the absence of heteroscedasticity in the data analyzed in all linear cases; because the oscillatory behaviour provides for an almost constant standard deviation in the time, homoscedasticity confirms the correctness of the results.

In my opinion, the contribution of this thesis represents an advancement in research in the Italian context compared to recent scientific publications (Avino et al. 2021), as trend research with parametric methods only limits the analysis and understanding of the results. In fact, although the results of the trends obtained with the MK on the annual hourly maxima appear to be consistent with what was presented in the discussion, namely: the presence of decreasing trends in long periods (6, 12, 24h) and spatially distributed in contained and localized areas, the confirmation of the direction of the trend can be only obtained by considering also the parametric tests.

Furthermore, Mazzoglio et al., 2022 analysed trends across the entire Italian territory, concluding, however, that it is necessary to divide the territory into segments to obtain more significant results; the contribution of the thesis goes in this direction.

In addition, note that in reference to the trends of the 1-hour annual maxima there is an analogy to Mazzoglio et al. (2022) results, in fact, the central area of the Puglia Region, in which the negative trends are evident, is easily identified.

In my opinion, the result of the Barletta station clearly confirms, regardless the methodology applied, the presence of a negative trend, starting from linear trend until the best polynomial type is reached. As novel, these results will be integrated into regional civil protection planning both to indicate the areas where in a short-medium term the forecast experience negative or positive trends, and to improve the management of the water resources in the reservoirs. In fact, although the density of the chosen stations is low, they are located within the river basins with the reservoirs, acting as a warning facility for civil protection purposes. Nonetheless, the choice of having few stations is limiting in terms of spatialization of the data, but on the other hand, the results obtained are very appreciable, as the data used for analyzes undergone a stringent selection in terms of their quality.

6 CONCLUSIONS

In the literature, the models detecting linear trends are more common because, in the field of the Earth science, linear models are simpler for the conceptualization of physical processes but also better understandable by the practitioners and decision maker. This is also because of the measurement tradition, where the simple regression-based trend analysis is still in use. Also, many researchers in earth sciences use common non-stationary models with the temporal covariate in the parameters of the parent distribution and use Maximum likelihood (ML), method of moments and L-Moments or others (Salas et al., 2014; Madsen et al., 2007; Martins and Stendinger, 2000; Lombardo et al., 2013; Koutsoyannis, 2019) for their estimation. The Two-Stage (TS) method goes beyond the concept of identifying the trend in parameters, but looks for the trends in the first and second moment, namely in mean and standard deviation (SD), (Strupczewski et al., 2001; Kochanek et al., 2013; Strupczewski et al., 2016).

One of the main objectives of this thesis is to contribute to the non-stationary treatment of extreme rainfall events, which are often the causes of floods. On the other hand, European legislation requires us to take note of ongoing climate change and start implementing a strategy to adapt to it. In this final chapter the salient results of the analyzes carried out are reviewed and highlighted, also with a look at possible future developments. In addition, the aim of this research is to provide auxiliary information for both decision makers and practitioners, based on cutting-edge scientific techniques, in the way of designing and managing water resources within a constantly evolving dynamic system.

6.1 Research findings

In Chapter 3, Starting from an orographic, hydrographic and climatological description of the study area, we move on to the analysis of the dataset of the historical series of annual daily and hourly precipitation maximums. The first fundamental step is the qualitative analysis of the data which is preparatory to obtaining results that are as reliable as possible. The criterion for choosing time series that have a single consecutive missing data and a percentage of valid data equal to 95% was applied. This criterion significantly reduced the number of time series analysed, counting 15 of them. This benefits the quality of the results found, as the sensitivity of the applied methodology can depend on them.

The methodologies proposed and described (see Chapter 4) are of two different types: non-parametric and non-parametric tests. Both used in the search for non-stationarity forms attributable to climate change. In particular, I focused on the search for change points and trends.

The change points, identified using the Pettitt test, were evaluated considering the complete and partial time series, from 1951 to 2019 and from 1980 to 2019. 1980 was chosen as the year of start of observation since from the analyzes carried out on the entire series, 1980 it seems to be the year in which the most frequent change points occur. 1951 instead represents, in literature, the year in which scientific studies began.

The results obtained for detecting the trend with both the Mann-Kendall test and the Sen's Slope are not very homogeneous in space. But what we notice is that by reducing the length of the sample, therefore observing the values since 1980, the trends tend to be increasing. On other hand results provided by Totaro et al (2020) provides that reducing the length of the time series to less than 30 years likely provides very low values of power. Hence, there are clear signs of statistically significant trends that needs to be analyzed on longer time periods, even involving not linear and\or not monotonous trends before leading to consider the presence of ongoing climate change. The main characteristic of non-parametric tests is that they are free from the probability distribution functions of the data, which already represent a first approximation of reality, since the true probability distribution is unknown.

Instead, parametric methods have the advantage of being more powerful when assumptions are satisfied.

As proposed by De Paola et al. (2008) non-stationarity in parametric methods is sought by adding the time parameter into the probability distribution. The proposed methodology, the Two-Stage, has never been applied in the Apulian territory therefore it is necessary to carry out a subsequent validation of the results. This method has the great advantage of considering the trends in the moments, in this case mean and variance, and not in the parameters of the probability distribution which facilitates the computational processes. Linear trends in both mean and standard deviation were assessed. What can be deduced from the various applications (see paragraph 5.2) is that there is no heteroscedasticity, in fact the results of the linear trends in the mean are of the same order of magnitude as those obtained also with the linear standard deviation.

The most relevant result is that relating to the presence of oscillatory-type trends in the mean which can refer to the influence of larger-scale phenomena such as El Niño or La Niña (Fedorov and Philander, 2000; Hoerling et al., 1997; Okumura and Deser, 2010). The presence of oscillatory trends was mainly observed in complete time series and therefore with a long length, which leads us to think of the presence of wavy trends rather than linearly increasing ones.

The analyzes achieved are preparatory and necessary for regional studies, both in compliance with the drafting of the adaptation strategy to climate change, and in the short-term forecast necessary for the management of the water resource in the reservoirs.

With the application of the Two-Stage method, in particular in the definition of the 50% quantiles, it was possible to reach a short-term forecast of 5 or 10 years, obtaining a quantile value greater than 50% corresponding to the average value. This time frame can be extended if the results are strengthened by considering other case studies. The need to obtain forecasts is increasingly compelling in the management of hydrogeological and hydraulic risks. Furthermore, it is necessary for these types of results to be incorporated into the urban planning of cities by engineers.

Additionally, awareness of the non-stationary character of extreme events will have to be acquired by practitioners in the design of new infrastructures and in the management of existing ones. It is good to consider that the context in which one acts is a dynamic system, in which the variables that affect the non-stationarity of the time series may be of different types, including the land use change, which contribute significantly to the propagation of runoff in urban areas, causing damage to goods and people in case of floods.

Ultimately, from the analyses conducted we can deduce that in the case of time series longer than 50 it is appropriate to use parametric trend estimation methods, such as the Two-Stage in which the chosen probability distribution has a better fit in presence of a high sample size, on the contrary in the case of data samples lower than 50 it is suggested to use non-parametric tests such as the Mann-Kendall or Sen's Slope whose result is independent of the chosen probability distribution function.

6.2 Future perspectives

The further developments of this research arise from the limitations observed in the analyses. First of all, to have a spatial interpolation of the data and to understand how the extremes are distributed over the territory it is necessary to have additional stations to consider. The restrictive criterion in the choice of stations undoubtedly guaranteed the excellent quality of the results obtained, but with the drawback of not having a convergent general vision. However, from the results of the oscillatory trends it would be very interesting to delve deeper into the correlations that exist with the El Nino Southern Oscillation (ENSO) that exist in the central-southern Pacific. In this sense, in addition to the annual maxima data, it is possible to proceed with the analysis of the cumulative monthly precipitation to look for seasonal trends.

Furthermore, it is appropriate to extend the Two-Stage methodology also to flood peaks to correlate rainfall with runoff.

8 LIST OF TABLES

9 LIST OF FIGURES

10 APPENDIX A - Dataset

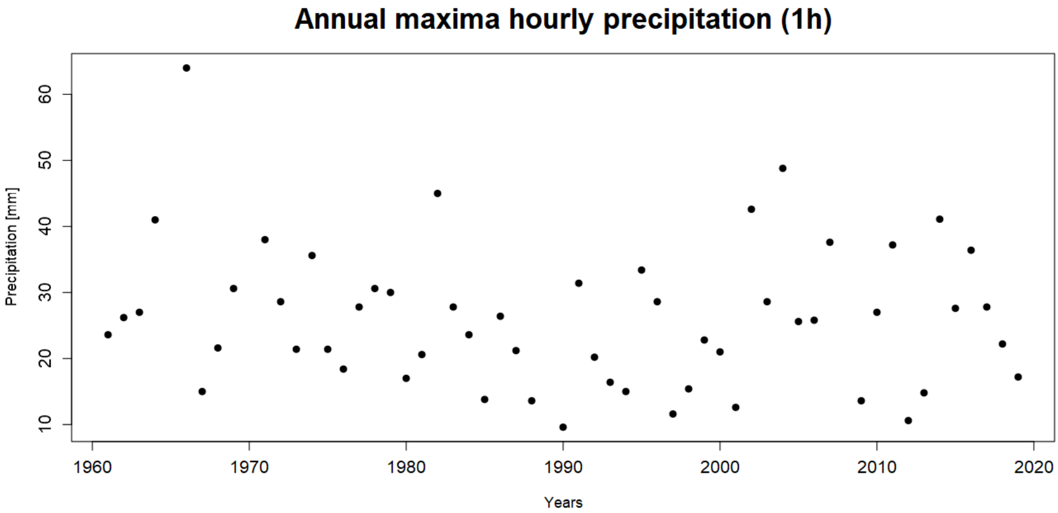


Fig. A 1 - Annual maxima hourly precipitation (1h) for Adelfia station

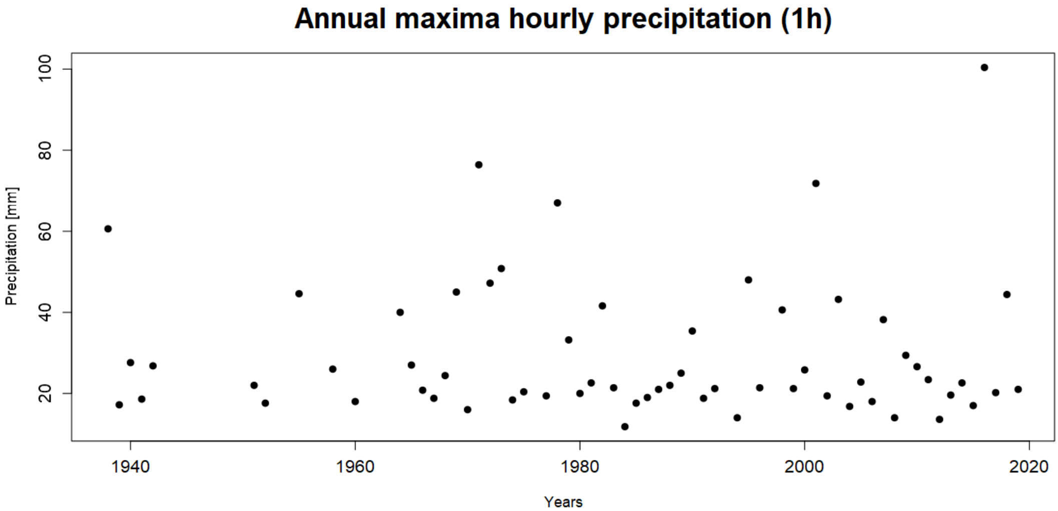


Fig. A 2 - Annual maxima hourly precipitation (1h) for Bari Presidenza Regione station

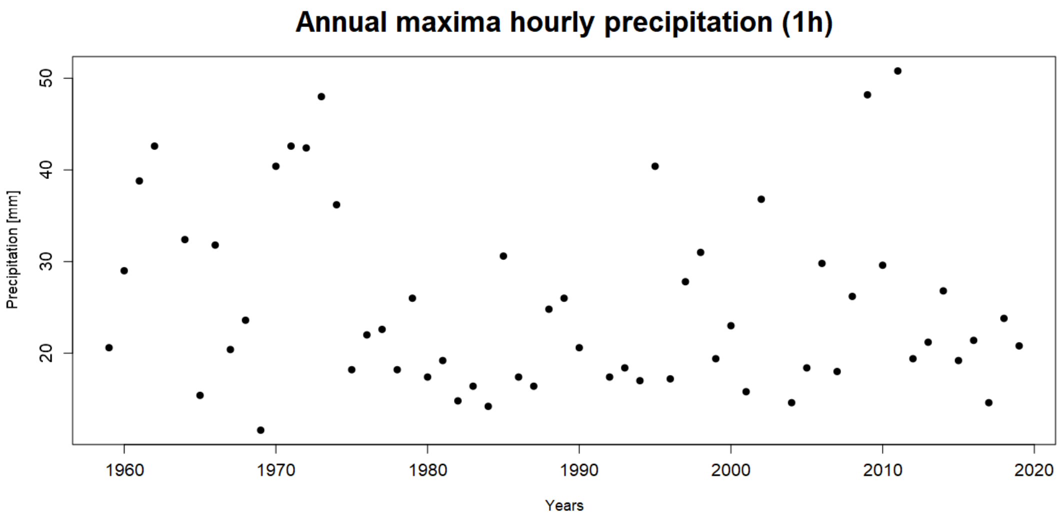


Fig. A 3 - Annual maxima hourly precipitation (1h) for Barletta station

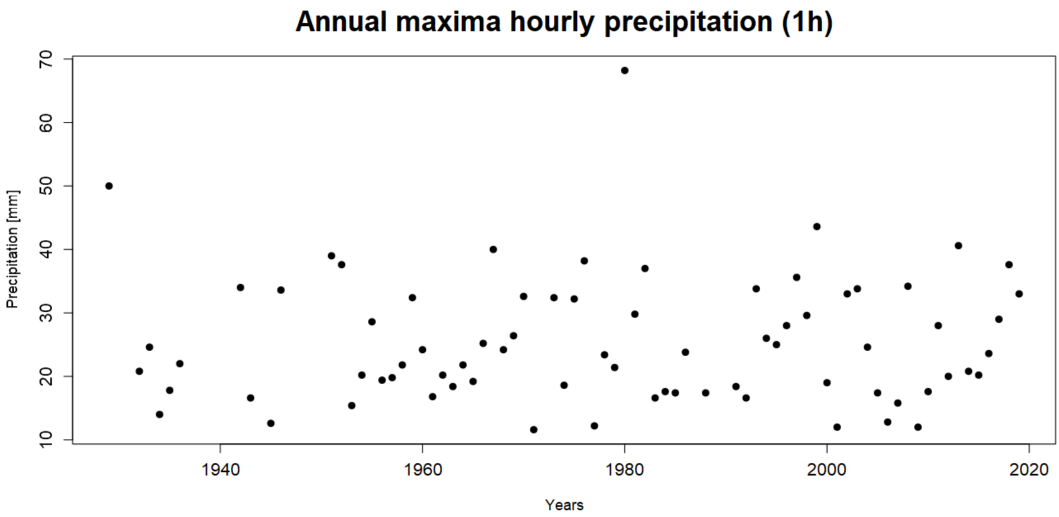


Fig. A 4 - Annual maxima hourly precipitation (1h) for Barletta station

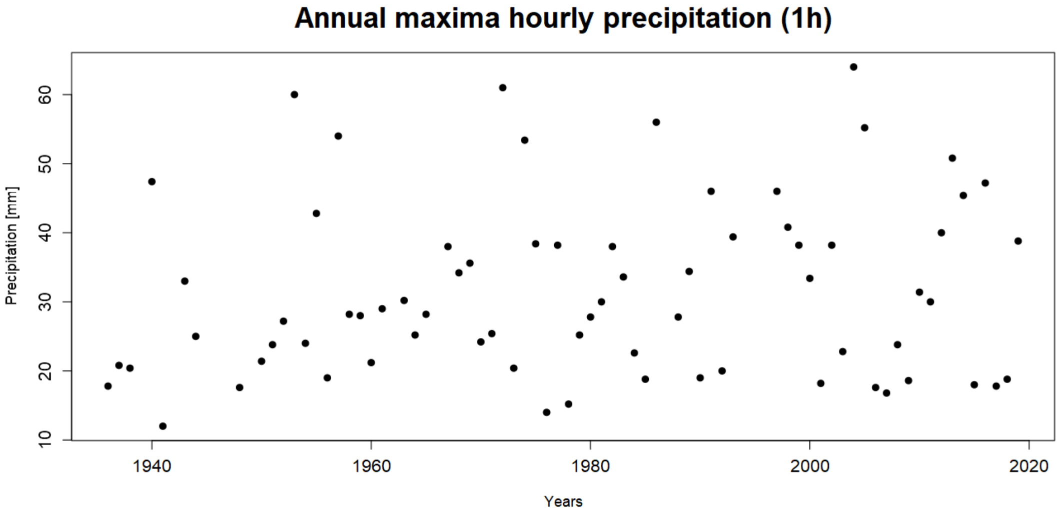


Fig. A 5 - Annual maxima hourly precipitation (1h) for Brindisi station

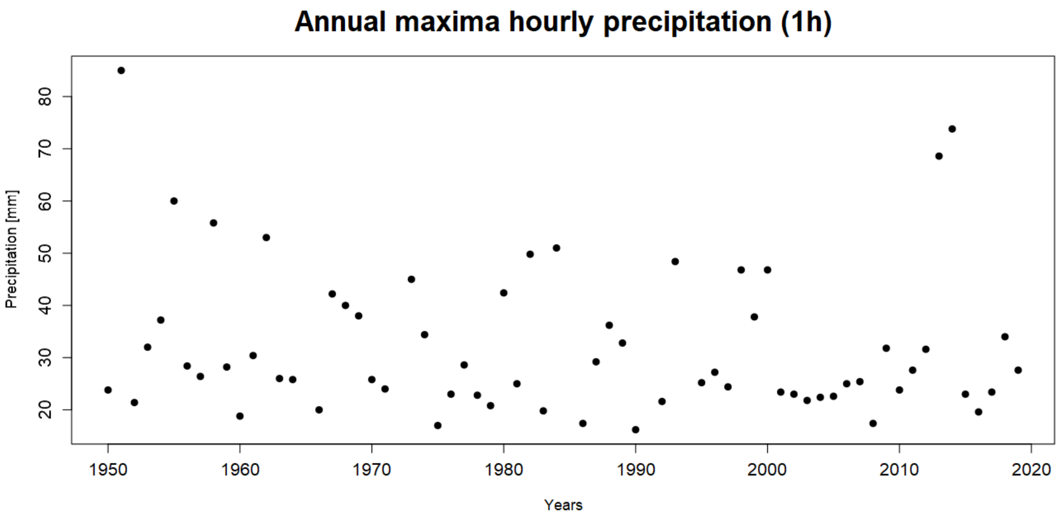


Fig. A 6 - Annual maxima hourly precipitation (1h) for Cagnano Varano station

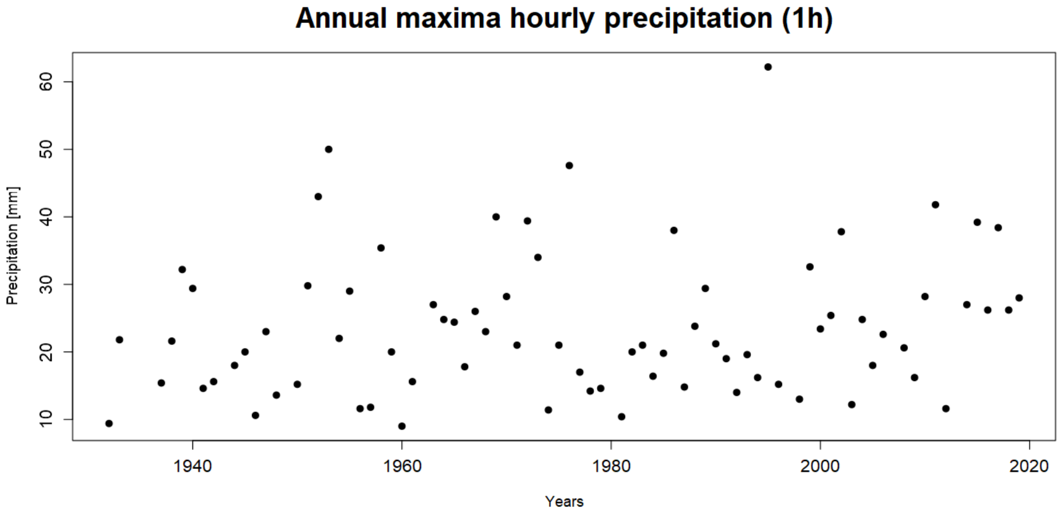


Fig. A 7 - Annual maxima hourly precipitation (1h) for Cerignola station

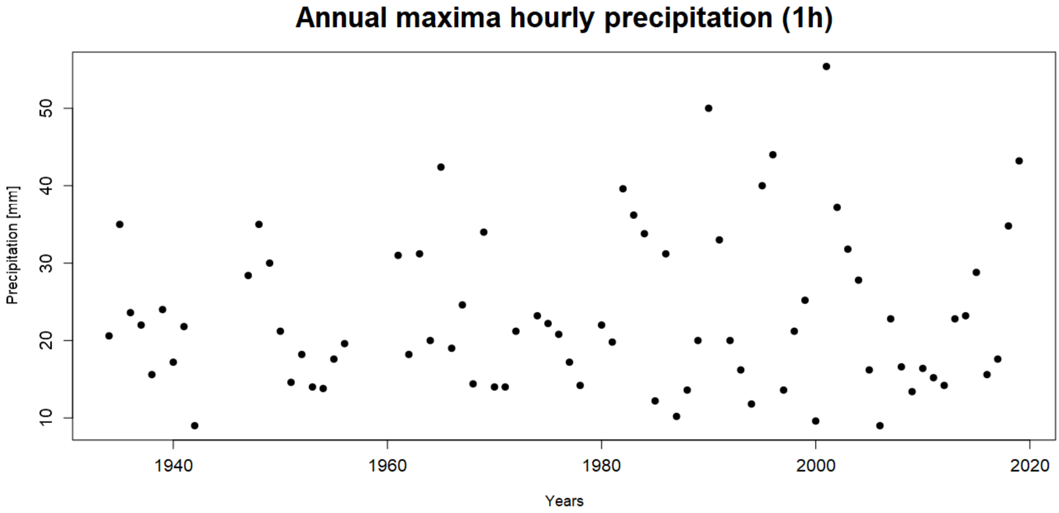


Fig. A 8 - Annual maxima hourly precipitation (1h) for Foggia Osservatorio station

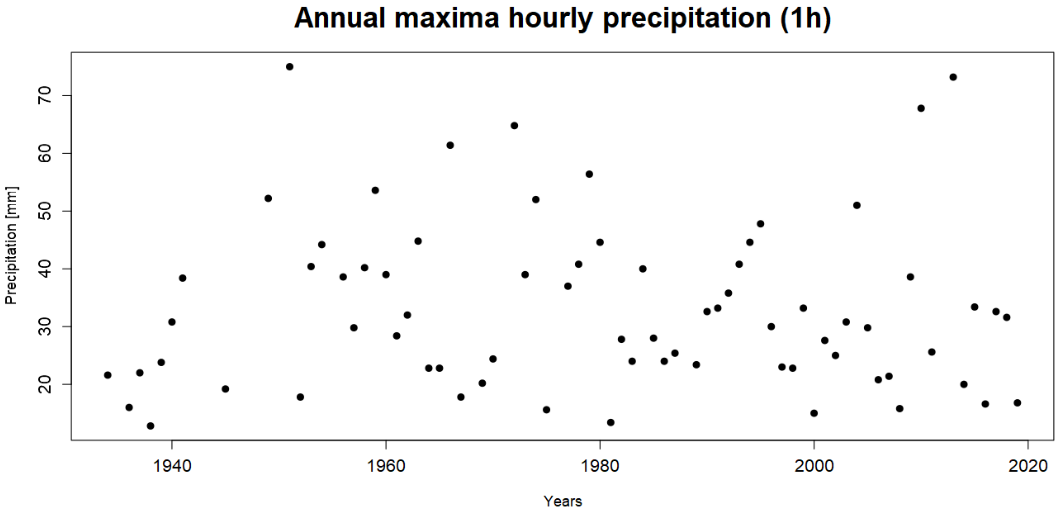


Fig. A 9 - Annual maxima hourly precipitation (1h) for Gallipoli station

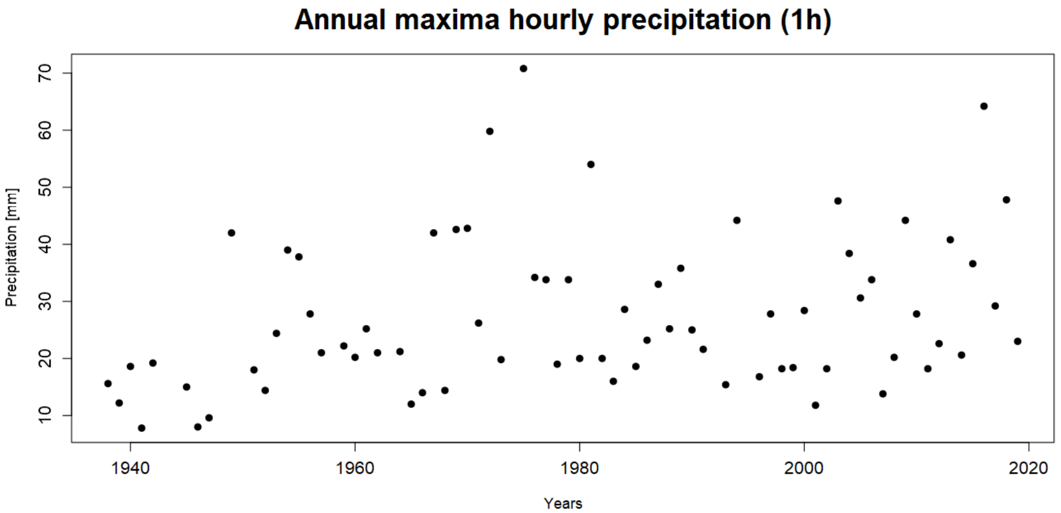


Fig. A 10 - Annual maxima hourly precipitation (1h) for Lesina station

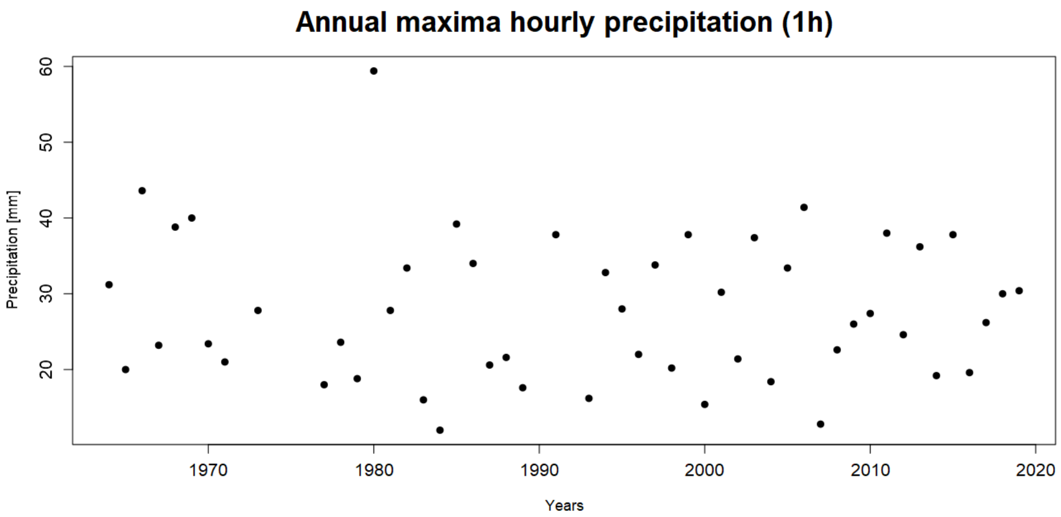


Fig. A 11 - Annual maxima hourly precipitation (1h) for Locorotondo station

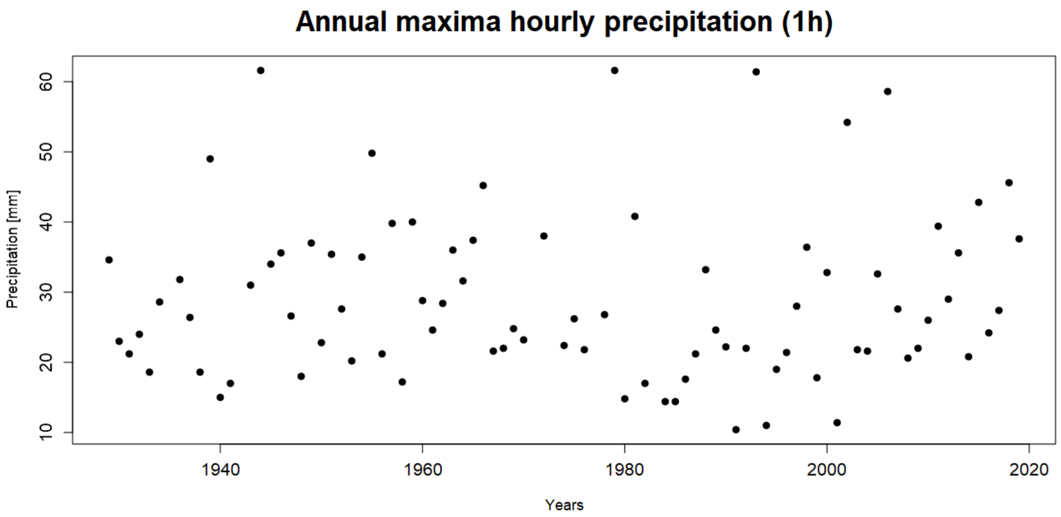


Fig. A 12 - Annual maxima hourly precipitation (1h) for Noci station

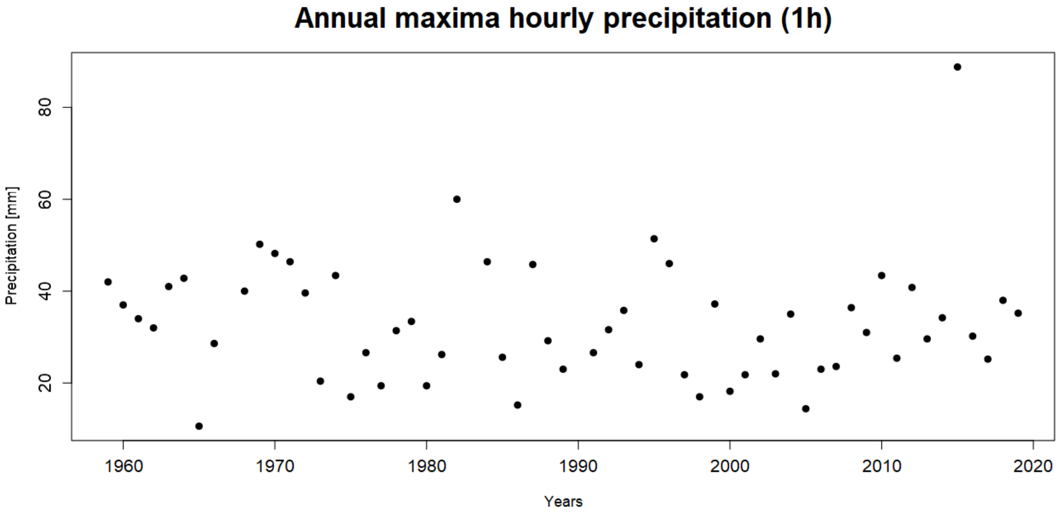


Fig. A 13 - Annual maxima hourly precipitation (1h) for Novoli station

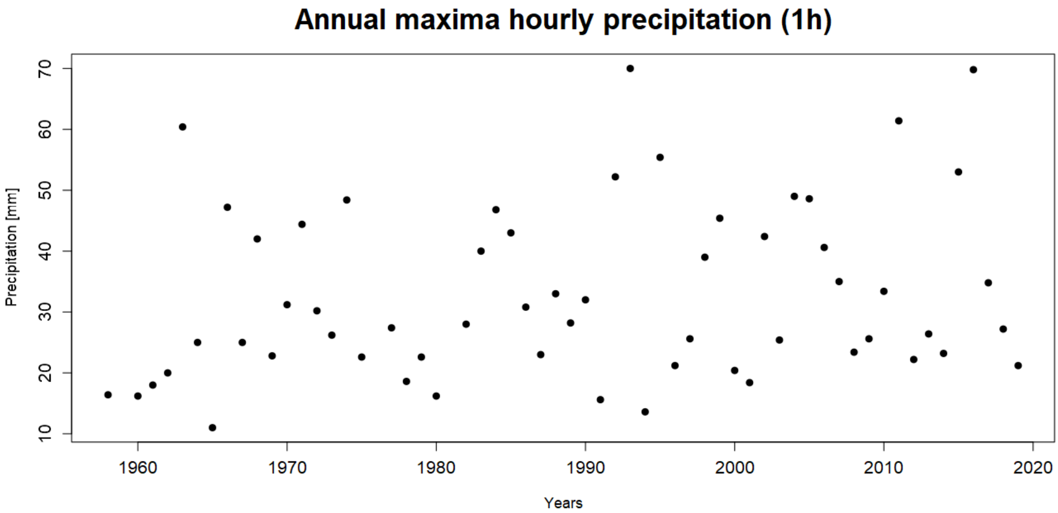


Fig. A 14 - Annual maxima hourly precipitation (1h) for Ostuni station

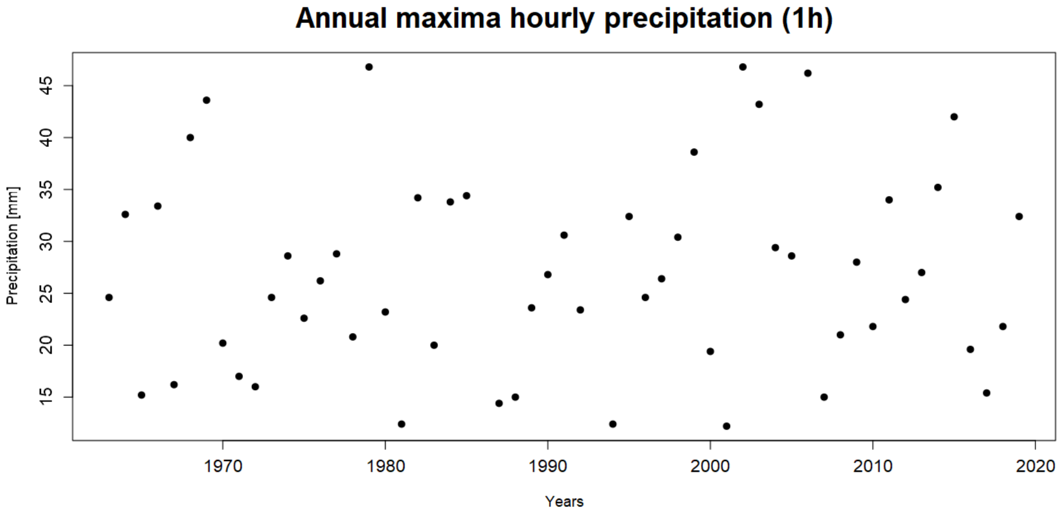


Fig. A 15 - Annual maxima hourly precipitation (1h) for Polignano a Mare station

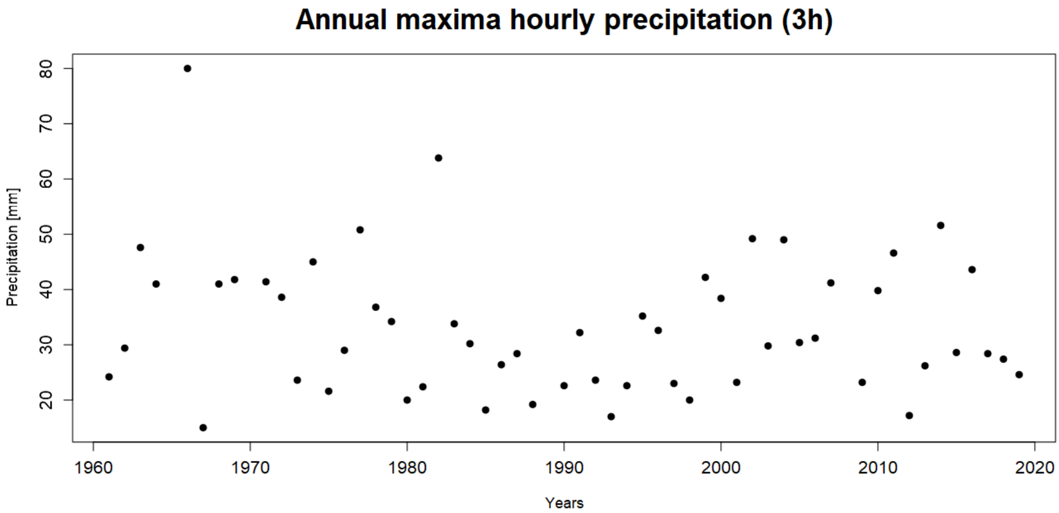


Fig. A 16 - Annual maxima hourly precipitation (3h) for Adelfia station

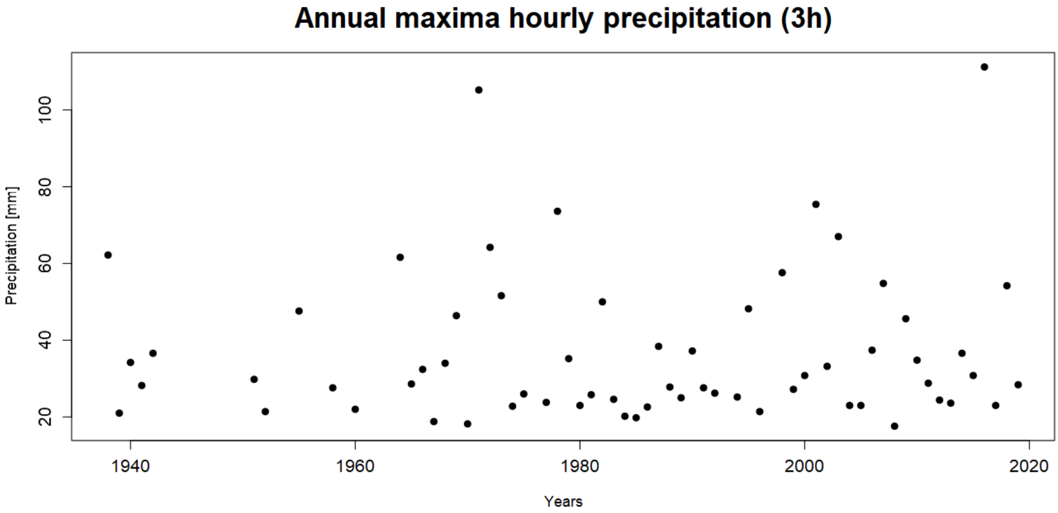


Fig. A 17 Annual maxima hourly precipitation (3h) for Bari Presidenza Regione station

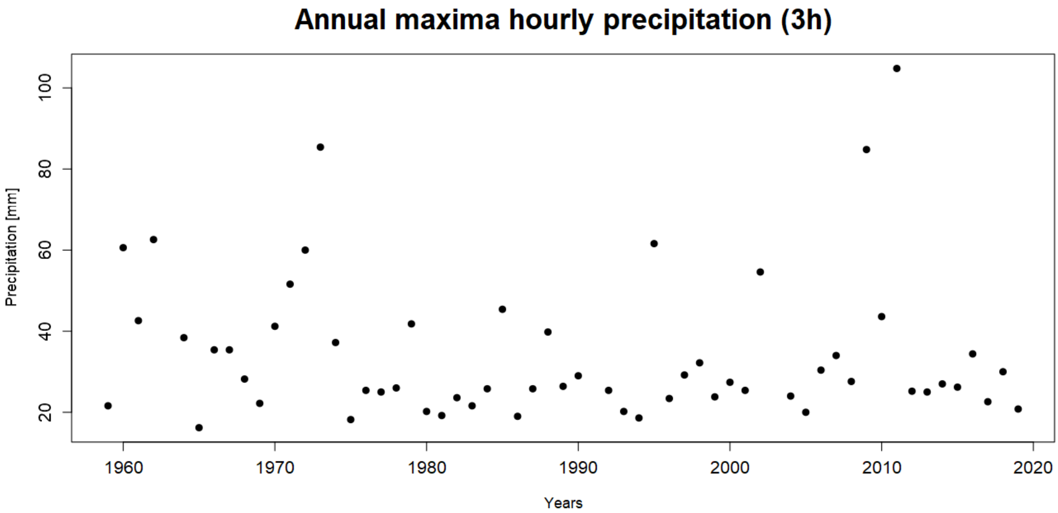


Fig. A 18 - Annual maxima hourly precipitation (3h) for Barletta station

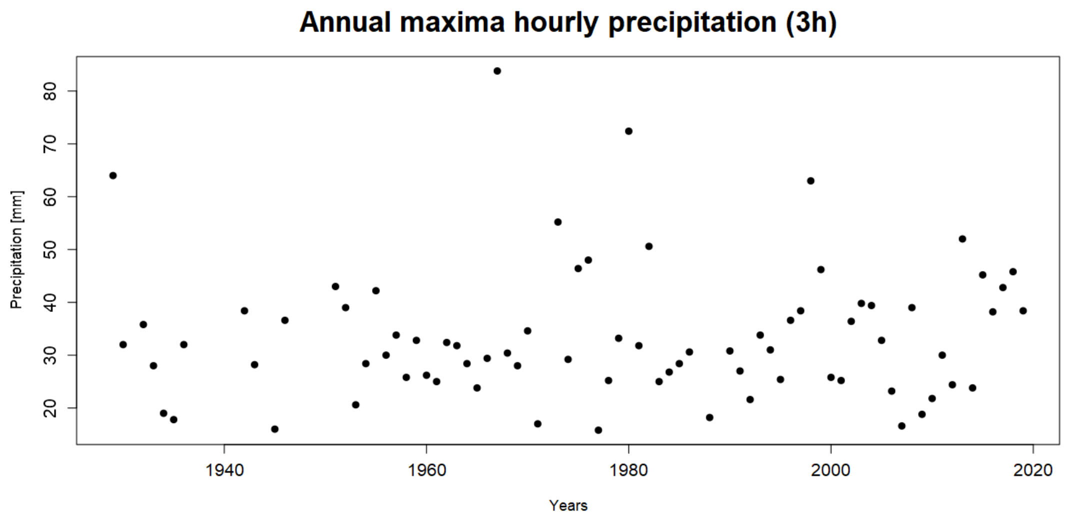


Fig. A 19 - Annual maxima hourly precipitation (3h) for Bovino station

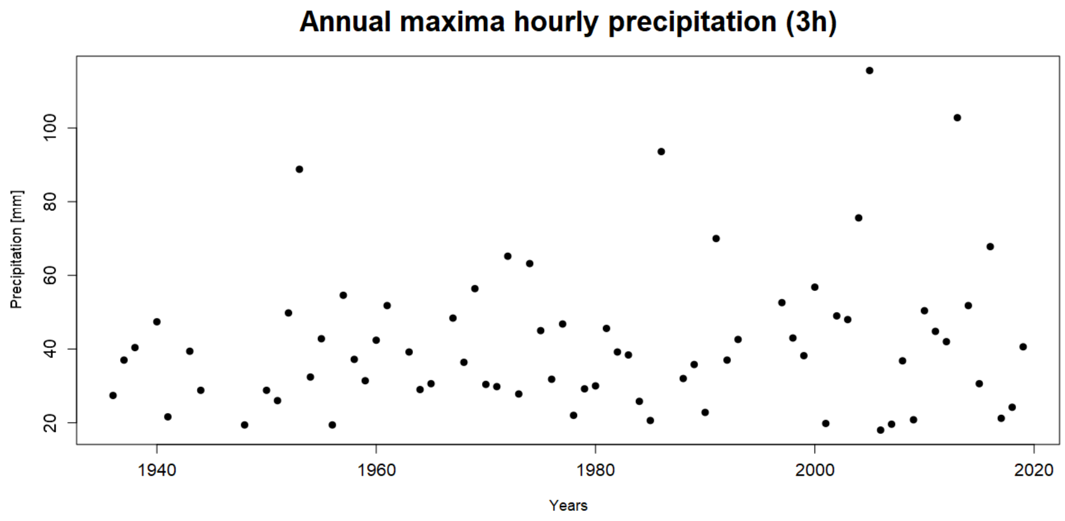


Fig. A 20 - Annual maxima hourly precipitation (3h) for Brindisi station

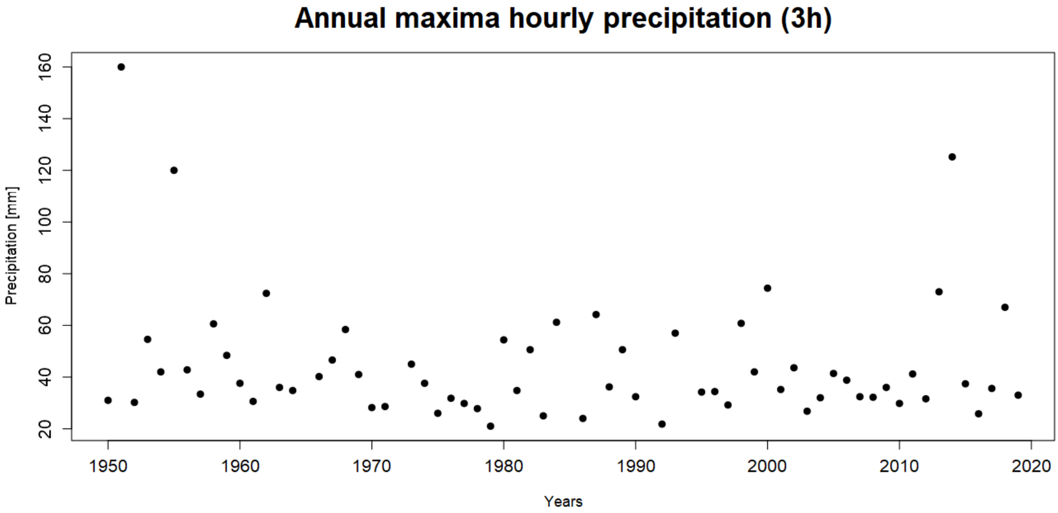


Fig. A 21 - Annual maxima hourly precipitation (3h) for Cagnano Varano station

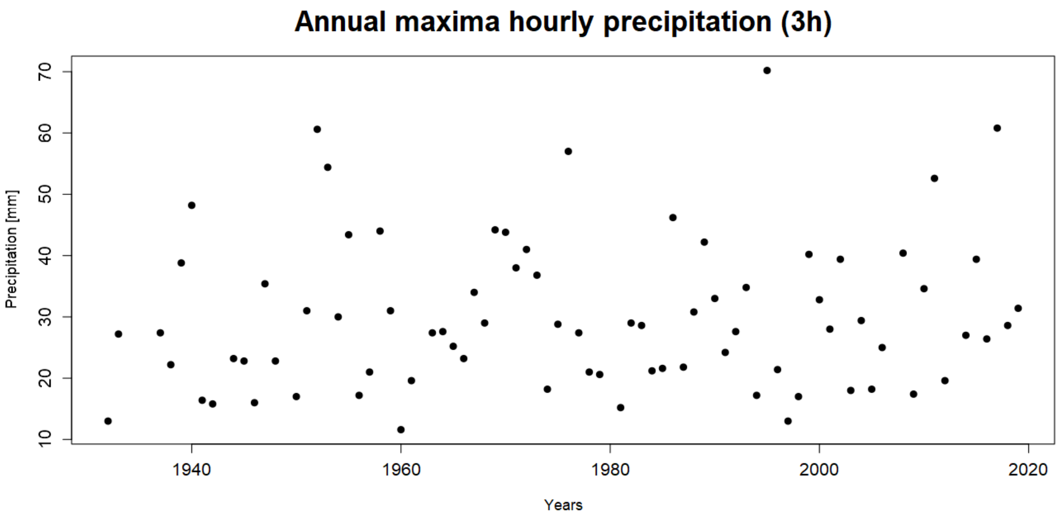


Fig. A 22 - Annual maxima hourly precipitation (3h) for Cerignola station

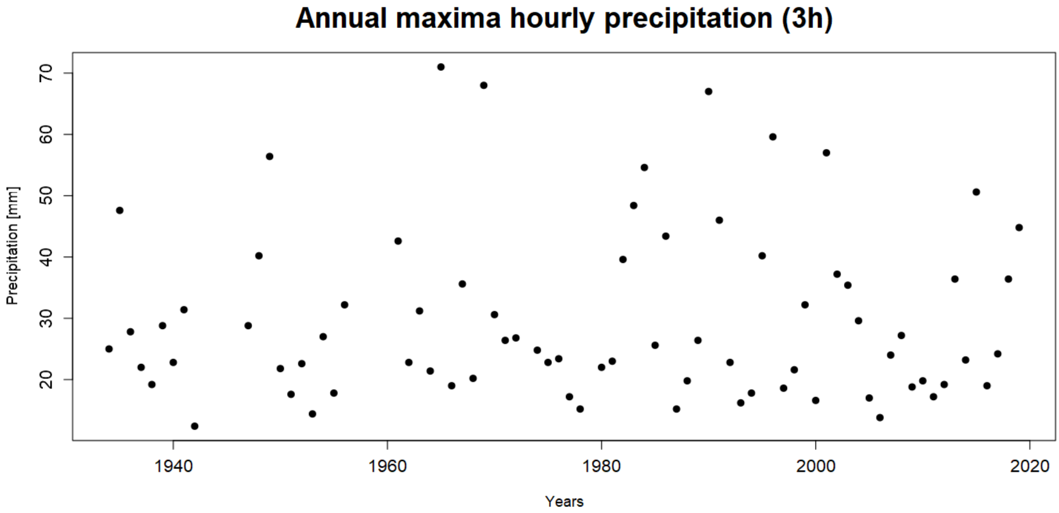


Fig. A 23 - Annual maxima hourly precipitation (3h) for Foggia Osservatorio station

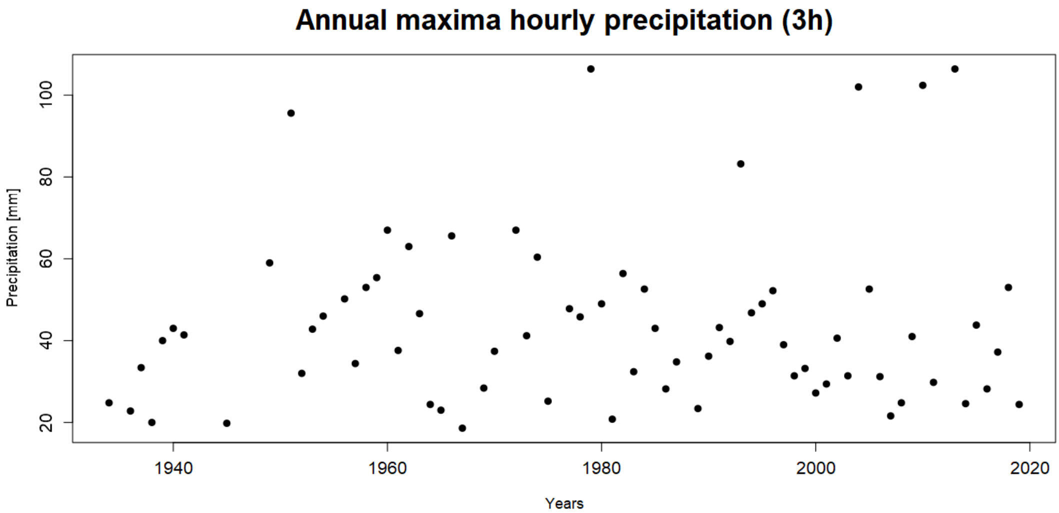


Fig. A 24 - Annual maxima hourly precipitation (3h) for Gallipoli station

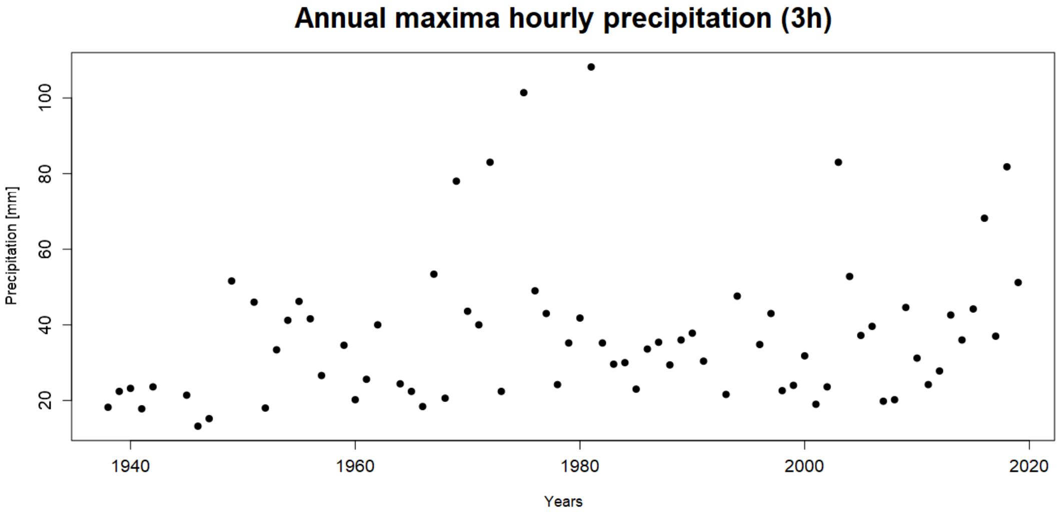


Fig. A 25 - Annual maxima hourly precipitation (3h) for Lesina station

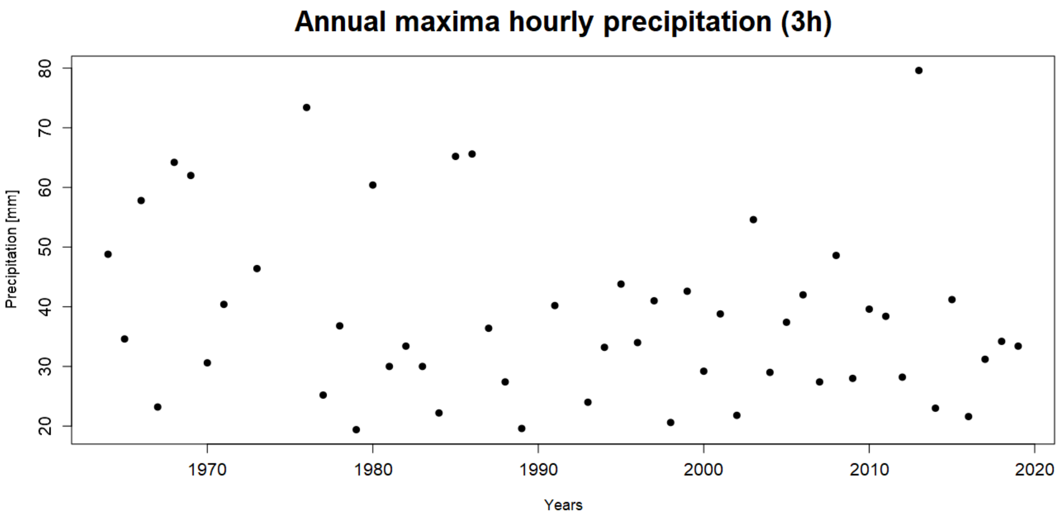


Fig. A 26 - Annual maxima hourly precipitation (3h) for Locorotondo station

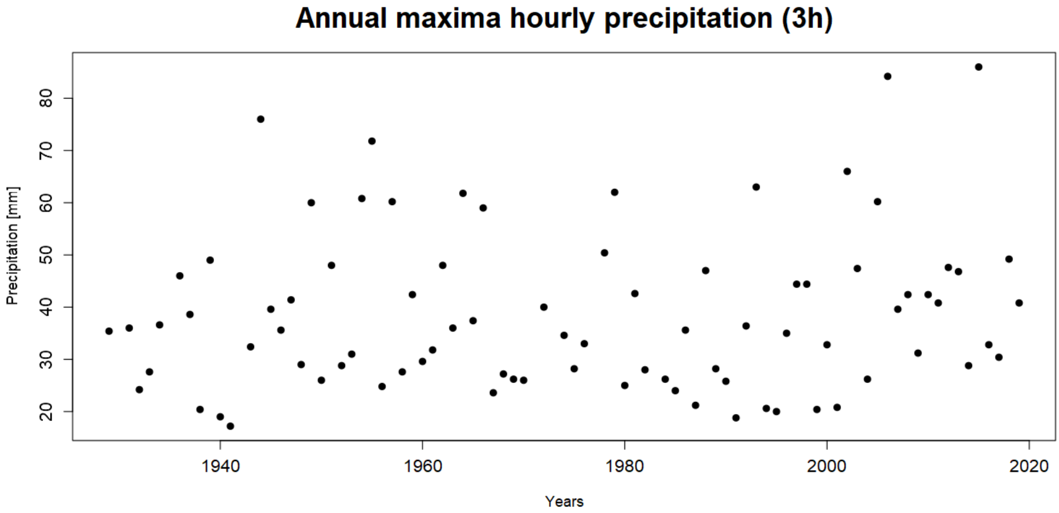


Fig. A 27 - Annual maxima hourly precipitation (3h) for Noci station

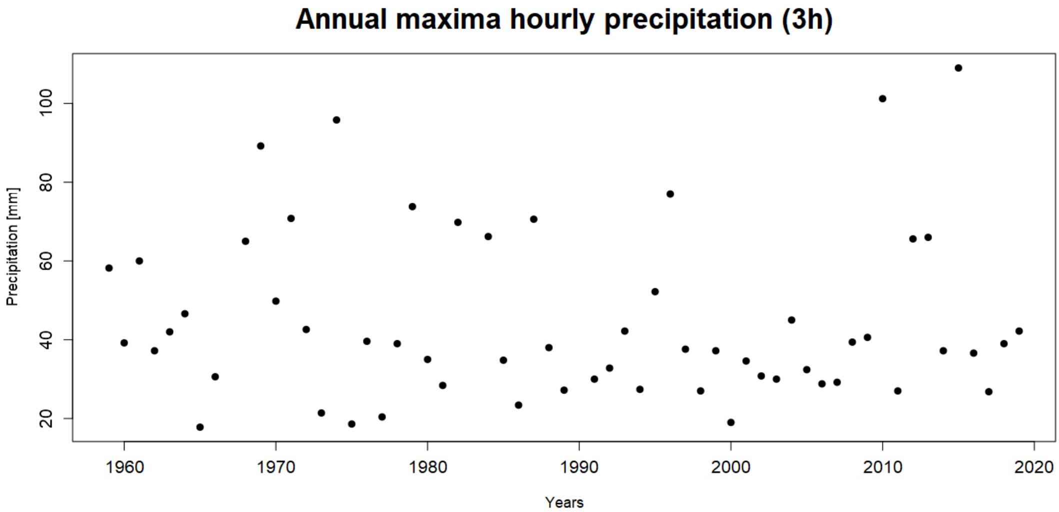


Fig. A 28 - Annual maxima hourly precipitation (3h) for Novoli station

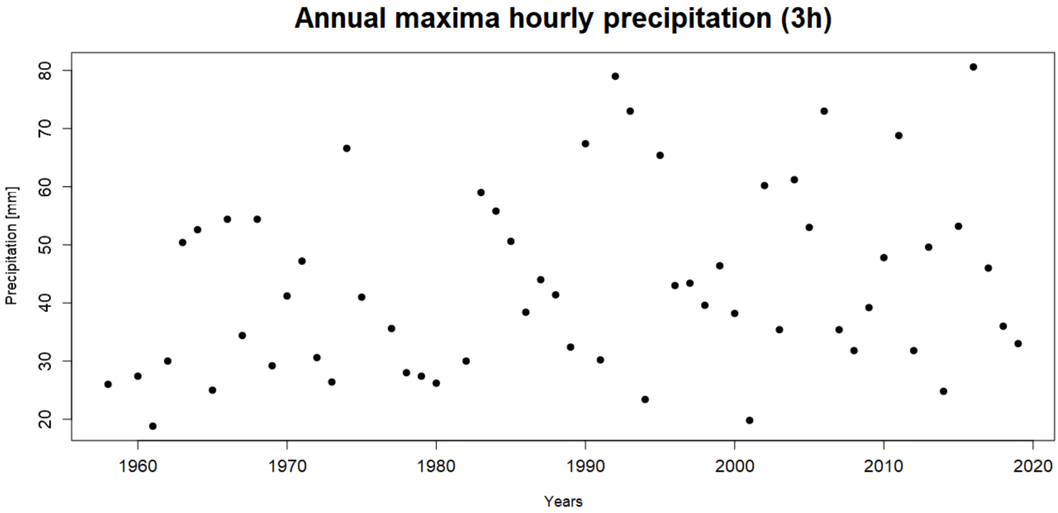


Fig. A 29 - Annual maxima hourly precipitation (3h) for Ostuni station

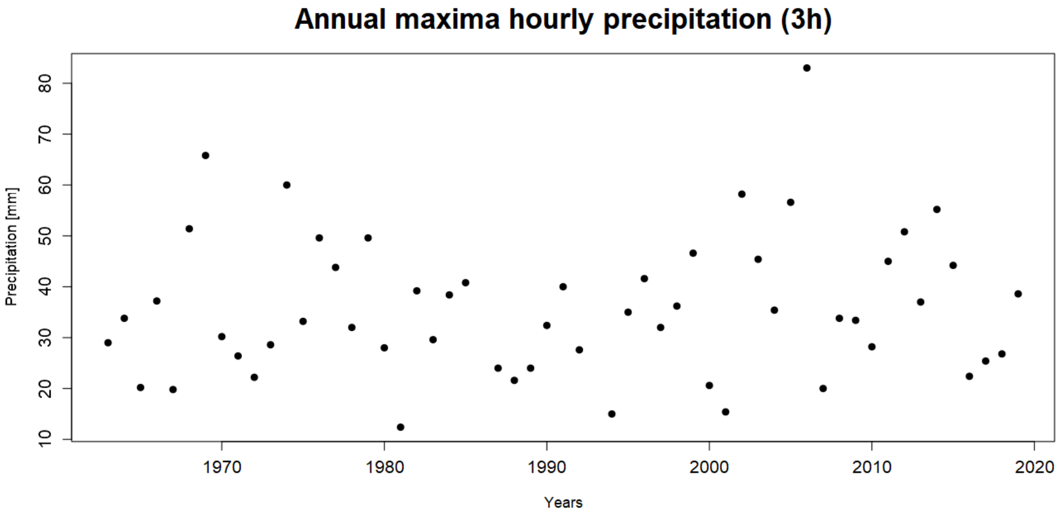


Fig. A 30 - Annual maxima hourly precipitation (3h) for Polignano a mare station

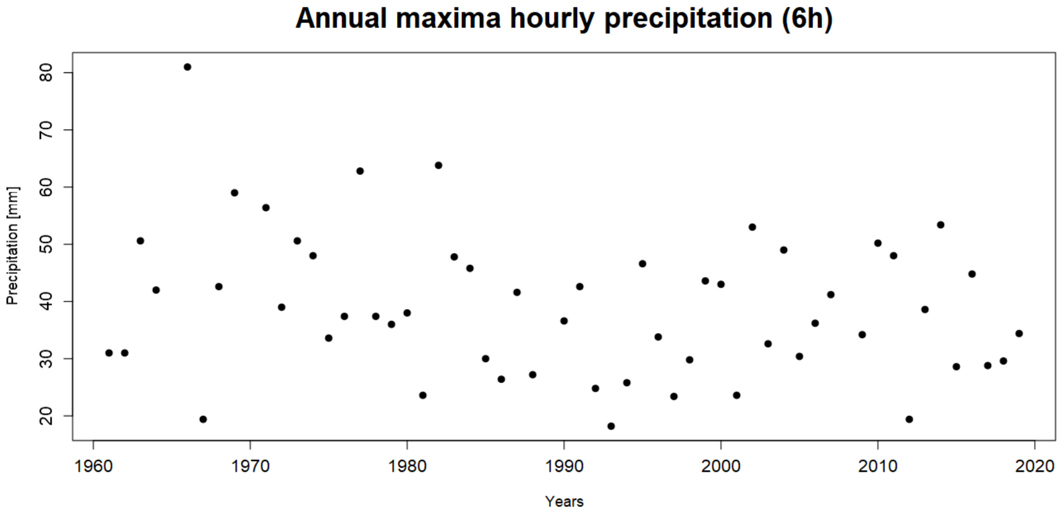


Fig. A 31 - Annual maxima hourly precipitation (6h) for Adelfia station

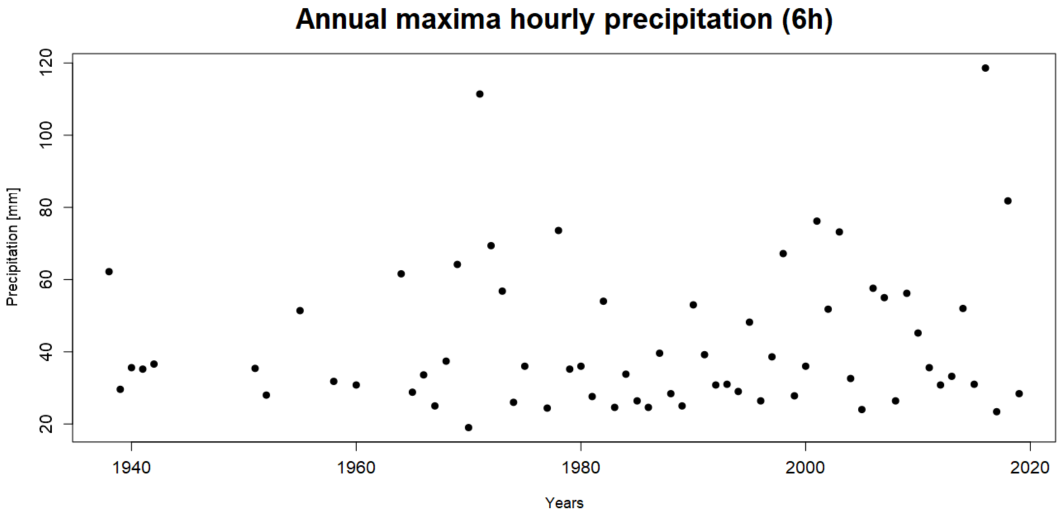


Fig. A 32 - Annual maxima hourly precipitation (6h) for Bari Presidenza Regione station

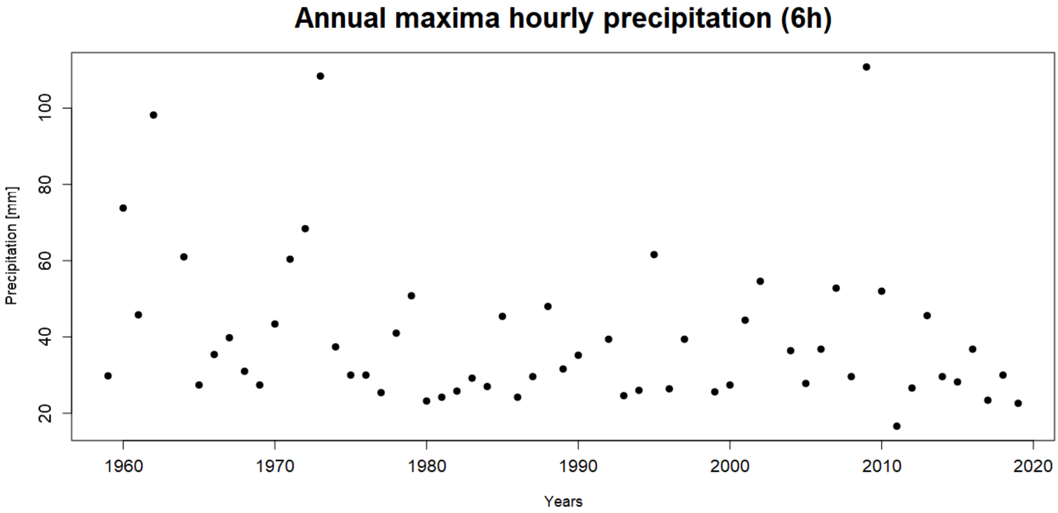


Fig. A 33 - Annual maxima hourly precipitation (6h) for Barletta station

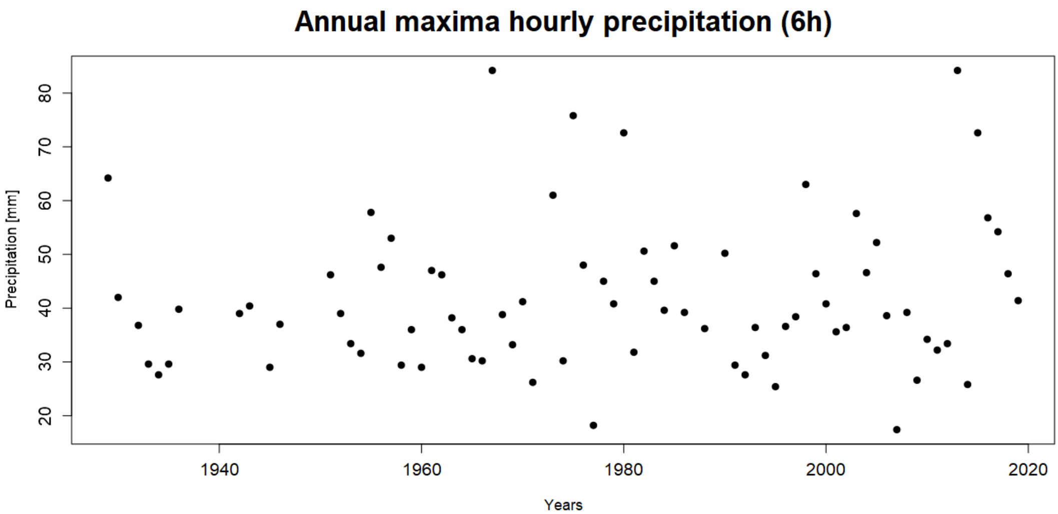


Fig. A 34 - Annual maxima hourly precipitation (6h) for Bovino station

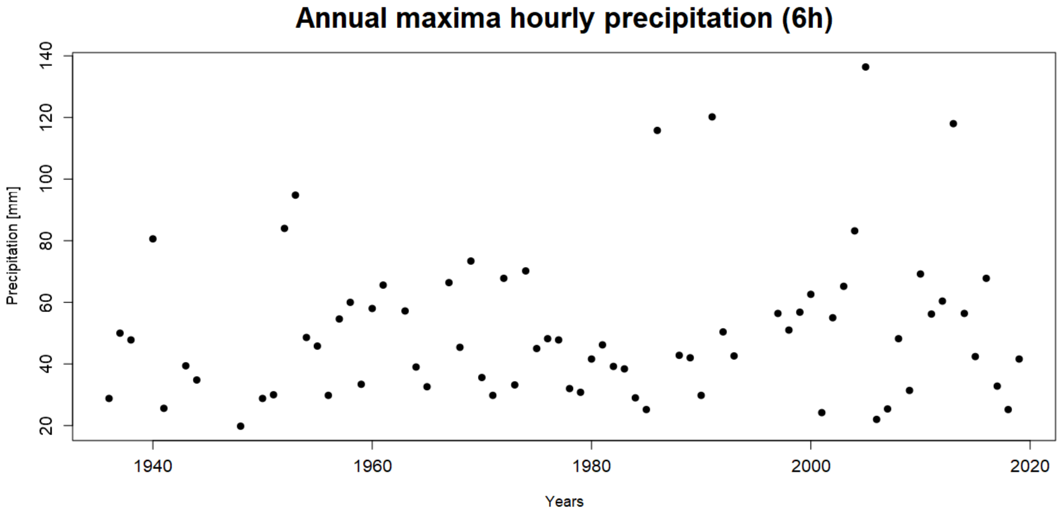


Fig. A 35 - Annual maxima hourly precipitation (6h) for Brindisi station

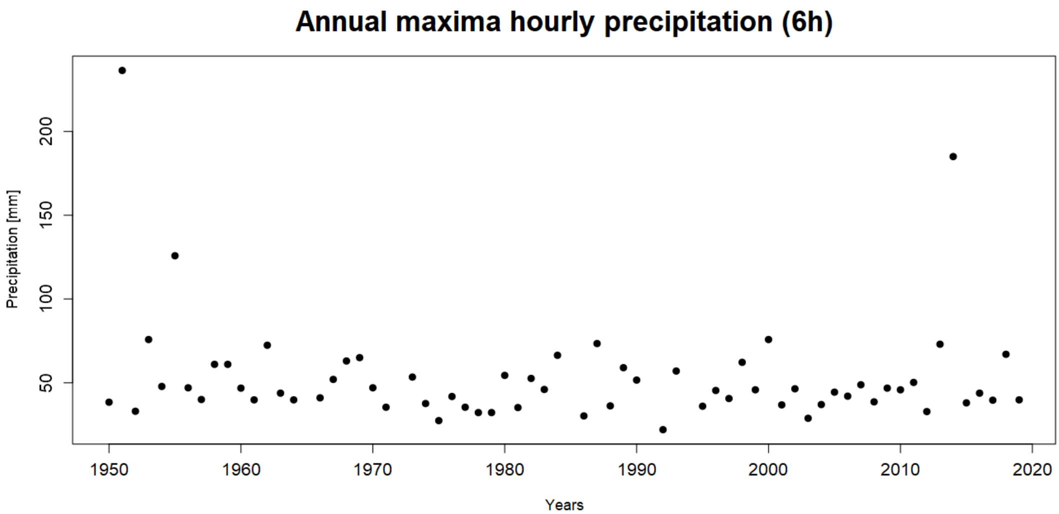


Fig. A 36 - Annual maxima hourly precipitation (6h) for Cagnano Varano station

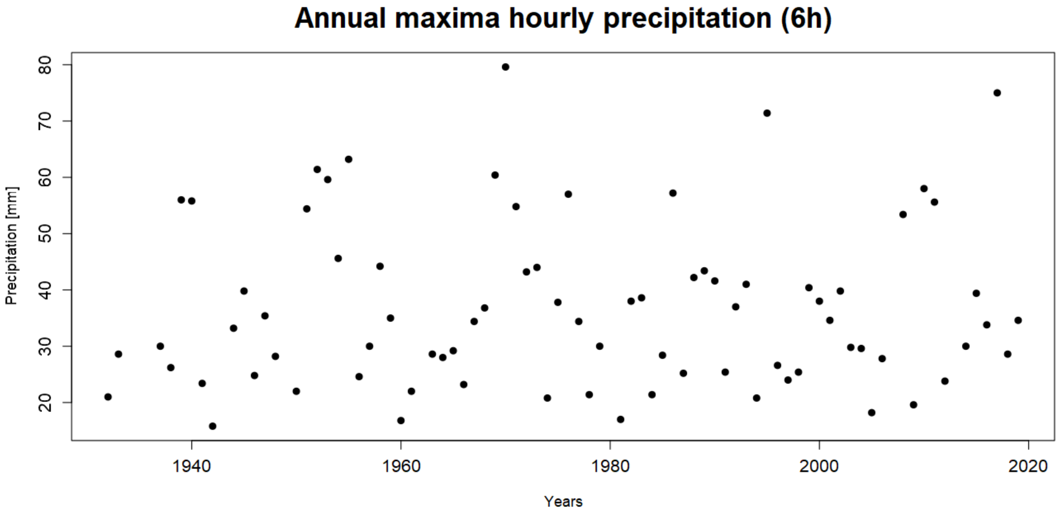


Fig. A 37 - Annual maxima hourly precipitation (6h) for Cerignola station

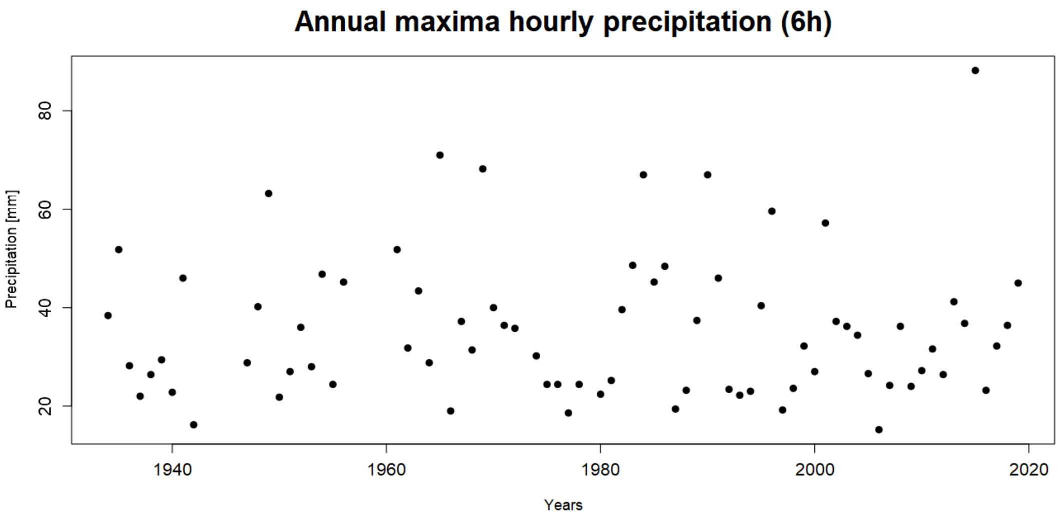


Fig. A 38 - Annual maxima hourly precipitation (6h) for Foggia Osservatorio station

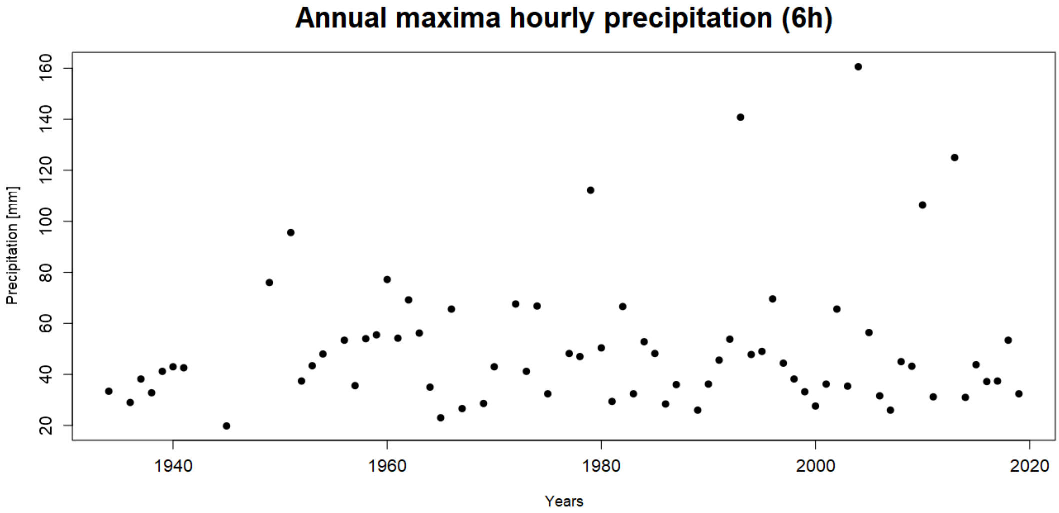


Fig. A 39 - Annual maxima hourly precipitation (6h) for Gallipoli station

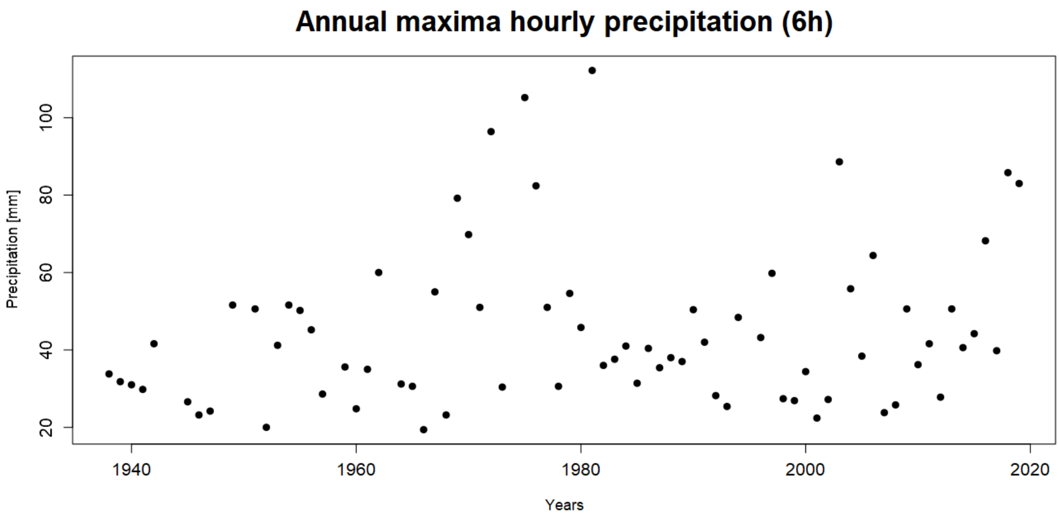


Fig. A 40 - Annual maxima hourly precipitation (6h) for Lesina station

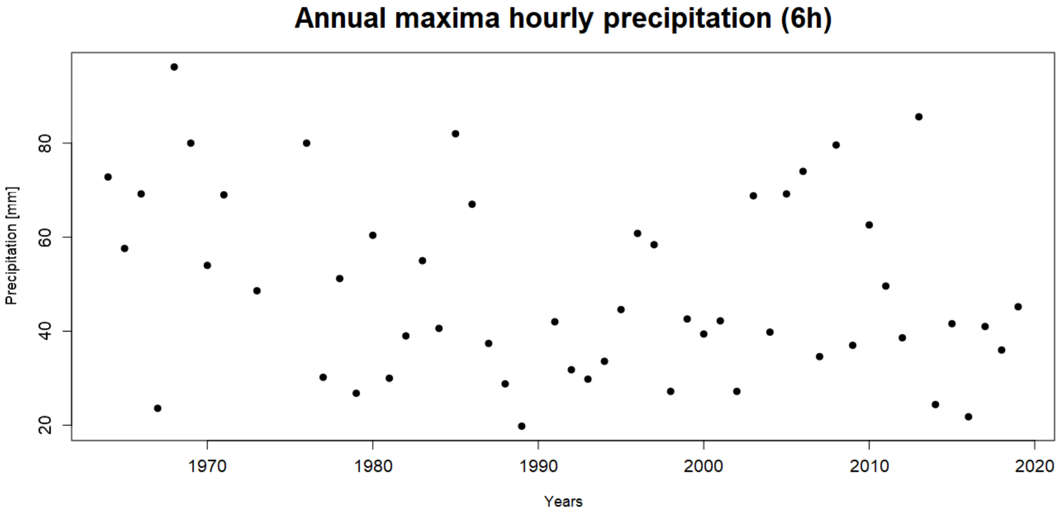


Fig. A 41 - Annual maxima hourly precipitation (6h) for Locorotondo station

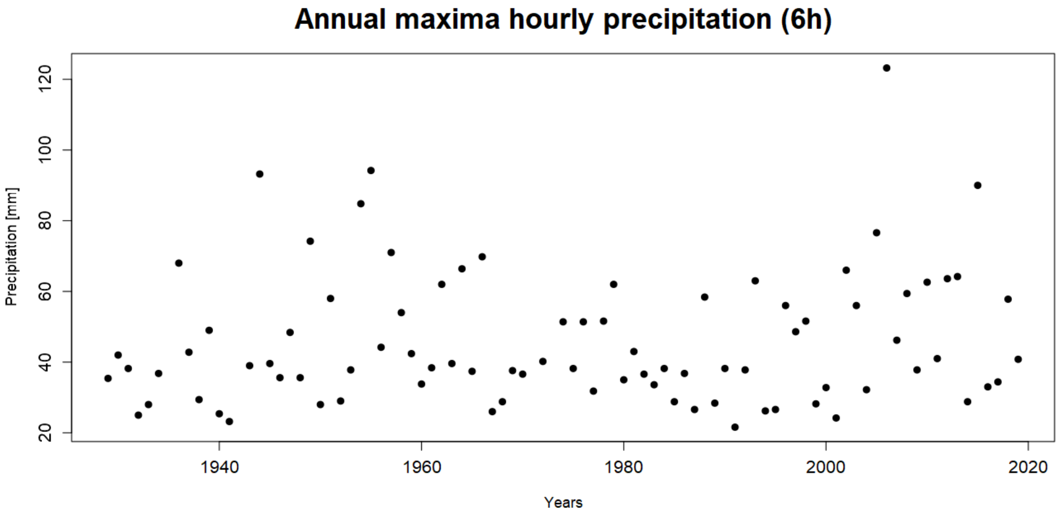


Fig. A 42 - Annual maxima hourly precipitation (6h) for Noci station

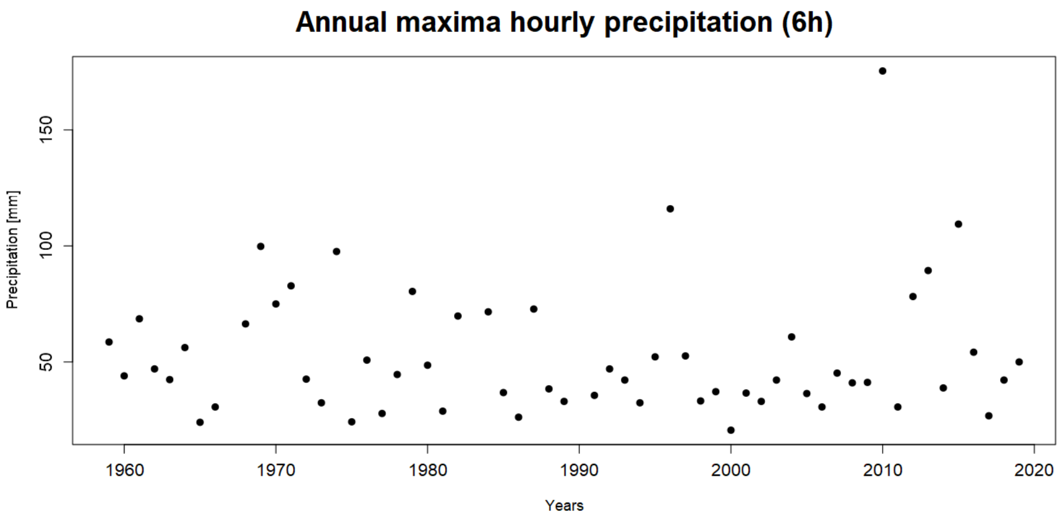


Fig. A 43 - Annual maxima hourly precipitation (6h) for Novolii station

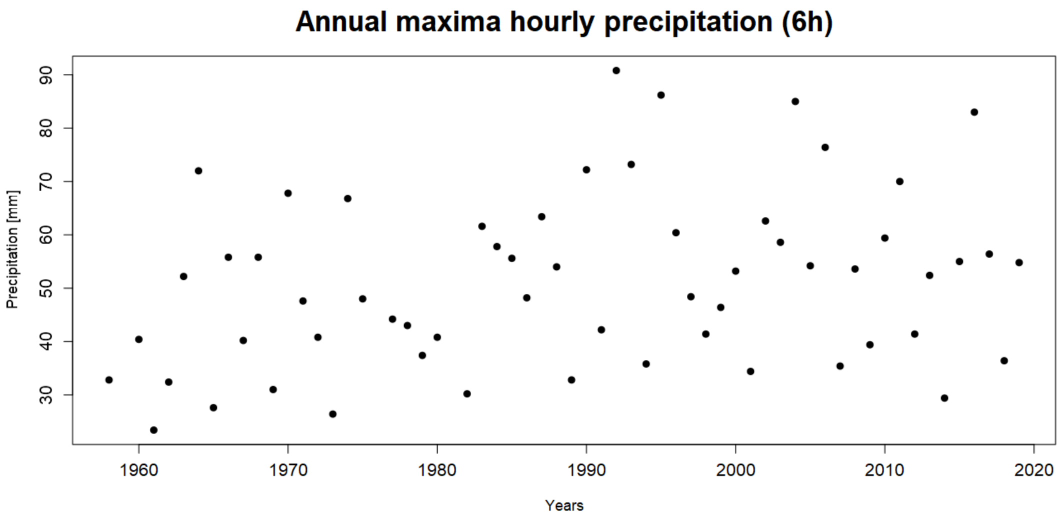


Fig. A 44 - Annual maxima hourly precipitation (6h) for Ostuni station

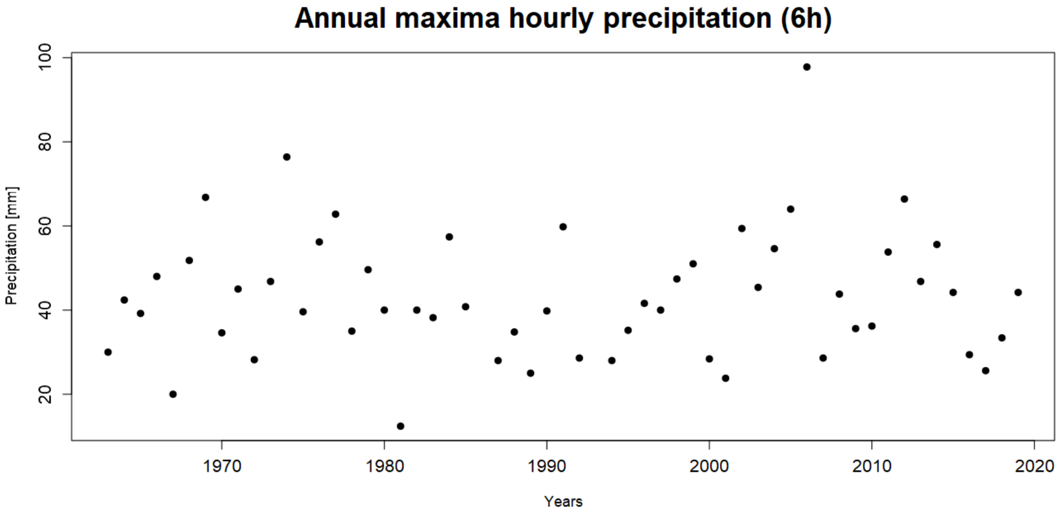


Fig. A 45 - Annual maxima hourly precipitation (6h) for Polignano a mare station

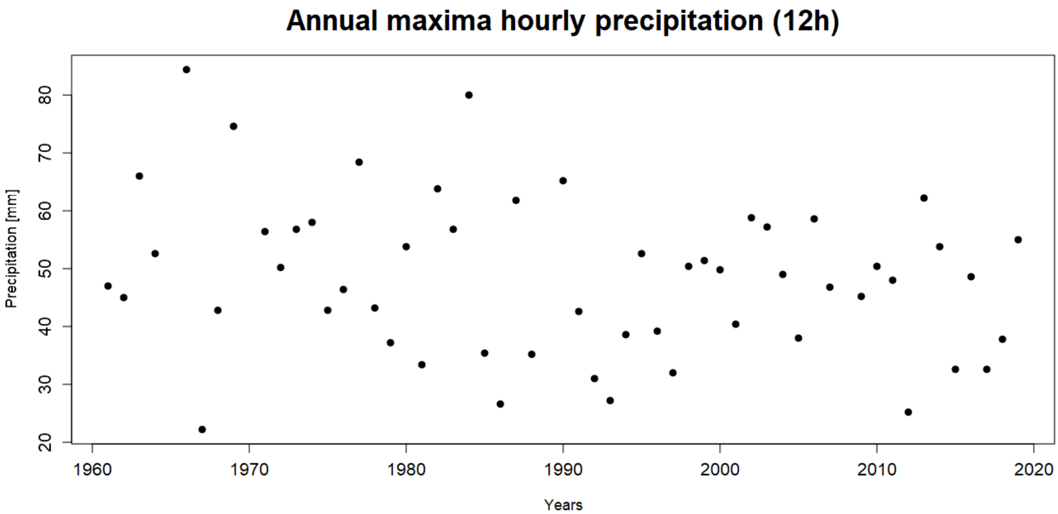


Fig. A 46 - Annual maxima hourly precipitation (12h) for Adelfia station

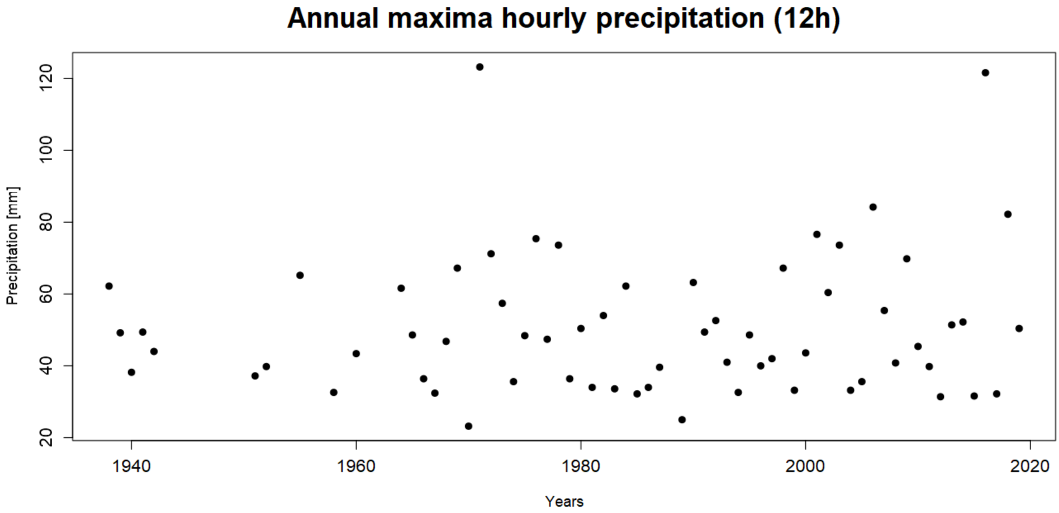


Fig. A 47 - Annual maxima hourly precipitation (12h) for Bari Presidenza Regione station

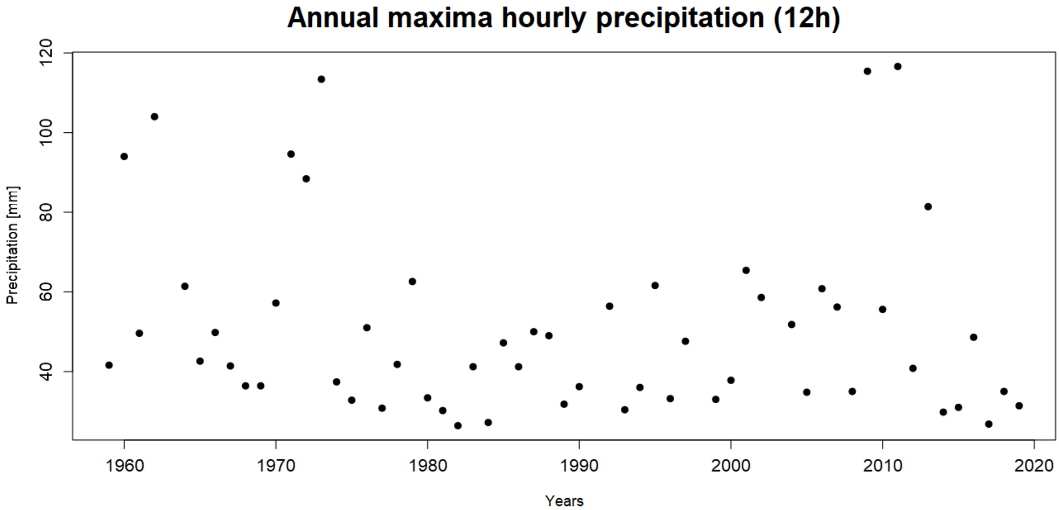


Fig. A 48 - Annual maxima hourly precipitation (12h) for Barletta station

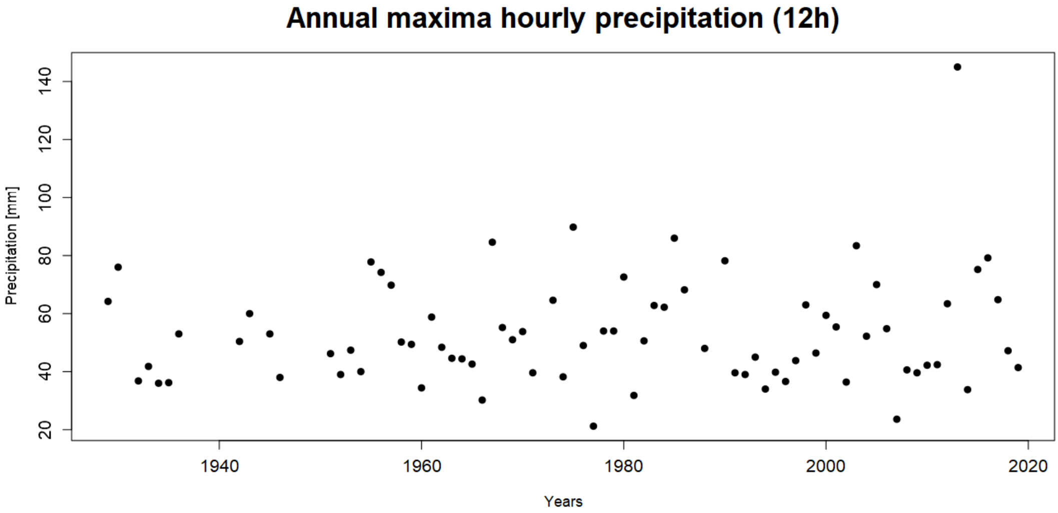


Fig. A 49 - Annual maxima hourly precipitation (12h) for Bovino station

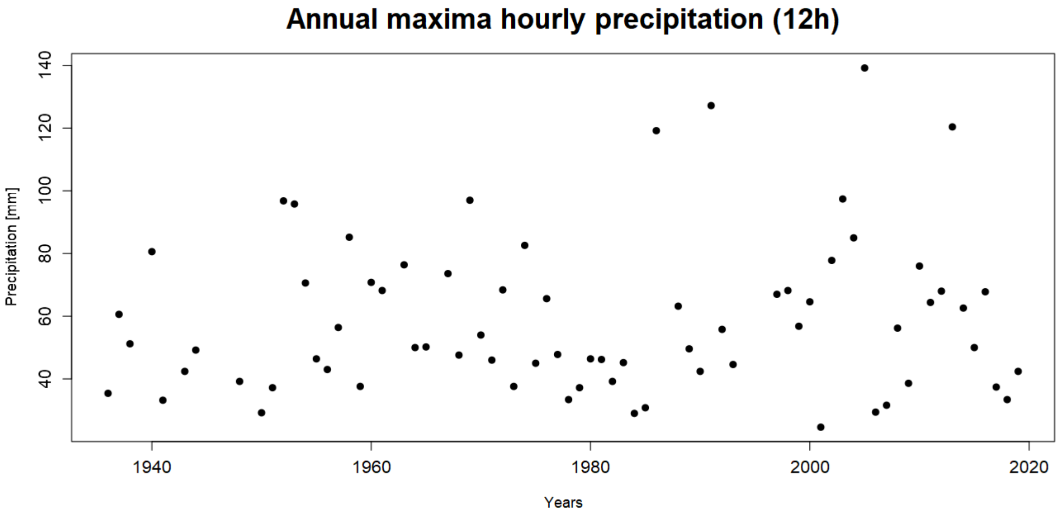


Fig. A 50 - Annual maxima hourly precipitation (12h) for Brindisi station

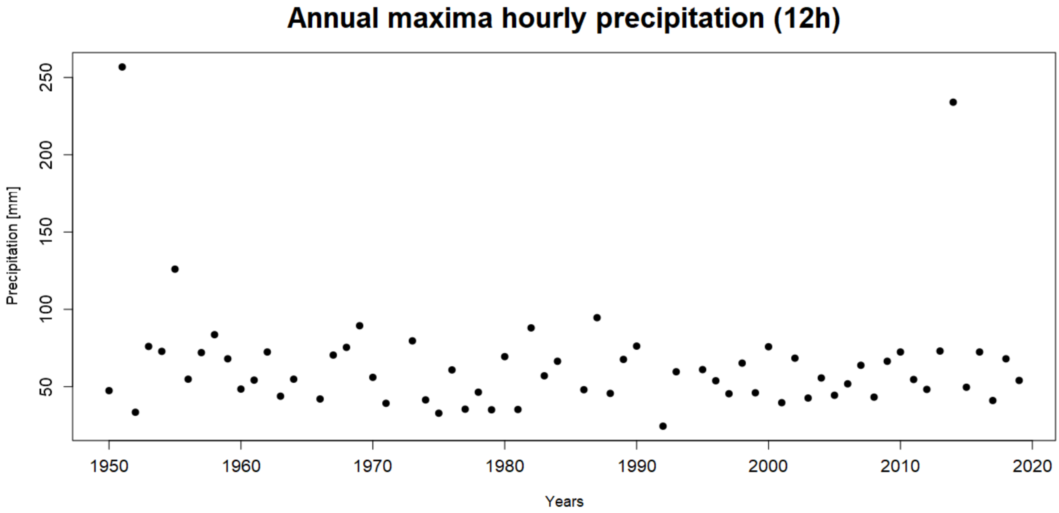


Fig. A 51 - Annual maxima hourly precipitation (12h) for Cagnano Varano station

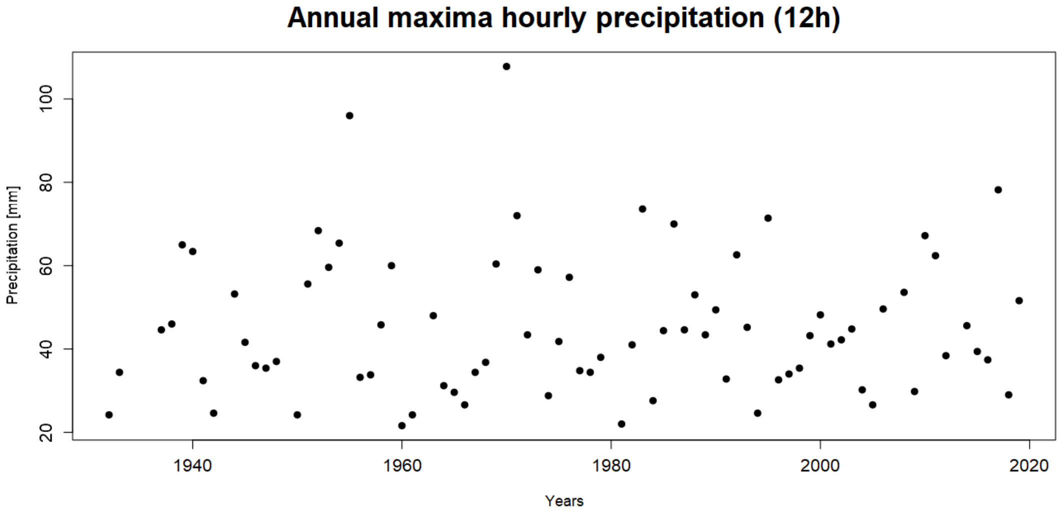


Fig. A 52 - Annual maxima hourly precipitation (12h) for Cerignola station

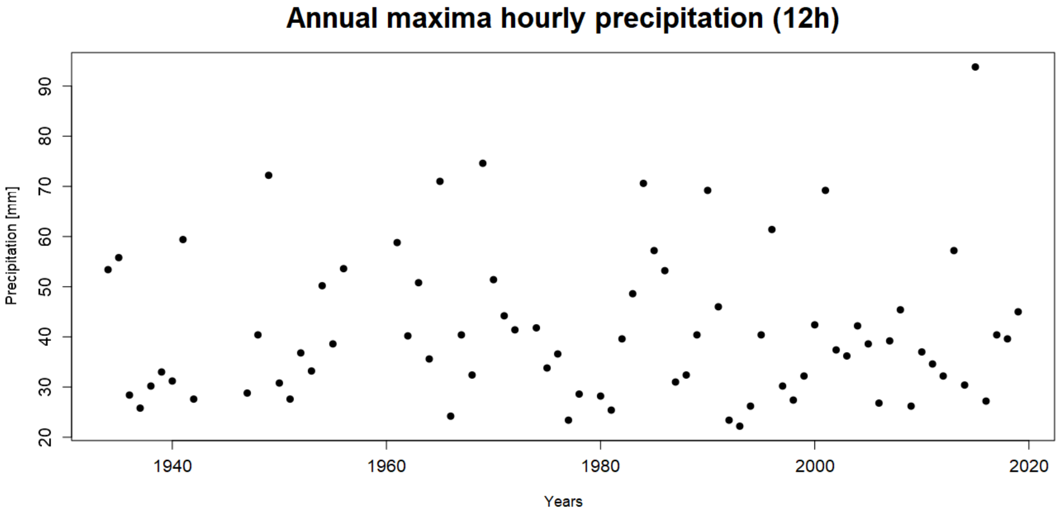


Fig. A 53 - Annual maxima hourly precipitation (12h) for Foggia Osservatorio station

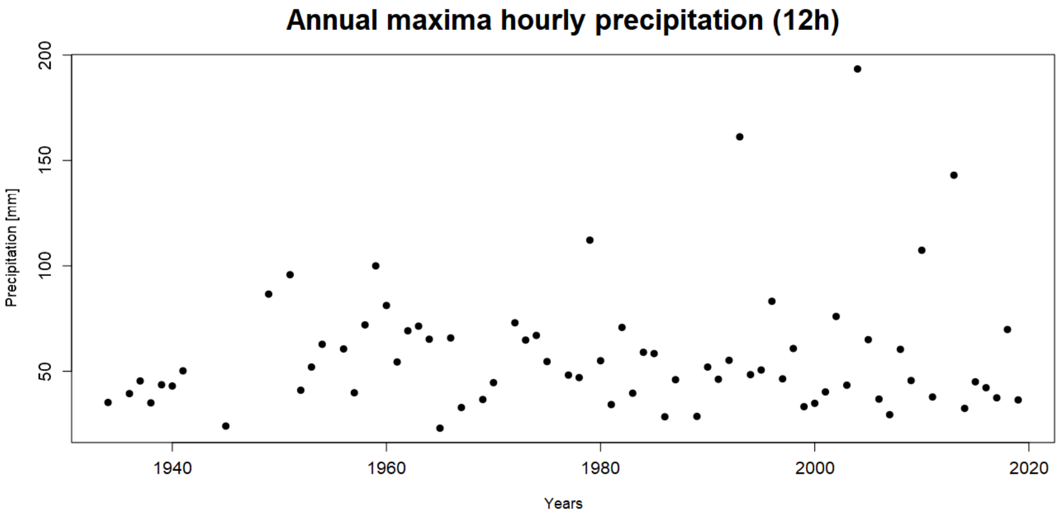


Fig. A 54 - Annual maxima hourly precipitation (12h) for Gallipoli station

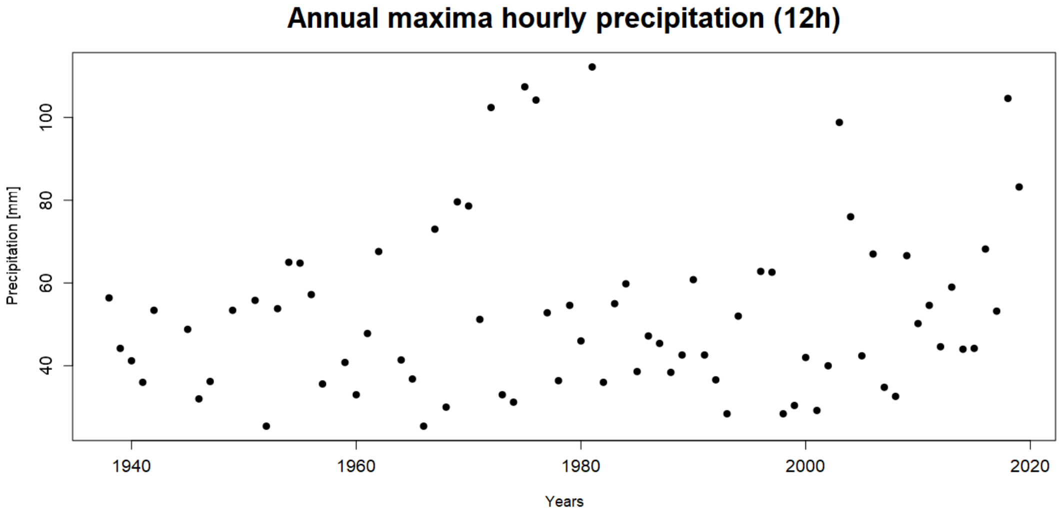


Fig. A 55 - Annual maxima hourly precipitation (12h) for Lesina station

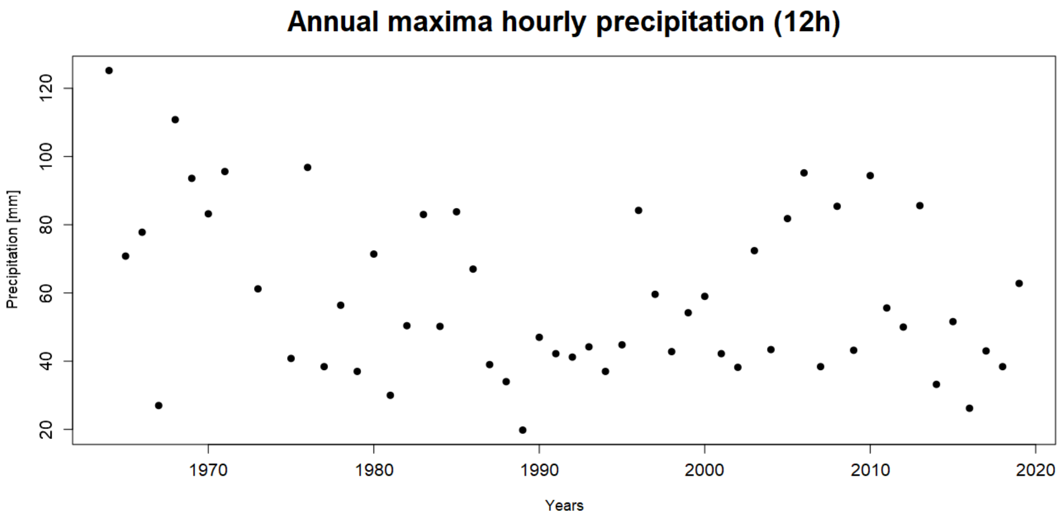


Fig. A 56 - Annual maxima hourly precipitation (12h) for Locorotondo station

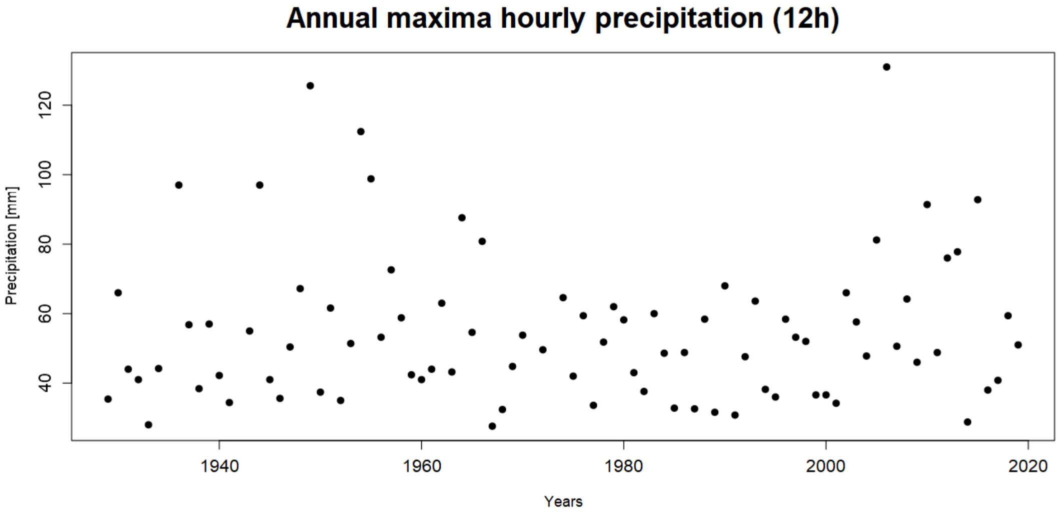


Fig. A 57 - Annual maxima hourly precipitation (12h) for Noci station

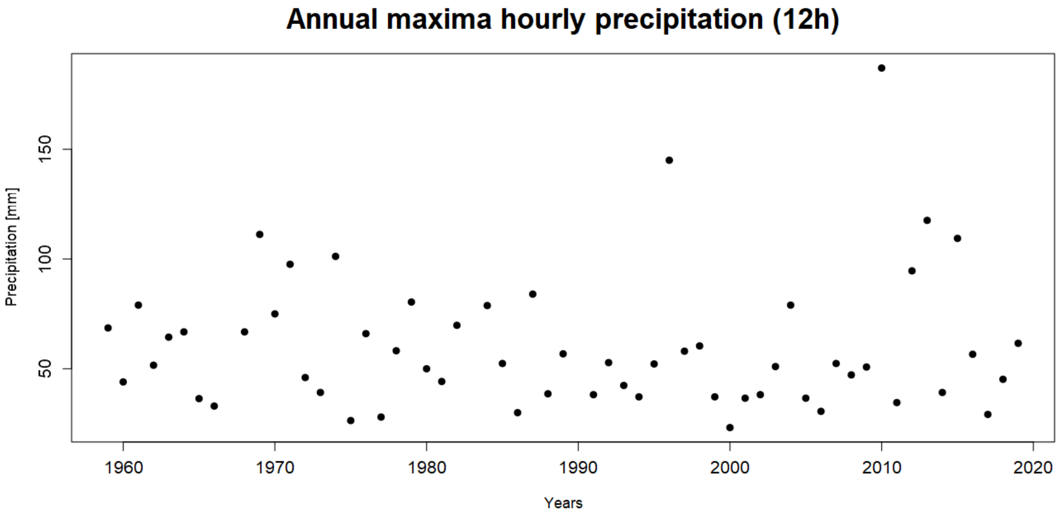


Fig. A 58 - Annual maxima hourly precipitation (12h) for Novoli station

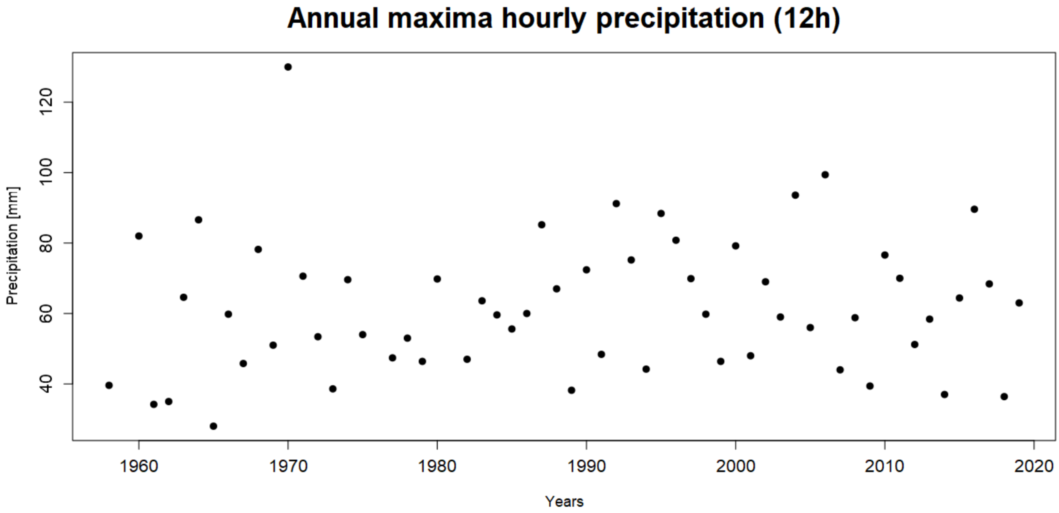


Fig. A 59 - Annual maxima hourly precipitation (12h) for Ostuni station

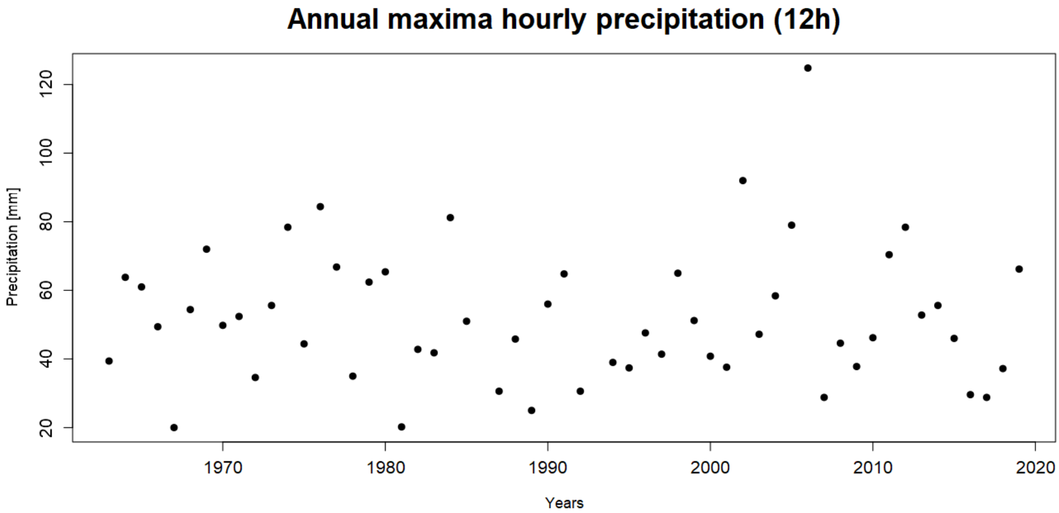


Fig. A 60 - Annual maxima hourly precipitation (12h) for Polignano a Mare station

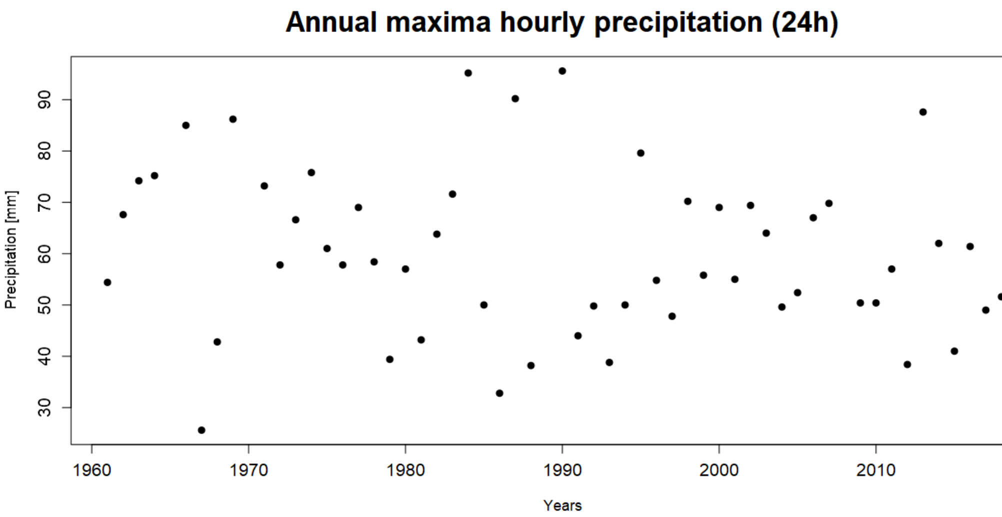


Fig. A 61 - Annual maxima hourly precipitation (24h) for Adelfia station

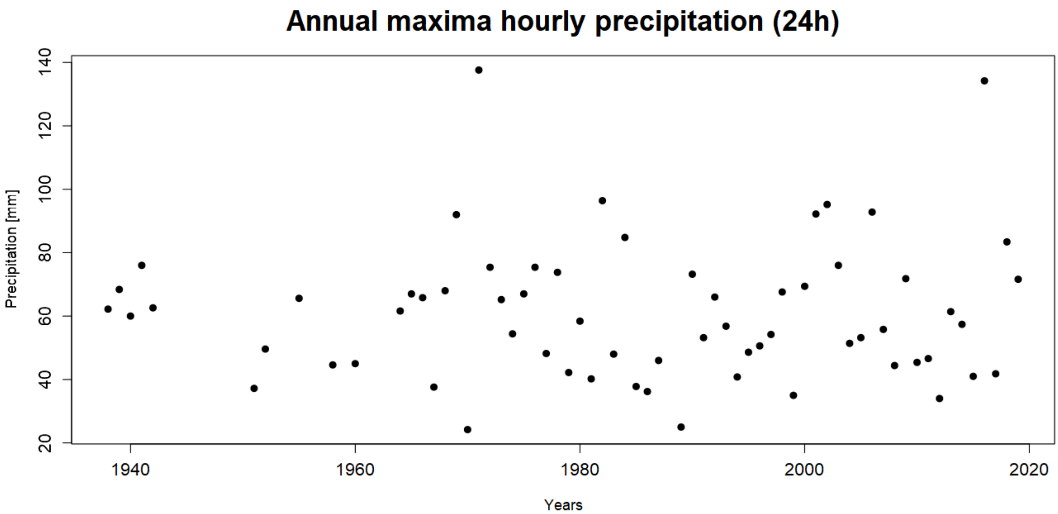


Fig. A 62 - Annual maxima hourly precipitation (24h) for Bari Presidenza Regione station

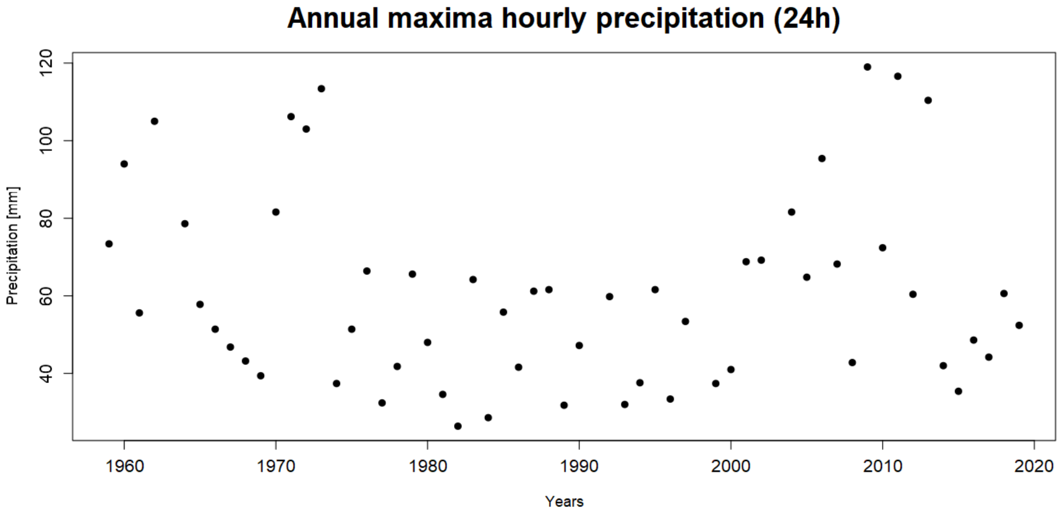


Fig. A 63 - Annual maxima hourly precipitation (24h) for Barletta station

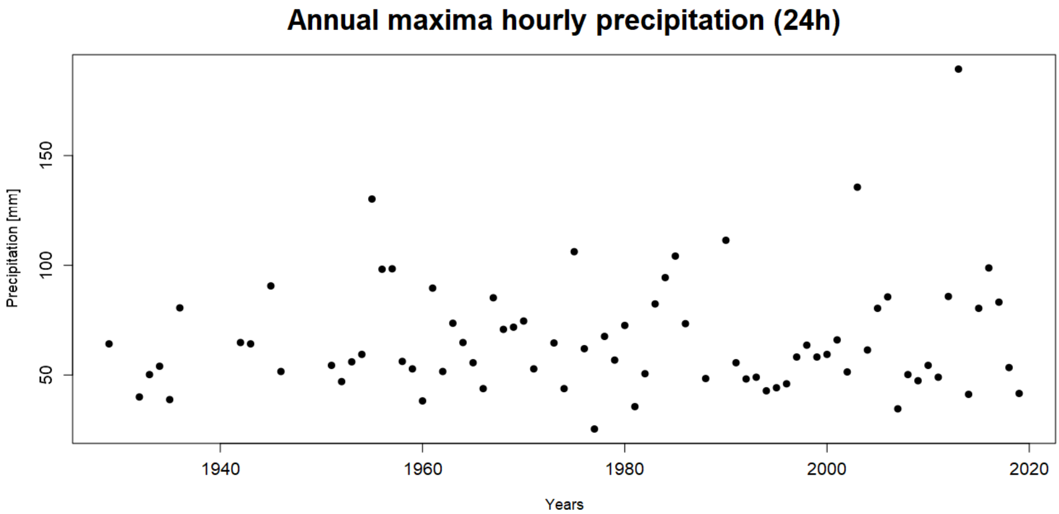


Fig. A 64 - Annual maxima hourly precipitation (24h) for Bovino station

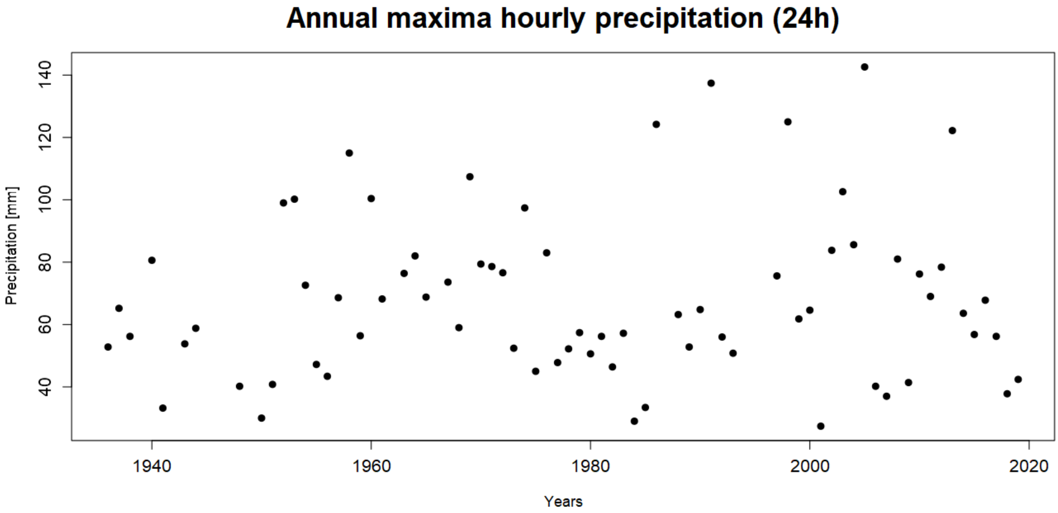


Fig. A 65 - Annual maxima hourly precipitation (24h) for Brindisi station

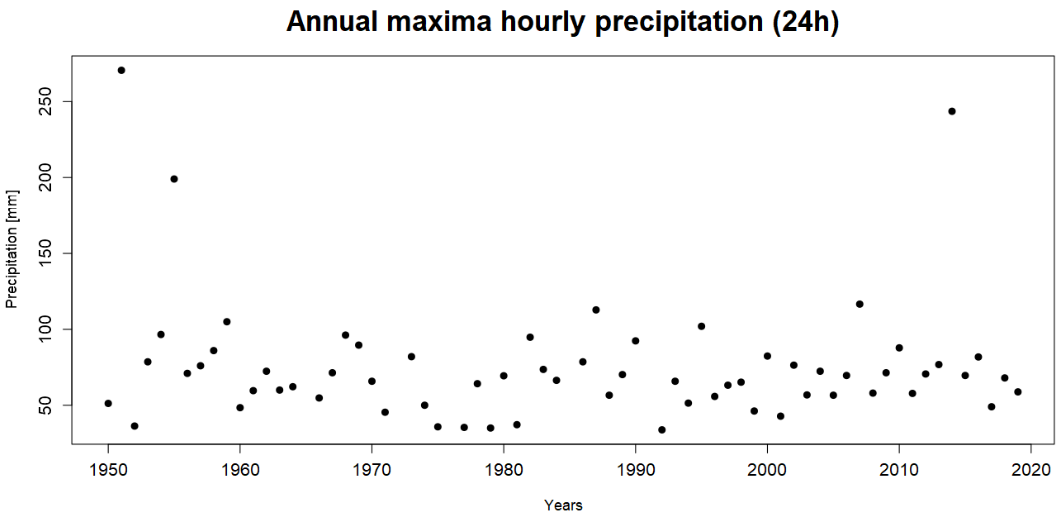


Fig. A 66 - Annual maxima hourly precipitation (24h) for Cagnano Varano station

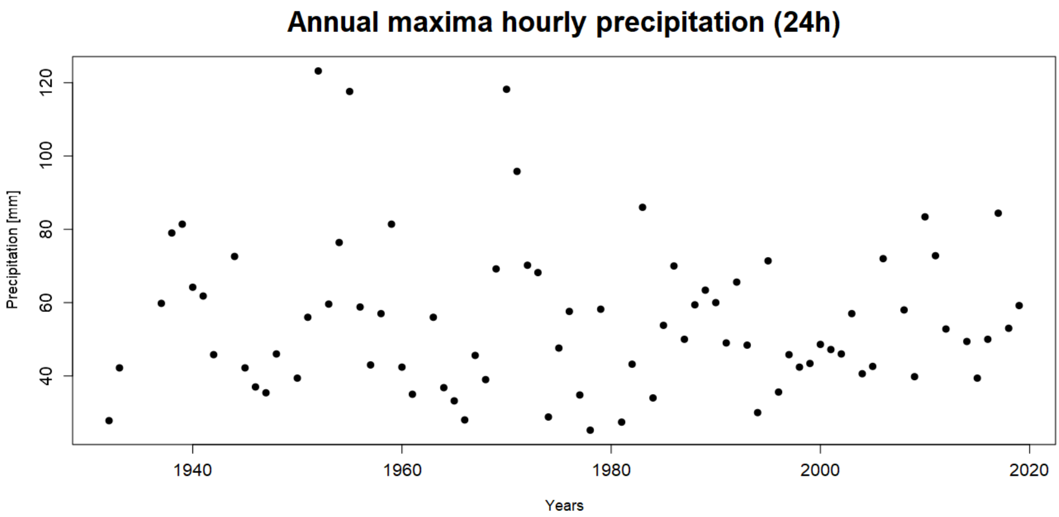


Fig. A 67 - Annual maxima hourly precipitation (24h) for Cerignola station

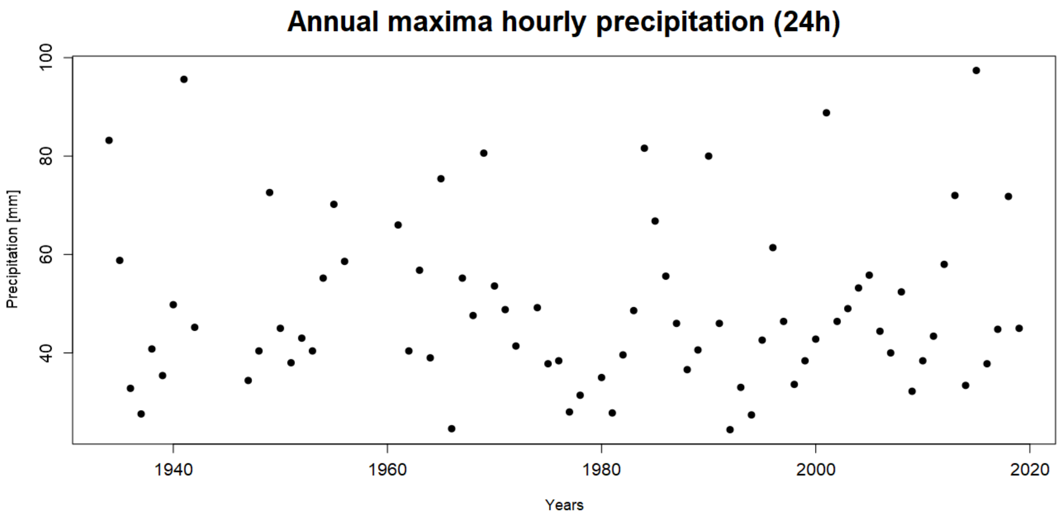


Fig. A 68 - Annual maxima hourly precipitation (24h) for Foggia Osservatorio station

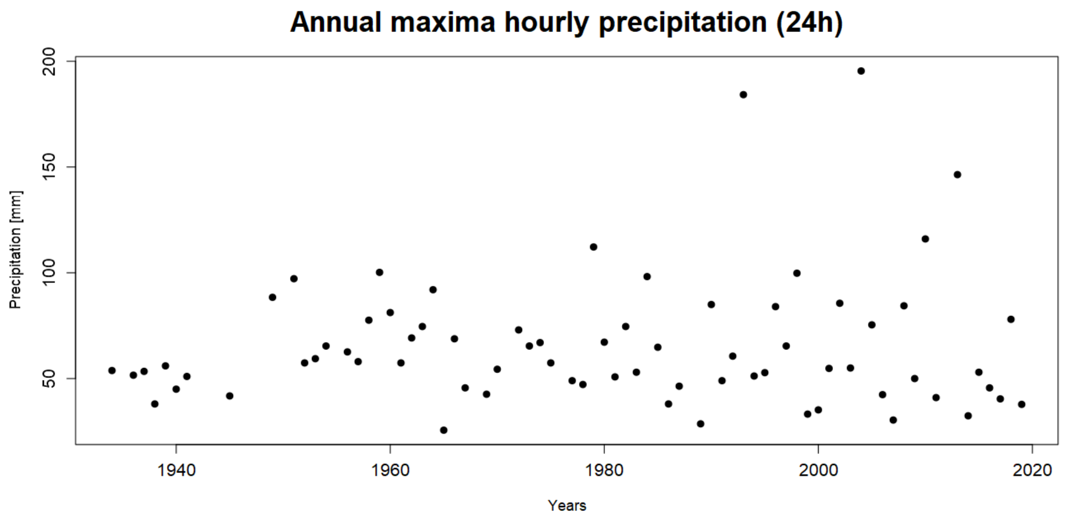


Fig. A 69 - Annual maxima hourly precipitation (24h) for station Gallipoli

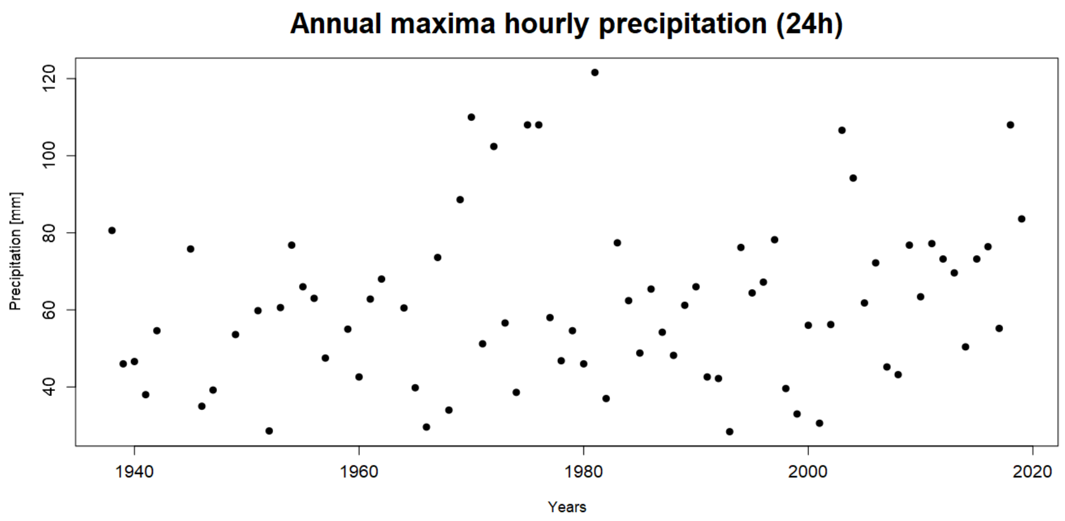


Fig. A 70 - Annual maxima hourly precipitation (24h) for Lesina station

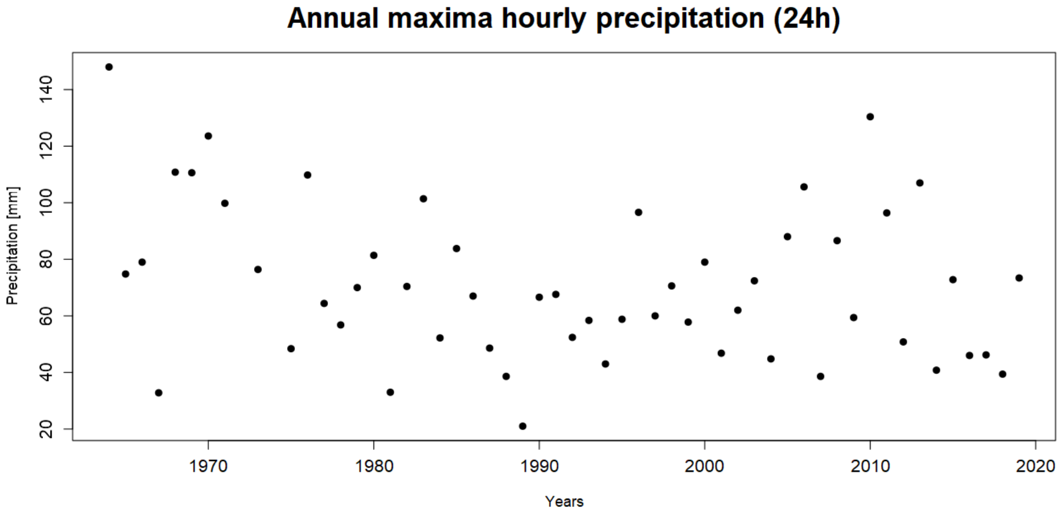


Fig. A 71 - Annual maxima hourly precipitation (24h) for Locorotondo station

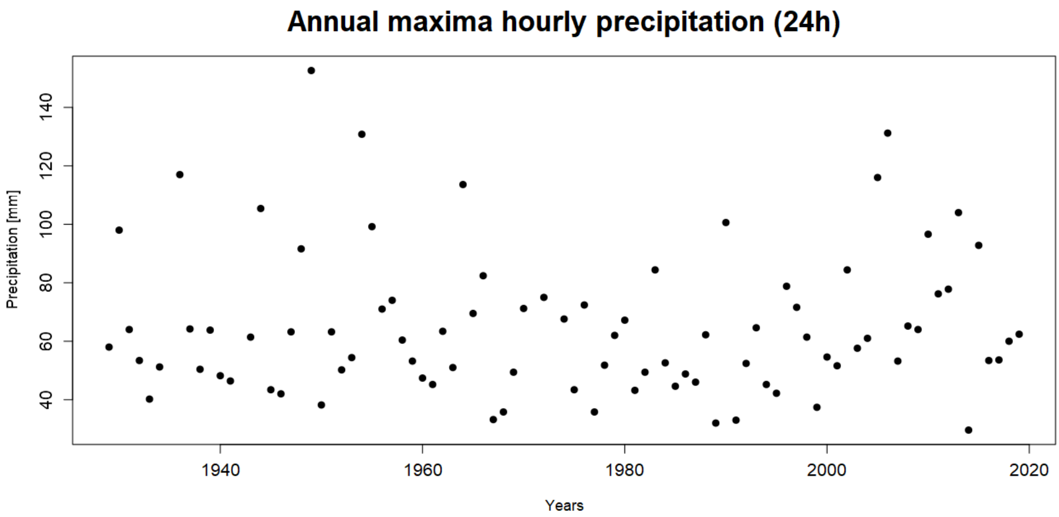


Fig. A 72 - Annual maxima hourly precipitation (24h) for Noci station

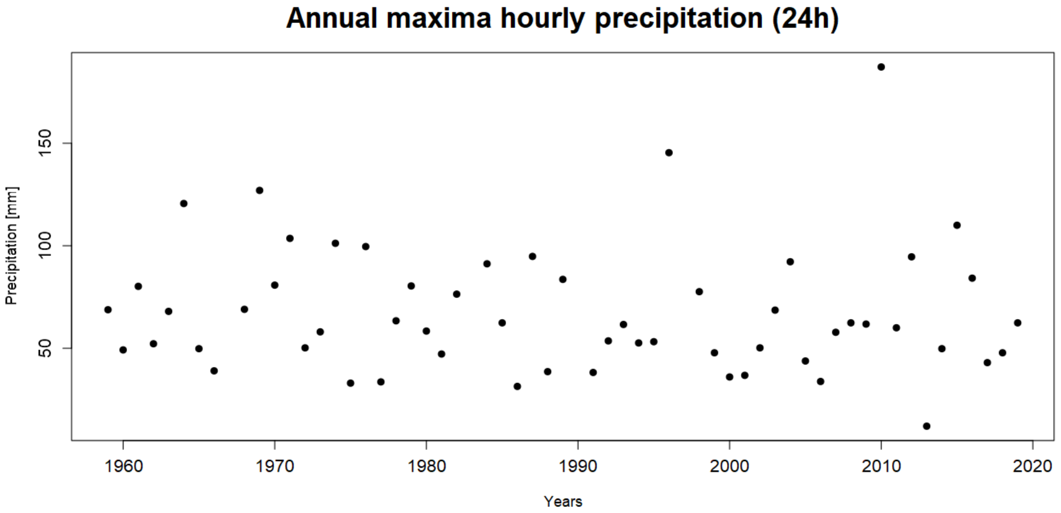


Fig. A 73 - Annual maxima hourly precipitation (24h) for Novoli station

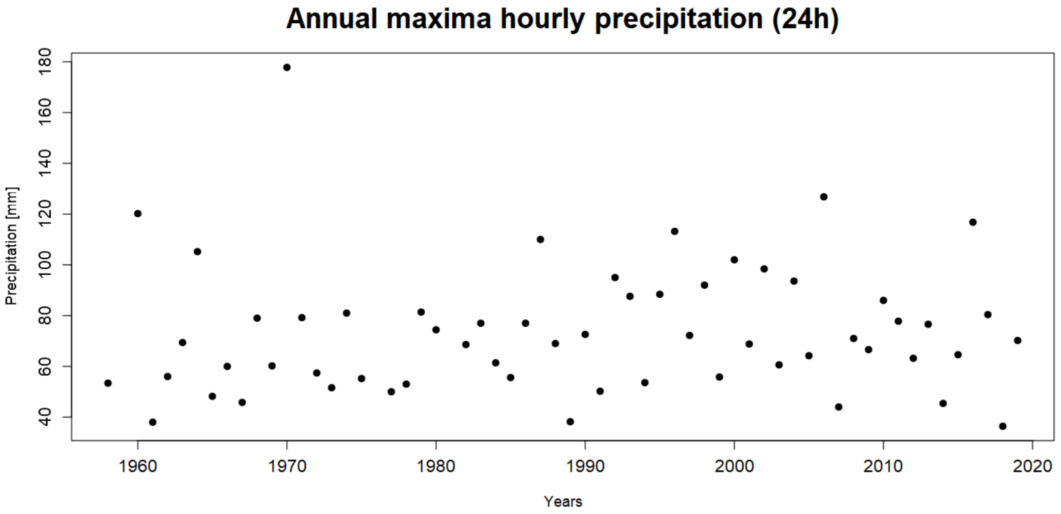


Fig. A 74 - Annual maxima hourly precipitation (24h) for Ostuni station

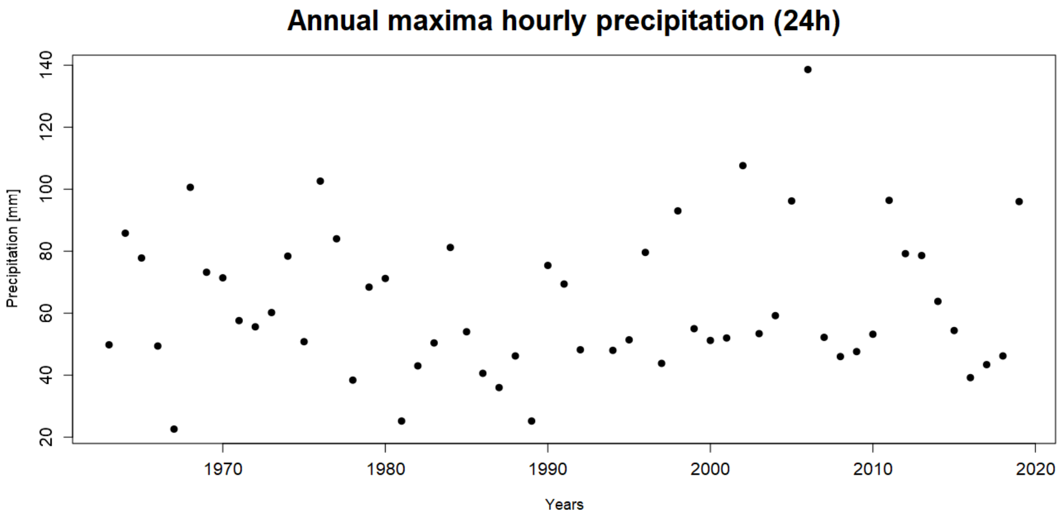


Fig. A 75 - Annual maxima hourly precipitation (24h) for Polignano a Mare station

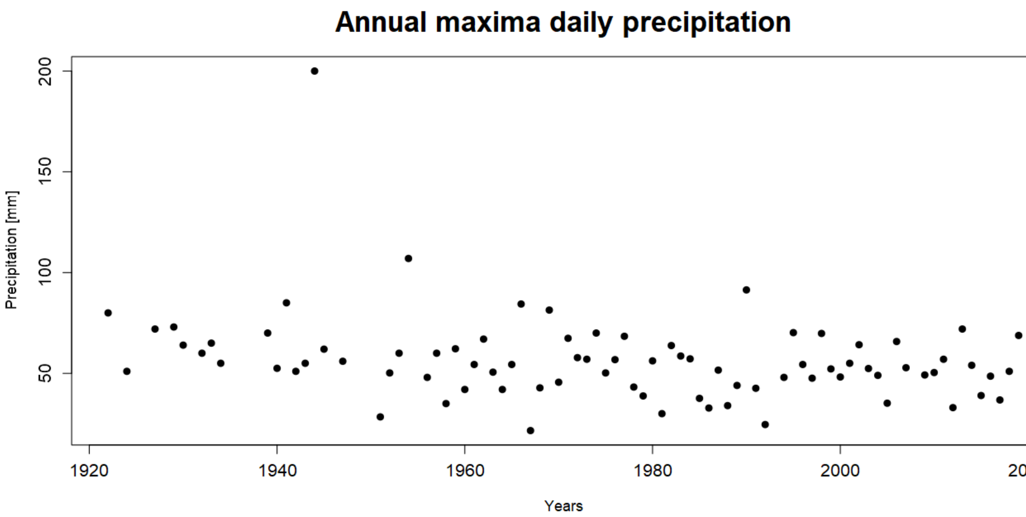


Fig. A 76 - Annual maxima daily precipitation for Adelfia station

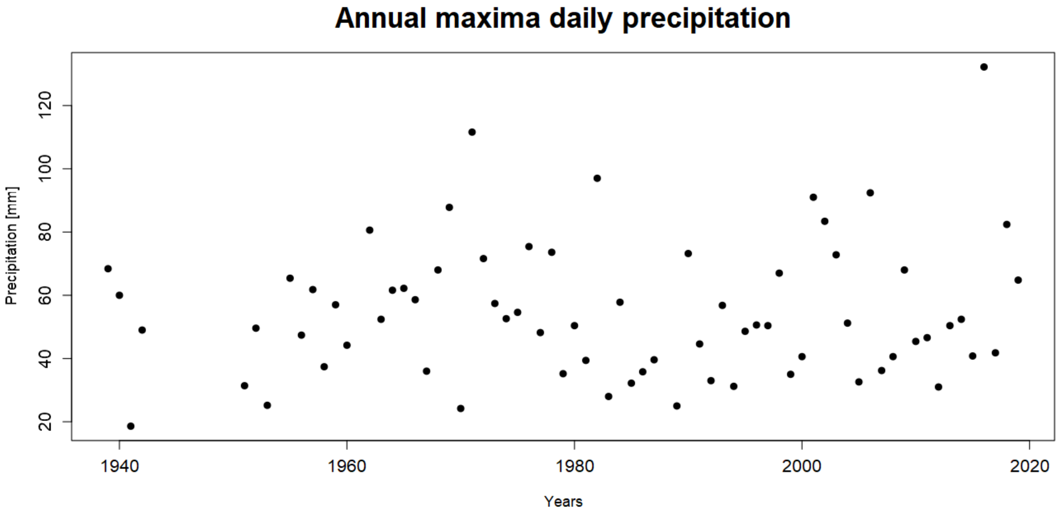


Fig. A 77 - Annual maxima daily precipitation for Bari Presidenza Regione station

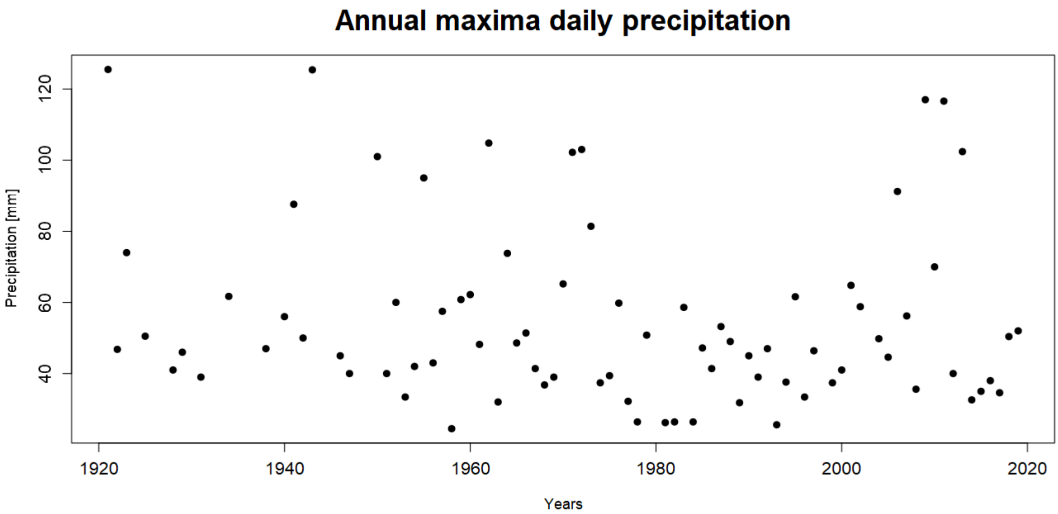


Fig. A 78 - Annual maxima daily precipitation for Barletta station

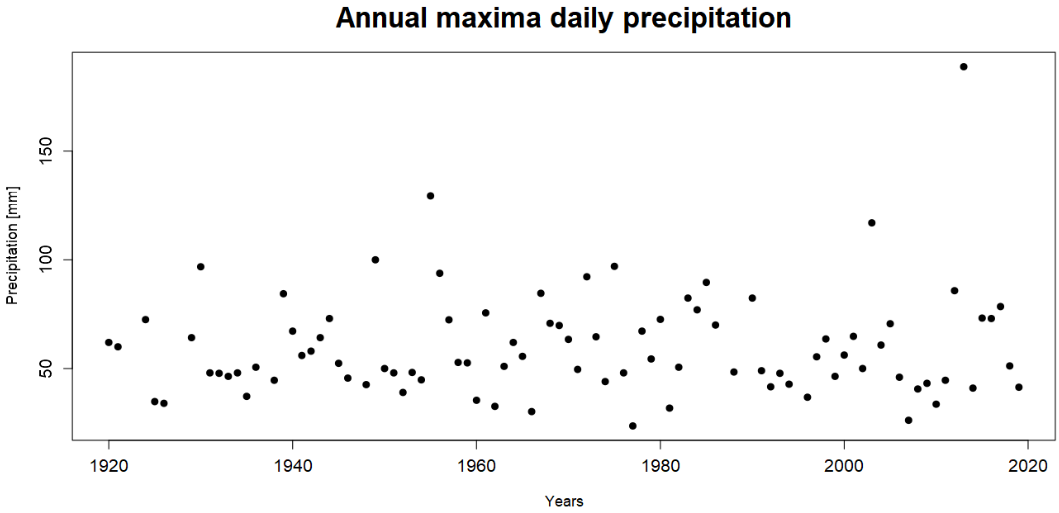


Fig. A 79 - Annual maxima daily precipitation for Bovino station

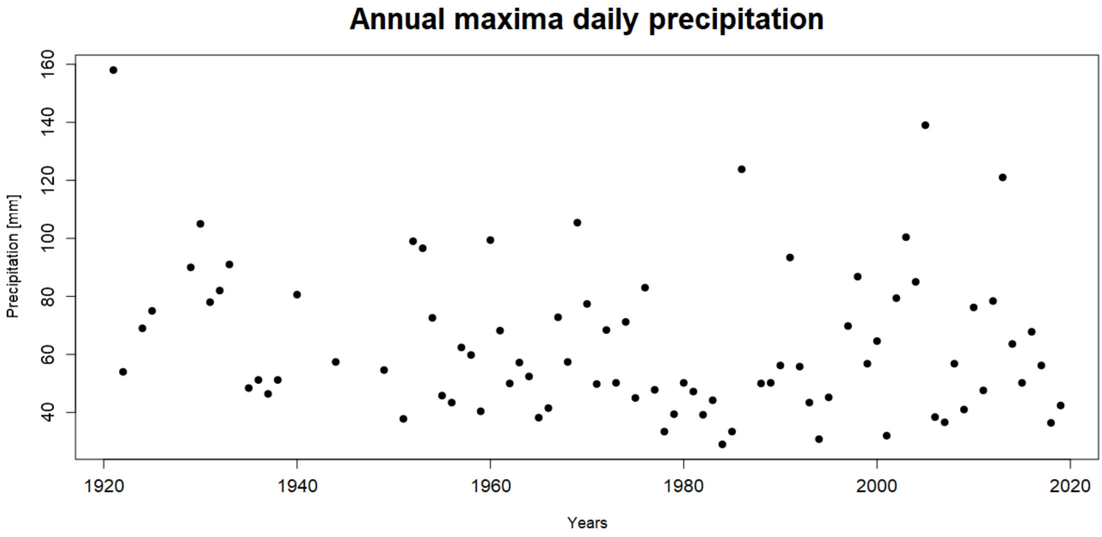


Fig. A 80 - Annual maxima daily precipitation for Brindisi station

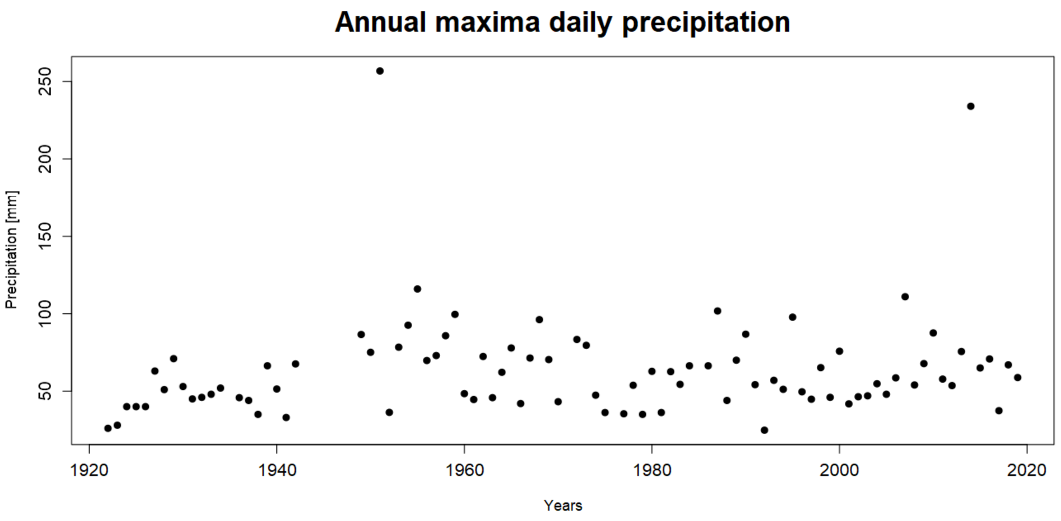


Fig. A 81 - Annual maxima daily precipitation for Cagnano Varano station

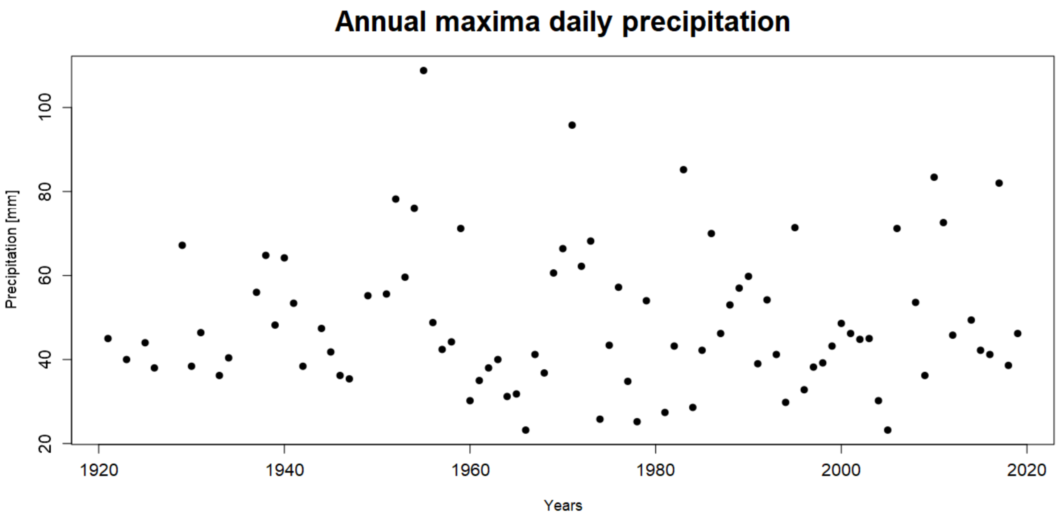


Fig. A 82 - Annual maxima daily precipitation for Cerignola station

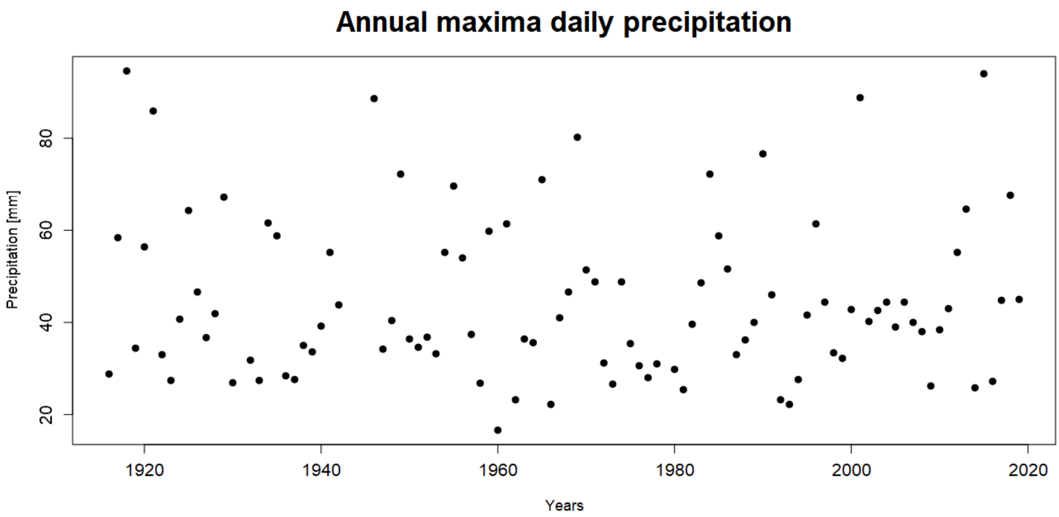


Fig. A 83 - Annual maxima daily precipitation for Foggia Osservatorio station

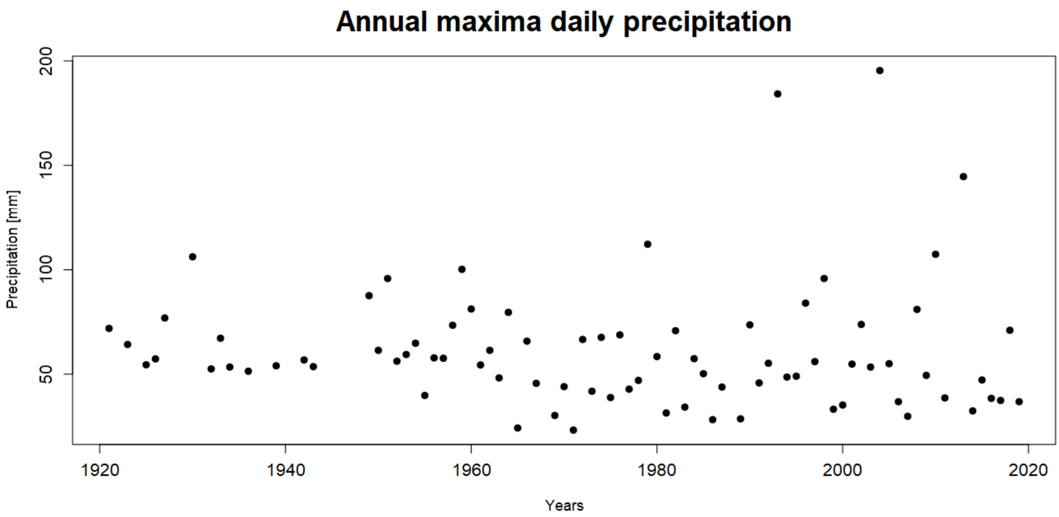


Fig. A 84 - Annual maxima daily precipitation for Gallipoli station

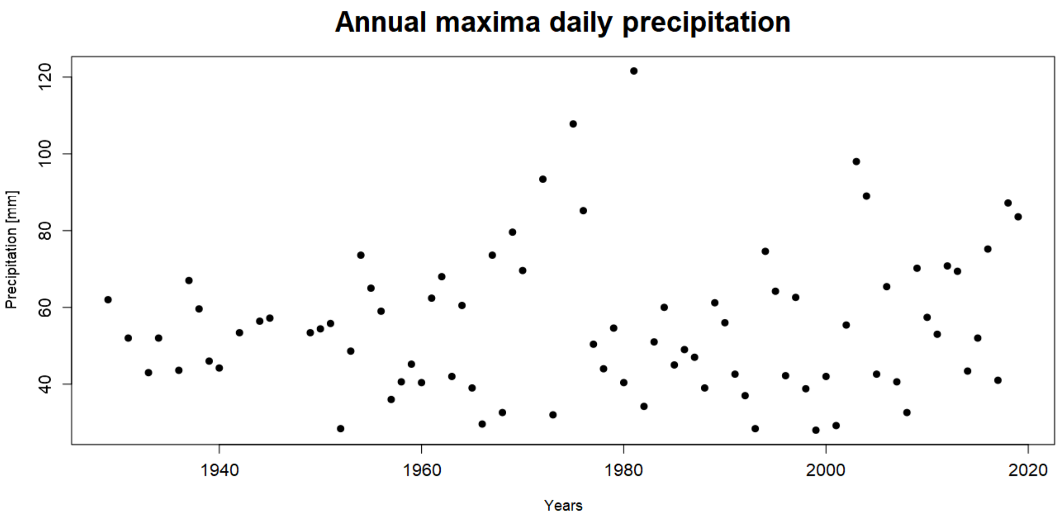


Fig. A 85 - Annual maxima daily precipitation for Lesina station

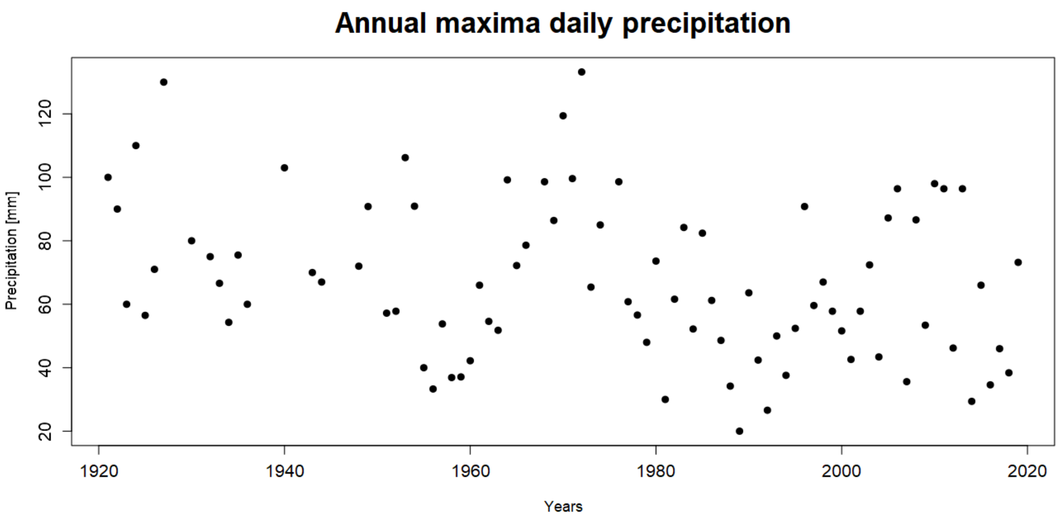


Fig. A 86 - Annual maxima daily precipitation for Locorotondo station

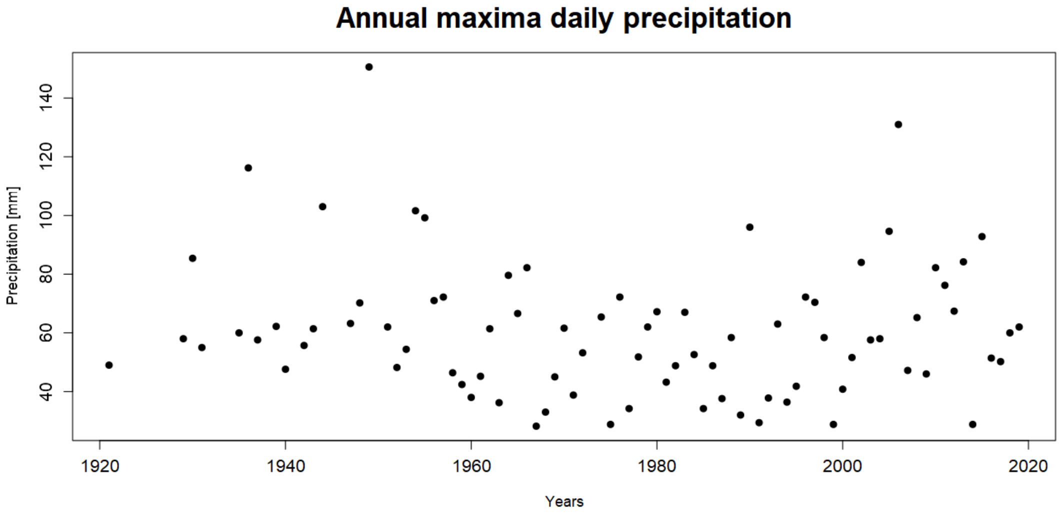


Fig. A 87 - Annual maxima daily precipitation for Noci station

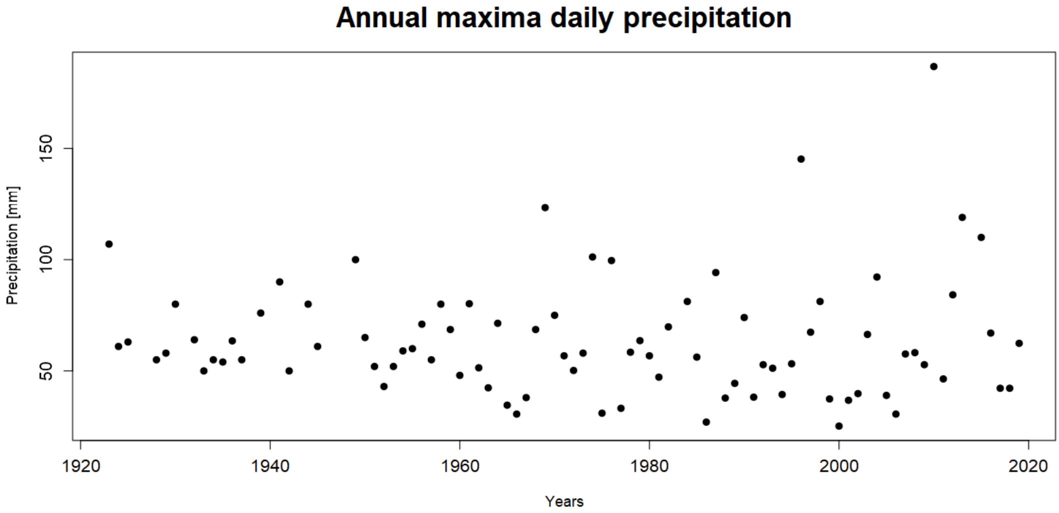


Fig. A 88 - Annual maxima daily precipitation for Novoli station

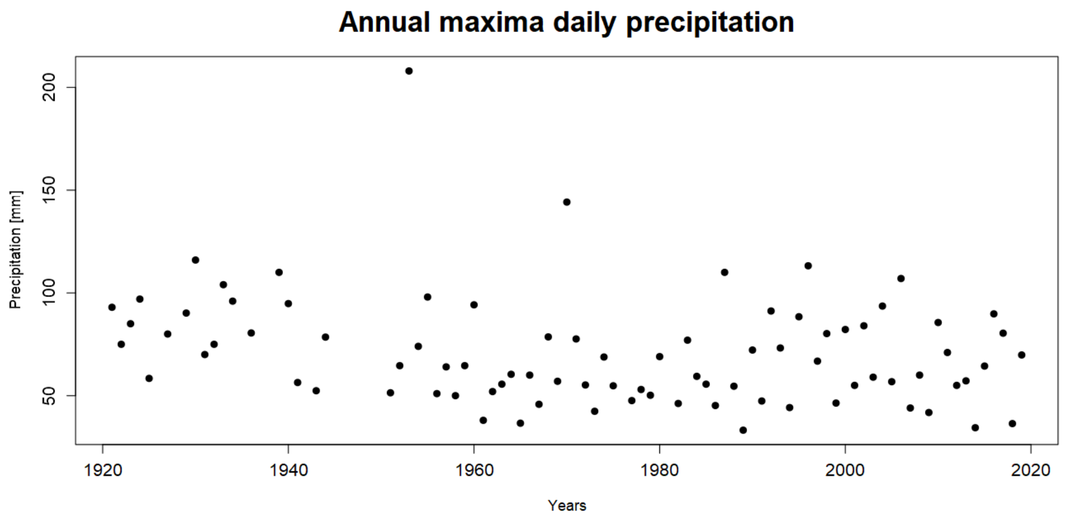


Fig. A 89 - Annual maxima daily precipitation for Ostuni station

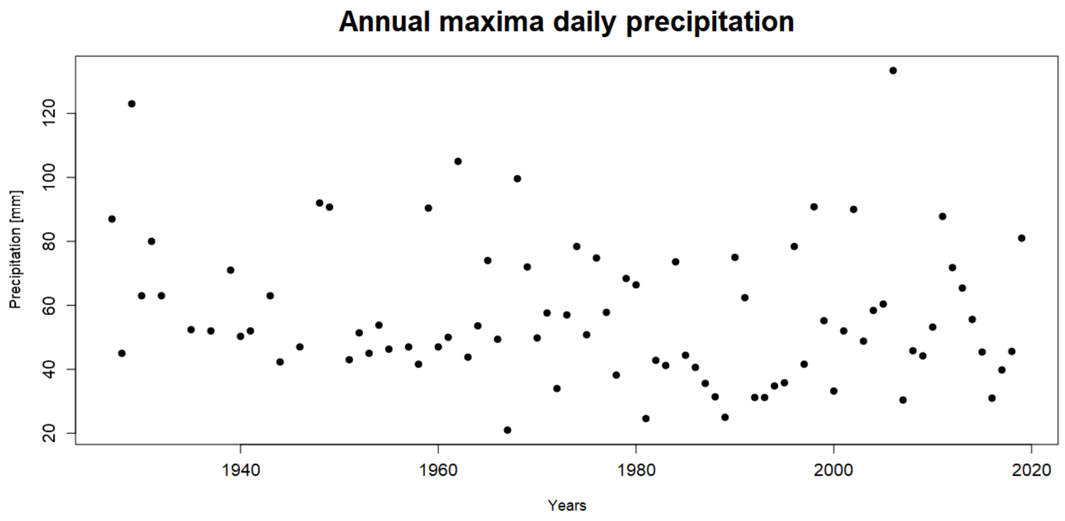


Fig. A 90 - Annual maxima daily precipitation for Polignano a Mare station

11 APPENDIX B - Missing values analyses

Tab. B 1 - Missing values analysis on annual maxima daily precipitation

RAIN GAUGE	*START*	*END*	*LENGTH SAMPLE*	*VALID DATA*	*MISSING VALUES*	*% VALID DATA*
Adelfia	1922	2019	98	82	16	83.67
Alberona	1919	2019	101	54	47	53.47
Alessano	1926	2019	94	28	66	29.79
Altamura	1921	2019	99	80	19	80.81
Andretta	1922	2019	98	68	30	69.39
Andria	1921	2019	99	84	15	84.85
Anzano di Puglia	2009	2018	10	6	4	60.00
Apricena	2010	2019	10	5	5	50.00
Ascoli Satriano	1920	2019	100	82	18	82.00
Atella	1923	2019	97	76	21	78.35
Avetrana	1929	2018	90	55	35	61.11
Bari (Presidenza Regione)	1951	2019	69	66	3	95.65
Bari Ingegneria	1974	2019	46	35	11	76.09
Bari Osservatorio	1921	2019	99	81	18	81.82
Barletta	1921	2019	99	82	17	82.83
Biccari	1924	2019	96	80	16	83.33
Bisaccia	1923	2019	97	74	23	76.29
Bisceglie	1929	2019	91	77	14	84.62
Bitonto	1922	2019	98	80	18	81.63
Borgo Libertà	1924	2019	96	71	25	73.96
Bosco Umbra	1926	2019	94	80	14	85.11
Bovino	1920	2019	100	91	9	91.00
Brindisi	1921	2019	99	83	16	83.84
Cagnano Varano	1922	2019	98	88	10	89.80
Calitri	1921	2019	99	65	34	65.66

Canale dell'Asso	2011	2019	9	9	0	100.00
Candela	2007	2019	13	8	5	61.54
Candelaro SS272	2018	2019	2	2	0	100.00
Canosa di Puglia	1923	2019	97	83	14	85.57
Carlatino	2017	2019	3	3	0	100.00
Carpino	2017	2019	3	3	0	100.00
Casalnuovo Monte-rotaro	2017	2019	3	3	0	100.00
Casamassima	1960	2019	60	53	7	88.33
Cassano Murge	1928	2019	92	72	20	78.26
Castel del Monte	1951	2019	69	53	16	76.81
Castellana Grotte	1924	2019	96	79	17	82.29
Castellaneta	1921	2019	99	87	12	87.88
Castelluccio dei Sauri	1924	2019	96	78	18	81.25
Ceglie Messapica	1922	2019	98	71	27	72.45
Celenza Valfortore	2010	2019	10	10	0	100.00
Cellino San Marco	2014	2019	6	6	0	100.00
Cerignola	1921	2019	99	86	13	86.87
Collepasso	1971	2019	49	37	12	75.51
Conversano	1921	2019	99	79	20	79.80
Copertino	1923	2019	97	78	19	80.41
Corato	1961	2019	59	56	3	94.92
Corigliano d'Otranto	1994	2019	26	24	2	92.31
Crispiano	1929	2019	91	70	21	76.92
Deliceto	2009	2019	11	6	5	54.55
Diga Locone	2017	2019	3	3	0	100.00
Diga Celone	2002	2019	18	14	4	77.78
Diga Osento	1994	2019	26	14	12	53.85

Diga sul Rendina	1961	2015	55	52	3	94.55
Faeto	1918	2019	102	59	43	57.84
Fasano	1922	2019	98	75	23	76.53
Foggia Ist. Agrario	1926	2019	94	64	30	68.09
Foggia Osservatorio	1916	2019	104	99	5	95.19
Fonte Rosa	1925	2019	95	65	30	68.42
Forenza	1924	2018	95	59	36	62.11
Galatina	1923	2019	97	80	17	82.47
Gallipoli	1921	2019	99	81	18	81.82
Ginosa Marina	1923	2019	97	77	20	79.38
Ginosa	1922	2019	98	80	18	81.63
Gioia del Colle	1921	2019	99	78	21	78.79
Giovinazzo	1923	2019	97	84	13	86.60
Grottaglie	1927	2019	93	74	19	79.57
Grumo Appula	1921	2019	99	71	28	71.72
Isole Tremiti	2017	2019	3	3	0	100.00
Lacedonia	1923	2010	88	54	34	61.36
Lagopesole	1923	2019	97	76	21	78.35
Laterza	2017	2019	3	3	0	100.00
Latiano	1925	2019	95	75	20	78.95
Lavello	1921	2019	99	79	20	79.80
Lecce	1921	2019	99	85	14	85.86
Lesina	1929	2019	91	81	10	89.01
Lizzano	1921	2019	99	80	19	80.81
Loconia	1971	2019	49	42	7	85.71
Locorotondo	1921	2019	99	85	14	85.86
Lucera	1918	2019	102	92	10	90.20
Maglie	1921	2019	99	71	28	71.72
Manduria	1929	2019	91	70	21	76.92
Manfredonia	1916	2019	104	93	11	89.42

Martina Franca	1992	2019	28	20	8	71.43
Massafra	1921	2019	99	77	22	77.78
Masseria Modesti	2010	2019	10	6	4	60.00
Masseria Monteruga	1930	2019	90	69	21	76.67
Masseria S.Chiara	1960	2019	60	55	5	91.67
Melendugno	1971	2019	49	36	13	73.47
Melfi	1922	2019	98	84	14	85.71
Mercadante	1930	2019	90	75	15	83.33
Minervino di Lecce	1929	2019	91	75	16	82.42
Minervino Murge	1921	2019	99	75	24	75.76
Monte Sant'Angelo	1920	2019	100	85	15	85.00
Monte Vulture	2000	2019	20	15	5	75.00
Monteleone di Puglia	1921	2019	99	89	10	89.90
Montemilone	1922	2019	98	74	24	75.51
Monticchio Bagni	1921	2019	99	67	32	67.68
Montursi	1995	2019	25	18	7	72.00
Mottola	1923	2019	97	22	75	22.68
Nardò	1923	2019	97	79	18	81.44
Noci	1921	2019	99	83	16	83.84
Novoli	1923	2019	97	86	11	88.66
Nusco	1921	2019	99	78	21	78.79
Orsara di Puglia	1919	2019	101	83	18	82.18
Ortanova	1920	2019	100	71	29	71.00
Orto di Zolfo	1969	2019	51	40	11	78.43
Ostuni	1921	2019	99	85	14	85.86
Otranto	1921	2019	99	82	17	82.83
Palagiano	2010	2019	10	6	4	60.00
Palagianello	2015	2019	5	5	0	100.00

Panni	2010	2019	10	5	5	50.00
Peschici	2017	2019	3	3	0	100.00
Pescopagano	1921	2019	99	80	19	80.81
Pietramontecorvino AQP	1969	2012	44	40	4	90.91
Pietramontecorvino Paese	1929	2019	91	74	17	81.32
Poggio Imperiale	1918	2019	102	8	94	7.84
Polignano a Mare	1927	2019	93	84	9	90.32
Presicce	1921	2019	99	81	18	81.82
Quasano	1951	2019	69	41	28	59.42
Ripacandida	1929	2019	91	74	17	81.32
Ripalta	2017	2019	3	3	0	100.00
Rocchetta S.Antonio Paese	1924	2019	96	64	32	66.67
Rocchetta S.Antonio Scalo	1925	2015	91	63	28	69.23
Rodi Garganico	2017	2019	3	3	0	100.00
Ruffano	1924	2019	96	74	22	77.08
Ruvo di Puglia	1923	2019	97	82	15	84.54
San Fele	1928	2019	92	65	27	70.65
Saccione SS16ter	2018	2019	2	2	0	100.00
SalsolaSS16	2018	2018	1	1	0	100.00
San Giorgio Jonico	1931	2019	89	60	29	67.42
San Giovanni Rotondo	1924	2019	96	81	15	84.38
San Marco in Lamis	1918	2019	102	97	5	95.10
San Nicandro Garganico	1918	2019	102	87	15	85.29

San Pancrazio Salentino	1938	2019	82	71	11	86.59
San Paolo Civitate	2016	2019	4	4	0	100.00
San Pietro Vernotico	1923	2019	97	84	13	86.60
San Samuele di Cafiero	2003	2019	17	11	6	64.71
San Severo	1918	2019	102	76	26	74.51
San Vito dei Normanni	1929	2019	91	39	52	42.86
Santa Maria di Leuca	1921	2019	99	83	16	83.84
Sant'Agata di Puglia	1918	2019	102	70	32	68.63
Sant'Angelo dei Lombardi	1924	2019	96	73	23	76.04
Santeramo in Colle	1922	2019	98	79	19	80.61
Savignano Irpino	1918	2019	102	75	27	73.53
Spinazzola	1921	2019	99	74	25	74.75
Talsano	1977	2019	43	41	2	95.35
Taranto	1921	2019	99	81	18	81.82
Taviano	1921	2019	99	80	19	80.81
Teora	1921	2019	99	82	17	82.83
Tertiveri	1969	2019	51	45	6	88.24
Torremaggiore	1918	2019	102	85	17	83.33
Troia	1916	2019	104	81	23	77.88
Turi	1927	2019	93	73	20	78.49
Venosa	1921	2019	99	71	28	71.72
Vico del Gargano	1921	2019	99	88	11	88.89
Vieste	1922	2018	97	91	6	93.81
Vignacastrisi	1932	2019	88	76	12	86.36

Volturara Appula	2010	2019	10	10	0	100.00
Volturino	1969	2019	51	32	19	62.75

Tab. B 2 - Missing values analysis on annual maxima hourly precipitation (1h)

RAIN GAUGE	***START***	***END***	***LENGTH SAMPLE***	***VALID DATA***	***MISSING VALUES***	***% VALID DATA***
Adelfia	1961	2019	59	55	4	93.22
Alberona	1952	2019	68	51	17	75.00
Alessano	2018	2019	2	2	0	100.00
Altamura	1952	2019	68	61	7	89.71
Andretta	1937	2019	83	49	34	59.04
Andria	1959	2019	61	51	10	83.61
Anzano di Puglia	2017	2018	2	2	0	100.00
Ascoli Satriano	1932	2019	88	63	25	71.59
Atella	1956	2019	64	48	16	75.00
Avetrana	1967	2018	52	42	10	80.77
Bari (Presidenza Regione)	1938	2019	82	63	19	76.83
Bari Ingegneria	1975	2019	45	34	11	75.56
Bari Osservatorio	1932	2019	88	79	9	89.77
Barletta	1959	2019	61	58	3	95.08
Biccari	1952	2019	68	55	13	80.88
Bisaccia	1959	2019	61	48	13	78.69
Bisceglie	1961	2019	59	50	9	84.75
Bitonto	1958	2019	62	50	12	80.65
Borgo Libertà	1929	2019	91	56	35	61.54
Bosco Umbra	1928	2019	92	70	22	76.09
Bovino	1929	2019	91	75	16	82.42

Brindisi	1936	2019	84	72	12	85.71
Cagnano Varano	1950	2019	70	65	5	92.86
Calitri	1937	2019	83	55	28	66.27
Canale dell'Asso	2010	2019	10	10	0	100.00
Candela	2008	2019	12	11	1	91.67
Candelaro SS272	2018	2019	2	2	0	100.00
Canosa di Puglia	1952	2019	68	61	7	89.71
Carlatino	2010	2019	10	10	0	100.00
Carpino	2017	2019	3	3	0	100.00
Casalnuovo Monte-rotaro	2011	2019	9	9	0	100.00
Casamassima	1961	2019	59	50	9	84.75
Cassano Murge	1929	2019	91	69	22	75.82
Castel del Monte	1932	2019	88	55	33	62.50
Castellana Grotte	1961	2019	59	51	8	86.44
Castellaneta	1962	2019	58	57	1	98.28
Castelluccio dei Sauri	1935	2019	85	59	26	69.41
Ceglie Messapica	1962	2019	58	42	16	72.41
Celenza Valfortore	2010	2019	10	10	0	100.00
Cellino San Marco	2014	2019	6	6	0	100.00
Cerignola	1932	2019	88	78	10	88.64
Collepasso	1971	2019	49	37	12	75.51
Conversano	1968	2019	52	44	8	84.62
Copertino	1961	2019	59	51	8	86.44
Corato	1963	2019	57	54	3	94.74
Corigliano d'Otranto	1994	2019	26	24	2	92.31
Crispiano	1958	2019	62	48	14	77.42
Diga Locone	2017	2019	3	3	0	100.00

Diga Sul Celone	2008	2019	12	12	0	100.00
Diga sull'Osento	2010	2019	10	10	0	100.00
Diga sul Rendina	1962	2016	55	47	8	85.45
Faeto	1941	2019	79	47	32	59.49
Fasano	1937	2019	83	57	26	68.67
Foggia Ist. Agrario	1972	2019	48	37	11	77.08
Foggia Osservatorio	1934	2019	86	76	10	88.37
Fonte Rosa	1963	2019	57	51	6	89.47
Forenza	1957	2018	62	39	23	62.90
Galatina	1959	2019	61	55	6	90.16
Gallipoli	1934	2019	86	72	14	83.72
Ginosa Marina	1928	2019	92	64	28	69.57
Ginosa	1932	2019	88	75	13	85.23
Gioia del Colle	1961	2019	59	52	7	88.14
Giovinazzo	1960	2019	60	55	5	91.67
Grottaglie	1958	2019	62	53	9	85.48
Grumo Appula	1928	2019	92	64	28	69.57
Isole Tremiti	2014	2019	6	6	0	100.00
Lacedonia	1932	2010	79	42	37	53.16
Lagopesole	1932	2019	88	70	18	79.55
Laterza	2015	2019	5	5	0	100.00
Latiano	1958	2019	62	55	7	88.71
Lavello	1951	2019	69	58	11	84.06
Lecce	1930	2019	90	76	14	84.44
Lesina	1938	2019	82	73	9	89.02
Lizzano	1957	2019	63	51	12	80.95
Loconia	1971	2019	49	40	9	81.63
Locorotondo	1964	2019	56	50	6	89.29
Lucera	1938	2019	82	66	16	80.49
Maglie	1935	2019	85	67	18	78.82

Manduria	1962	2019	58	47	11	81.03
Manfredonia	1932	2019	88	65	23	73.86
Massafra	1958	2019	62	54	8	87.10
Masseria Monteruga	1967	2019	53	44	9	83.02
Masseria S.Chiara	1960	2019	60	52	8	86.67
Melendugno	1971	2019	49	34	15	69.39
Melfi	1932	2019	88	76	12	86.36
Mercadante	1967	2019	53	50	3	94.34
Minervino di Lecce	1949	2019	71	64	7	90.14
Minervino Murge	1960	2019	60	50	10	83.33
Monte Sant'Angelo	1933	2019	87	63	24	72.41
Monte Vulture	2008	2019	12	10	2	83.33
Monteleone di Puglia	1936	2019	84	66	18	78.57
Montemilone	1940	2019	80	53	27	66.25
Monticchio Bagni	1948	2019	72	57	15	79.17
Montursi	2008	2019	12	12	0	100.00
Nardò	1957	2019	63	53	10	84.13
Noci	1929	2019	91	85	6	93.41
Novoli	1959	2019	61	58	3	95.08
Nusco	1936	2019	84	61	23	72.62
Orsara di Puglia	1962	2019	58	48	10	82.76
Ortanova	1959	2019	61	47	14	77.05
Orto di Zolfo	1969	2019	51	40	11	78.43
Ostuni	1958	2019	62	59	3	95.16
Otranto	1934	2019	86	77	9	89.53
Palagiano	2010	2019	10	10	0	100.00
Palagianello	2015	2019	5	5	0	100.00
Peschici	2017	2019	3	3	0	100.00

Pescopagano	1964	2019	56	48	8	85.71
Pietramontecorvino AQP	1970	2012	43	37	6	86.05
Pietramontecorvino Paese	1951	2019	69	58	11	84.06
Poggio Imperiale	2014	2019	6	6	0	100.00
Polignano a Mare	1963	2019	57	55	2	96.49
Presicce	1954	2019	66	59	7	89.39
Quasano	1928	2019	92	41	51	44.57
Ripacandida	1940	2019	80	64	16	80.00
Ripalta	2017	2019	3	3	0	100.00
Rocchetta S.Antonio Paese	1961	2014	54	48	6	88.89
Rocchetta S.Antonio Scalo	1947	2016	70	51	19	72.86
Rodi Garganico	2017	2019	3	3	0	100.00
Ruffano	1943	2019	77	59	18	76.62
Ruvo di Puglia	1964	2019	56	43	13	76.79
San Fele	1941	2019	79	51	28	64.56
Saccione SS16ter	2018	2019	2	2	0	100.00
Salsola SS16	2018	2018	1	1	0	100.00
San Giorgio Jonico	1934	2019	86	47	39	54.65
San Giovanni Ro-tondo	1932	2019	88	52	36	59.09
San Marco in Lamis	1933	2019	87	72	15	82.76
San Nicandro Gar-ganico	1967	2019	53	42	11	79.25
San Pancrazio Sa-lentino	1957	2019	63	51	12	80.95
San Paolo Civitate	2010	2019	10	9	1	90.00

San Pietro Vernotico	1958	2019	62	50	12	80.65
San Samuele di Ca-fiero	2008	2019	12	11	1	91.67
San Severo	1932	2019	88	67	21	76.14
San Vito dei Nor-manni	1992	2019	28	26	2	92.86
Santa Maria di Leuca	1942	2019	78	67	11	85.90
Sant'Agata di Puglia	1930	2019	90	55	35	61.11
Sant'Angelo dei Lombardi	1932	2019	88	52	36	59.09
Santeramo in Colle	1963	2019	57	48	9	84.21
Savignano Irpino	1932	2019	88	50	38	56.82
Spinazzola	1936	2019	84	61	23	72.62
Talsano	1976	2019	44	43	1	97.73
Taranto	1935	2019	85	71	14	83.53
Taviano	1961	2019	59	54	5	91.53
Teora	1938	2019	82	62	20	75.61
Tertieveri	1969	2019	51	45	6	88.24
Torremaggiore	1940	2019	80	52	28	65.00
Troia	1932	2019	88	54	34	61.36
Turi	1960	2019	60	48	12	80.00
Venosa	1957	2019	63	49	14	77.78
Vico del Gargano	1967	2019	53	44	9	83.02
Vieste	1946	2018	73	59	14	80.82
Vignacastrisi	1959	2019	61	48	13	78.69
Volturara Appula	2010	2019	10	10	0	100.00
Volturino	1977	2019	43	30	13	69.77

Tab. B 3 - Missing values analysis on annual maxima hourly precipitation (3h)

RAIN GAUGE	***START***	***END***	***LENGTH SAMPLE***	***VALID DATA***	***MISSING VALUES***	***% VALID DATA***
Adelfia	1961	2019	59	55	4	93.22
Alberona	1952	2019	68	51	17	75.00
Alessano	2018	2019	2	2	0	100.00
Altamura	1952	2019	68	61	7	89.71
Andretta	1937	2019	83	49	34	59.04
Andria	1959	2019	61	55	6	90.16
Anzano di Puglia	2017	2018	2	2	0	100.00
Ascoli Satriano	1932	2019	88	63	25	71.59
Atella	1956	2019	64	48	16	75.00
Avetrana	1967	2018	52	42	10	80.77
Bari (Presidenza Re-gione)	1938	2019	82	63	19	76.83
Bari Ingegneria	1975	2019	45	36	9	80.00
Bari Osservatorio	1932	2019	88	79	9	89.77
Barletta	1959	2019	61	58	3	95.08
Biccari	1952	2019	68	54	14	79.41
Bisaccia	1959	2019	61	48	13	78.69
Bisceglie	1961	2019	59	50	9	84.75
Bitonto	1958	2019	62	53	9	85.48
Borgo Libertà	1929	2019	91	57	34	62.64
Bosco Umbra	1928	2019	92	71	21	77.17
Bovino	1929	2019	91	77	14	84.62
Brindisi	1936	2019	84	72	12	85.71
Cagnano Varano	1950	2019	70	65	5	92.86
Calitri	1937	2019	83	56	27	67.47
Canale dell’Asso	2010	2019	10	10	0	100.00
Candela	2008	2019	12	11	1	91.67

Candelaro SS272	2018	2019	2	2	0	100.00
Canosa di Puglia	1952	2019	68	60	8	88.24
Carlantino	2010	2019	10	10	0	100.00
Carpino	2017	2019	3	3	0	100.00
Casalnuovo Monte-rotaro	2011	2019	9	9	0	100.00
Casamassima	1961	2019	59	51	8	86.44
Cassano Murge	1929	2019	91	70	21	76.92
Castel del Monte	1932	2019	88	58	30	65.91
Castellana Grotte	1961	2019	59	50	9	84.75
Castellaneta	1962	2019	58	58	0	100.00
Castelluccio dei Sauri	1935	2019	85	59	26	69.41
Ceglie Messapica	1962	2019	58	45	13	77.59
Celenza Valfortore	2010	2019	10	10	0	100.00
Cellino San Marco	2014	2019	6	6	0	100.00
Cerignola	1932	2019	88	79	9	89.77
Collepasso	1971	2019	49	38	11	77.55
Conversano	1968	2019	52	44	8	84.62
Copertino	1961	2019	59	51	8	86.44
Corato	1963	2019	57	55	2	96.49
Corigliano d’Otranto	1994	2019	26	24	2	92.31
Crispiano	1958	2019	62	49	13	79.03
Diga Locone	2017	2019	3	3	0	100.00
Diga Sul Celone	2008	2019	12	12	0	100.00
Diga sull’Osento	2010	2019	10	10	0	100.00
Diga sul Rendina	1962	2016	55	48	7	87.27
Faeto	1941	2019	79	46	33	58.23
Fasano	1937	2019	83	57	26	68.67

Foggia Ist. Agrario	1972	2019	48	39	9	81.25
Foggia Osservatorio	1934	2019	86	76	10	88.37
Fonte Rosa	1963	2019	57	51	6	89.47
Forenza	1957	2018	62	40	22	64.52
Galatina	1959	2019	61	55	6	90.16
Gallipoli	1934	2019	86	72	14	83.72
Ginosa Marina	1930	2019	90	64	26	71.11
Ginosa	1932	2019	88	76	12	86.36
Gioia del Colle	1961	2019	59	51	8	86.44
Giovinazzo	1960	2019	60	55	5	91.67
Grottaglie	1958	2019	62	53	9	85.48
Grumo Appula	1932	2019	88	63	25	71.59
Isole Tremiti	2014	2019	6	6	0	100.00
Lacedonia	1932	2010	79	41	38	51.90
Lagopesole	1929	2019	91	72	19	79.12
Laterza	2015	2019	5	5	0	100.00
Latiano	1958	2019	62	55	7	88.71
Lavello	1951	2019	69	58	11	84.06
Lecce	1930	2019	90	75	15	83.33
Lesina	1938	2019	82	73	9	89.02
Lizzano	1957	2019	63	51	12	80.95
Loconia	1971	2019	49	41	8	83.67
Locorotondo	1964	2019	56	51	5	91.07
Lucera	1938	2019	82	66	16	80.49
Maglie	1935	2019	85	67	18	78.82
Manduria	1962	2019	58	49	9	84.48
Manfredonia	1932	2019	88	65	23	73.86
Massafra	1958	2019	62	55	7	88.71
Masseria Monteruga	1967	2019	53	45	8	84.91
Masseria S.Chiara	1960	2019	60	52	8	86.67

Melendugno	1971	2019	49	35	14	71.43
Melfi	1932	2019	88	77	11	87.50
Mercadante	1967	2019	53	51	2	96.23
Minervino di Lecce	1949	2019	71	64	7	90.14
Minervino Murge	1960	2019	60	53	7	88.33
Monte Sant’Angelo	1933	2019	87	64	23	73.56
Monte Vulture	2008	2019	12	10	2	83.33
Monteleone di Puglia	1936	2019	84	65	19	77.38
Montemilone	1940	2019	80	53	27	66.25
Monticchio Bagni	1948	2019	72	58	14	80.56
Montursi	2008	2019	12	12	0	100.00
Nardò	1957	2019	63	53	10	84.13
Noci	1929	2019	91	84	7	92.31
Novoli	1959	2019	61	58	3	95.08
Nusco	1936	2019	84	63	21	75.00
Orsara di Puglia	1962	2019	58	49	9	84.48
Ortanova	1959	2019	61	47	14	77.05
Orto di Zolfo	1969	2019	51	40	11	78.43
Ostuni	1958	2019	62	59	3	95.16
Otranto	1934	2019	86	78	8	90.70
Palagiano	2010	2019	10	10	0	100.00
Palagianello	2015	2019	5	5	0	100.00
Peschici	2017	2019	3	3	0	100.00
Pescopagano	1964	2019	56	47	9	83.93
Pietramontecorvino AQP	1970	2012	43	37	6	86.05
Pietramontecorvino Paese	1951	2019	69	60	9	86.96

Poggio Imperiale	2014	2019	6	6	0	100.00
Polignano a Mare	1963	2019	57	55	2	96.49
Presicce	1954	2019	66	59	7	89.39
Quasano	1928	2019	92	41	51	44.57
Ripacandida	1940	2019	80	64	16	80.00
Ripalta	2017	2019	3	3	0	100.00
Rocchetta S.Antonio Paese	1961	2014	54	48	6	88.89
Rocchetta S.Antonio Scalo	1947	2016	70	53	17	75.71
Rodi Garganico	2017	2019	3	3	0	100.00
Ruffano	1943	2019	77	59	18	76.62
Ruvo di Puglia	1964	2019	56	43	13	76.79
San Fele	1941	2019	79	51	28	64.56
Saccione SS16ter	2018	2019	2	2	0	100.00
Salsola SS16	2018	2018	1	1	0	100.00
San Giorgio Jonico	1934	2019	86	48	38	55.81
San Giovanni Rotondo	1932	2019	88	55	33	62.50
San Marco in Lamis	1930	2019	90	73	17	81.11
San Nicandro Garganico	1967	2019	53	41	12	77.36
San Pancrazio Salentino	1957	2019	63	53	10	84.13
San Paolo Civitate	2010	2019	10	9	1	90.00
San Pietro Vernotico	1958	2019	62	50	12	80.65
San Samuele di Cafiero	2008	2019	12	11	1	91.67
San Severo	1932	2019	88	69	19	78.41

San Vito dei Normanni	1992	2019	28	27	1	96.43
Santa Maria di Leuca	1942	2019	78	68	10	87.18
Sant'Agata di Puglia	1930	2019	90	55	35	61.11
S.Angelo dei Lombardi	1932	2019	88	52	36	59.09
Santeramo in Colle	1963	2019	57	48	9	84.21
Savignano Irpino	1932	2019	88	50	38	56.82
Spinazzola	1936	2019	84	61	23	72.62
Talsano	1976	2019	44	43	1	97.73
Taranto	1935	2019	85	71	14	83.53
Taviano	1961	2019	59	54	5	91.53
Teora	1938	2019	82	63	19	76.83
Tertieveri	1969	2019	51	45	6	88.24
Torremaggiore	1940	2019	80	52	28	65.00
Troia	1932	2019	88	54	34	61.36
Turi	1960	2019	60	48	12	80.00
Venosa	1957	2019	63	49	14	77.78
Vico del Gargano	1967	2019	53	44	9	83.02
Vieste	1946	2018	73	59	14	80.82
Vignacastrisi	1959	2019	61	48	13	78.69
Volturara Appula	2010	2019	10	10	0	100.00
Volturino	1977	2019	43	31	12	72.09

Tab. B 4 - Missing values analysis on annual maxima hourly precipitation (6h)

RAIN GAUGE	***START***	***END***	***LENGTH SAMPLE***	***VALID DATA***	***MISSING VALUES***	***% VALID DATA***

Adelfia	1961	2019	59	55	4	93.22
Alberona	1952	2019	68	51	17	75.00
Alessano	2018	2019	2	2	0	100.00
Altamura	1952	2019	68	61	7	89.71
Andretta	1937	2019	83	49	34	59.04
Andria	1959	2019	61	56	5	91.80
Anzano di Puglia	2017	2018	2	2	0	100.00
Ascoli Satriano	1929	2019	91	65	26	71.43
Atella	1956	2019	64	49	15	76.56
Avetrana	1967	2018	52	42	10	80.77
Bari (Presidenza Regione)	1938	2019	82	65	17	79.27
Bari Ingegneria	1975	2019	45	36	9	80.00
Bari Osservatorio	1932	2019	88	79	9	89.77
Barletta	1959	2019	61	57	4	93.44
Biccari	1952	2019	68	55	13	80.88
Bisaccia	1959	2019	61	49	12	80.33
Bisceglie	1961	2019	59	50	9	84.75
Bitonto	1958	2019	62	55	7	88.71
Borgo Libertà	1929	2019	91	57	34	62.64
Bosco Umbra	1928	2019	92	72	20	78.26
Bovino	1929	2019	91	77	14	84.62
Brindisi	1936	2019	84	72	12	85.71
Cagnano Varano	1950	2019	70	65	5	92.86
Calitri	1937	2019	83	57	26	68.67
Canale dell’Asso	2010	2019	10	10	0	100.00
Candela	2008	2019	12	11	1	91.67
Candelaro SS272	2018	2019	2	2	0	100.00
Canosa di Puglia	1952	2019	68	61	7	89.71
Carlantino	2010	2019	10	10	0	100.00

Carpino	2017	2019	3	3	0	100.00
Casalnuovo Monte-rotaro	2011	2019	9	9	0	100.00
Casamassima	1961	2019	59	51	8	86.44
Cassano Murge	1929	2019	91	70	21	76.92
Castel del Monte	1932	2019	88	58	30	65.91
Castellana Grotte	1961	2019	59	50	9	84.75
Castellaneta	1962	2019	58	58	0	100.00
Castelluccio dei Sauri	1935	2019	85	59	26	69.41
Ceglie Messapica	1962	2019	58	45	13	77.59
Celenza Valfortore	2010	2019	10	10	0	100.00
Cellino San Marco	2014	2019	6	6	0	100.00
Cerignola	1932	2019	88	79	9	89.77
Collepasso	1971	2019	49	38	11	77.55
Conversano	1968	2019	52	45	7	86.54
Copertino	1961	2019	59	51	8	86.44
Corato	1963	2019	57	54	3	94.74
Corigliano d'Otranto	1994	2019	26	24	2	92.31
Crispiano	1958	2019	62	49	13	79.03
Diga Locone	2017	2019	3	3	0	100.00
Diga Sul Celone	2008	2019	12	12	0	100.00
Diga sull'Osento	2010	2019	10	10	0	100.00
Diga sul Rendina	1962	2016	55	49	6	89.09
Faeto	1941	2019	79	46	33	58.23
Fasano	1937	2019	83	57	26	68.67
Foggia Ist.Agrario	1972	2019	48	39	9	81.25
Foggia Osservatorio	1934	2019	86	76	10	88.37
Fonte Rosa	1963	2019	57	50	7	87.72

Forenza	1957	2018	62	43	19	69.35
Galatina	1959	2019	61	55	6	90.16
Gallipoli	1934	2019	86	72	14	83.72
Ginosa Marina	1933	2019	87	63	24	72.41
Ginosa	1932	2019	88	76	12	86.36
Gioia del Colle	1961	2019	59	50	9	84.75
Giovinazzo	1960	2019	60	55	5	91.67
Grottaglie	1958	2019	62	54	8	87.10
Grumo Appula	1932	2019	88	63	25	71.59
Isole Tremiti	2014	2019	6	6	0	100.00
Lacedonia	1932	2010	79	42	37	53.16
Lagopesole	1929	2019	91	71	20	78.02
Laterza	2015	2019	5	5	0	100.00
Latiano	1958	2019	62	55	7	88.71
Lavello	1951	2019	69	58	11	84.06
Lecce	1930	2019	90	75	15	83.33
Lesina	1938	2019	82	74	8	90.24
Lizzano	1957	2019	63	50	13	79.37
Loconia	1971	2019	49	41	8	83.67
Locorotondo	1964	2019	56	52	4	92.86
Lucera	1938	2019	82	66	16	80.49
Maglie	1935	2019	85	67	18	78.82
Manduria	1962	2019	58	50	8	86.21
Manfredonia	1932	2019	88	66	22	75.00
Massafra	1958	2019	62	55	7	88.71
Masseria Monteruga	1967	2019	53	45	8	84.91
Masseria S.Chiara	1960	2019	60	53	7	88.33
Melendugno	1971	2019	49	35	14	71.43
Melfi	1932	2019	88	75	13	85.23
Mercadante	1967	2019	53	51	2	96.23

Minervino di Lecce	1949	2019	71	65	6	91.55
Minervino Murge	1960	2019	60	53	7	88.33
Monte Sant'Angelo	1933	2019	87	64	23	73.56
Monte Vulture	2008	2019	12	10	2	83.33
Monteleone di Puglia	1936	2019	84	65	19	77.38
Montemilone	1940	2019	80	54	26	67.50
Monticchio Bagni	1948	2019	72	59	13	81.94
Montursi	2008	2019	12	12	0	100.00
Nardò	1957	2019	63	54	9	85.71
Noci	1929	2019	91	87	4	95.60
Novoli	1959	2019	61	58	3	95.08
Nusco	1936	2019	84	63	21	75.00
Orsara di Puglia	1962	2019	58	49	9	84.48
Ortanova	1959	2019	61	47	14	77.05
Orto di Zolfo	1969	2019	51	43	8	84.31
Ostuni	1958	2019	62	59	3	95.16
Otranto	1934	2019	86	79	7	91.86
Palagiano	2010	2019	10	10	0	100.00
Palagianello	2015	2019	5	5	0	100.00
Peschici	2017	2019	3	3	0	100.00
Pescopagano	1964	2019	56	48	8	85.71
Pietramontecorvino AQP	1970	2012	43	37	6	86.05
Pietramontecorvino Paese	1951	2019	69	62	7	89.86
Poggio Imperiale	2014	2019	6	6	0	100.00
Polignano a Mare	1963	2019	57	55	2	96.49
Presicce	1954	2019	66	59	7	89.39

Quasano	1928	2019	92	41	51	44.57
Ripacandida	1940	2019	80	63	17	78.75
Ripalta	2017	2019	3	3	0	100.00
Rocchetta S.Antonio Paese	1961	2014	54	48	6	88.89
Rocchetta S.Antonio Scalo	1947	2016	70	52	18	74.29
Rodi Garganico	2017	2019	3	3	0	100.00
Ruffano	1943	2019	77	58	19	75.32
Ruvo di Puglia	1964	2019	56	45	11	80.36
San Fele	1941	2019	79	49	30	62.03
Saccione SS16ter	2018	2019	2	2	0	100.00
Salsola SS16	2018	2018	1	1	0	100.00
San Giorgio Jonico	1934	2019	86	48	38	55.81
San Giovanni Ro-tondo	1932	2019	88	55	33	62.50
San Marco in Lamis	1928	2019	92	73	19	79.35
San Nicandro Gar-ganico	1967	2019	53	41	12	77.36
San Pancrazio Sa-lentino	1957	2019	63	53	10	84.13
San Paolo Civitate	2010	2019	10	9	1	90.00
San Pietro Vernotico	1958	2019	62	50	12	80.65
San Samuele di Ca-fiero	2008	2019	12	11	1	91.67
San Severo	1932	2019	88	71	17	80.68
San Vito dei Nor-manni	1992	2019	28	27	1	96.43
Santa Maria di Leuca	1942	2019	78	68	10	87.18

Sant'Agata di Puglia	1932	2019	88	54	34	61.36
S.Angelo dei Lombardi	1932	2019	88	52	36	59.09
Santeramo in Colle	1963	2019	57	48	9	84.21
Savignano Irpino	1932	2019	88	50	38	56.82
Spinazzola	1936	2019	84	61	23	72.62
Talsano	1976	2019	44	43	1	97.73
Taranto	1935	2019	85	72	13	84.71
Taviano	1961	2019	59	54	5	91.53
Teora	1938	2019	82	63	19	76.83
Tertieveri	1969	2019	51	43	8	84.31
Torremaggiore	1940	2019	80	54	26	67.50
Troia	1930	2019	90	55	35	61.11
Turi	1960	2019	60	48	12	80.00
Venosa	1957	2019	63	49	14	77.78
Vico del Gargano	1967	2019	53	46	7	86.79
Vieste	1946	2018	73	59	14	80.82
Vignacastrisi	1959	2019	61	48	13	78.69
Volturara Appula	2010	2019	10	10	0	100.00
Volturino	1978	2019	42	29	13	69.05

Tab. B 5 - Missing values analysis on annual maxima hourly precipitation (12h)

RAIN GAUGE	***START***	***END***	***LENGTH SAMPLE***	***VALID DATA***	***MISSING VALUES***	***% VALID DATA***
Adelfia	1961	2019	59	55	4	93.22
Alberona	1952	2019	68	51	17	75.00
Alessano	2018	2019	2	2	0	100.00
Altamura	1952	2019	68	61	7	89.71

Andretta	1937	2019	83	49	34	59.04
Andria	1959	2019	61	55	6	90.16
Anzano di Puglia	2017	2018	2	2	0	100.00
Ascoli Satriano	1929	2019	91	65	26	71.43
Atella	1956	2019	64	48	16	75.00
Avetrana	1967	2018	52	42	10	80.77
Bari (Presidenza Regione)	1938	2019	82	65	17	79.27
Bari Ingegneria	1975	2019	45	36	9	80.00
Bari Osservatorio	1932	2019	88	79	9	89.77
Barletta	1959	2019	61	57	4	93.44
Biccari	1952	2019	68	57	11	83.82
Bisaccia	1959	2019	61	49	12	80.33
Bisceglie	1961	2019	59	50	9	84.75
Bitonto	1958	2019	62	55	7	88.71
Borgo Libertà	1929	2019	91	59	32	64.84
Bosco Umbra	1929	2019	91	72	19	79.12
Bovino	1929	2019	91	77	14	84.62
Brindisi	1936	2019	84	72	12	85.71
Cagnano Varano	1950	2019	70	65	5	92.86
Calitri	1937	2019	83	57	26	68.67
Canale dell'Asso	2010	2019	10	10	0	100.00
Candela	2008	2019	12	11	1	91.67
Candelaro SS272	2018	2019	2	2	0	100.00
Canosa di Puglia	1952	2019	68	62	6	91.18
Carlantino	2010	2019	10	10	0	100.00
Carpino	2017	2019	3	3	0	100.00
Casalnuovo Monterotaro	2011	2019	9	9	0	100.00
Casamassima	1961	2019	59	53	6	89.83

Cassano Murge	1929	2019	91	71	20	78.02
Castel del Monte	1932	2019	88	58	30	65.91
Castellana Grotte	1961	2019	59	50	9	84.75
Castellaneta	1962	2019	58	58	0	100.00
Castelluccio dei Sauri	1935	2019	85	60	25	70.59
Ceglie Messapica	1962	2019	58	45	13	77.59
Celenza Valfortore	2010	2019	10	10	0	100.00
Cellino San Marco	2014	2019	6	6	0	100.00
Cerignola	1932	2019	88	79	9	89.77
Collepasso	1971	2019	49	37	12	75.51
Conversano	1968	2019	52	45	7	86.54
Copertino	1961	2019	59	51	8	86.44
Corato	1963	2019	57	54	3	94.74
Corigliano d'Otranto	1994	2019	26	24	2	92.31
Crispiano	1958	2019	62	50	12	80.65
Diga Locone	2017	2019	3	3	0	100.00
Diga Sul Celone	2008	2019	12	12	0	100.00
Diga sull'Osento	2010	2019	10	10	0	100.00
Diga sul Rendina	1962	2016	55	51	4	92.73
Faeto	1941	2019	79	46	33	58.23
Fasano	1937	2019	83	57	26	68.67
Foggia Ist.Agrario	1972	2019	48	39	9	81.25
Foggia Osservatorio	1934	2019	86	76	10	88.37
Fonte Rosa	1963	2019	57	50	7	87.72
Forenza	1957	2018	62	43	19	69.35
Galatina	1959	2019	61	56	5	91.80
Gallipoli	1934	2019	86	72	14	83.72
Ginosa Marina	1933	2019	87	64	23	73.56

Ginosa	1932	2019	88	76	12	86.36
Gioia del Colle	1961	2019	59	50	9	84.75
Giovinazzo	1960	2019	60	55	5	91.67
Grottaglie	1958	2019	62	54	8	87.10
Grumo Appula	1932	2019	88	63	25	71.59
Isole Tremiti	2014	2019	6	6	0	100.00
Lacedonia	1932	2010	79	41	38	51.90
Lagopesole	1929	2019	91	71	20	78.02
Laterza	2015	2019	5	5	0	100.00
Latiano	1958	2019	62	55	7	88.71
Lavello	1951	2019	69	58	11	84.06
Lecce	1932	2019	88	76	12	86.36
Lesina	1938	2019	82	75	7	91.46
Lizzano	1957	2019	63	50	13	79.37
Loconia	1971	2019	49	42	7	85.71
Locorotondo	1964	2019	56	54	2	96.43
Lucera	1938	2019	82	66	16	80.49
Maglie	1935	2019	85	67	18	78.82
Manduria	1962	2019	58	49	9	84.48
Manfredonia	1932	2019	88	66	22	75.00
Massafra	1958	2019	62	55	7	88.71
Masseria Monteruga	1967	2019	53	45	8	84.91
Masseria S.Chiara	1960	2019	60	52	8	86.67
Melendugno	1971	2019	49	34	15	69.39
Melfi	1932	2019	88	74	14	84.09
Mercadante	1967	2019	53	51	2	96.23
Minervino di Lecce	1949	2019	71	65	6	91.55
Minervino Murge	1960	2019	60	53	7	88.33
Monte Sant'Angelo	1933	2019	87	64	23	73.56
Monte Vulture	2008	2019	12	10	2	83.33

Monteleone di Puglia	1936	2019	84	66	18	78.57
Montemilone	1940	2019	80	55	25	68.75
Monticchio Bagni	1948	2019	72	58	14	80.56
Montursi	2008	2019	12	12	0	100.00
Nardò	1957	2019	63	55	8	87.30
Noci	1929	2019	91	87	4	95.60
Novoli	1959	2019	61	58	3	95.08
Nusco	1936	2019	84	63	21	75.00
Orsara di Puglia	1962	2019	58	49	9	84.48
Ortanova	1959	2019	61	46	15	75.41
Orto di Zolfo	1969	2019	51	44	7	86.27
Ostuni	1958	2019	62	59	3	95.16
Otranto	1934	2019	86	79	7	91.86
Palagiano	2010	2019	10	10	0	100.00
Palagianello	2015	2019	5	5	0	100.00
Peschici	2017	2019	3	3	0	100.00
Pescopagano	1964	2019	56	48	8	85.71
Pietramontecorvino AQP	1970	2012	43	38	5	88.37
Pietramontecorvino Paese	1951	2019	69	64	5	92.75
Poggio Imperiale	2014	2019	6	6	0	100.00
Polignano a Mare	1963	2019	57	55	2	96.49
Presicce	1954	2019	66	59	7	89.39
Quasano	1933	2019	87	40	47	45.98
Ripacandida	1940	2019	80	63	17	78.75
Ripalta	2017	2019	3	3	0	100.00

Rocchetta S.Antonio Paese	1961	2014	54	47	7	87.04
Rocchetta S.Antonio Scalo	1947	2016	70	51	19	72.86
Rodi Garganico	2017	2019	3	3	0	100.00
Ruffano	1943	2019	77	58	19	75.32
Ruvo di Puglia	1964	2019	56	46	10	82.14
San Fele	1941	2019	79	49	30	62.03
Saccione SS16ter	2018	2019	2	2	0	100.00
Salsola SS16	2018	2018	1	1	0	100.00
San Giorgio Jonico	1934	2019	86	47	39	54.65
San Giovanni Rotondo	1932	2019	88	55	33	62.50
San Marco in Lamis	1928	2019	92	74	18	80.43
San Nicandro Garganico	1967	2019	53	41	12	77.36
San Pancrazio Salentino	1957	2019	63	54	9	85.71
San Paolo Civitate	2010	2019	10	9	1	90.00
San Pietro Vernotico	1958	2019	62	53	9	85.48
San Samuele di Cafiero	2008	2019	12	11	1	91.67
San Severo	1932	2019	88	73	15	82.95
San Vito dei Normanni	1992	2019	28	27	1	96.43
Santa Maria di Leuca	1942	2019	78	68	10	87.18
Sant'Agata di Puglia	1932	2019	88	55	33	62.50
S.Angelo dei Lombardi	1932	2019	88	53	35	60.23

Santeramo in Colle	1963	2019	57	47	10	82.46
Savignano Irpino	1932	2019	88	50	38	56.82
Spinazzola	1936	2019	84	61	23	72.62
Talsano	1976	2019	44	43	1	97.73
Taranto	1935	2019	85	72	13	84.71
Taviano	1961	2019	59	54	5	91.53
Teora	1938	2019	82	63	19	76.83
Tertieveri	1969	2019	51	44	7	86.27
Torremaggiore	1940	2019	80	54	26	67.50
Troia	1930	2019	90	56	34	62.22
Turi	1960	2019	60	48	12	80.00
Venosa	1957	2019	63	49	14	77.78
Vico del Gargano	1967	2019	53	47	6	88.68
Vieste	1946	2018	73	59	14	80.82
Vignacastrisi	1959	2019	61	48	13	78.69
Volturara_Appula	2010	2019	10	10	0	100.00
Volturino	1978	2019	42	29	13	69.05

Tab. B 6 - Missing values analysis on annual maxima hourly precipitation (24h)

RAIN GAUGE	***START***	***END***	***LENGTH SAMPLE***	***VALID DATA***	***MISSING VALUES***	***% VALID DATA***
Adelfia	1961	2019	59	55	4	93.22
Alberona	1952	2019	68	50	18	73.53
Alessano	2018	2019	2	2	0	100.00
Altamura	1952	2019	68	63	5	92.65
Andretta	1937	2019	83	49	34	59.04
Andria	1959	2019	61	56	5	91.80
Anzano di Puglia	2017	2018	2	2	0	100.00

Ascoli Satriano	1929	2019	91	66	25	72.53
Atella	1956	2019	64	47	17	73.44
Avetrana	1967	2018	52	42	10	80.77
Bari (Presidenza Regione)	1938	2019	82	65	17	79.27
Bari Ingegneria	1975	2019	45	37	8	82.22
Bari Osservatorio	1932	2019	88	79	9	89.77
Barletta	1959	2019	61	57	4	93.44
Biccari	1952	2019	68	57	11	83.82
Bisaccia	1959	2019	61	49	12	80.33
Bisceglie	1961	2019	59	50	9	84.75
Bitonto	1958	2019	62	56	6	90.32
Borgo Liberta	1929	2019	91	58	33	63.74
Bosco Umbra	1929	2019	91	71	20	78.02
Bovino	1929	2019	91	76	15	83.52
Brindisi	1936	2019	84	72	12	85.71
Cagnano Varano	1950	2019	70	65	5	92.86
Calitri	1937	2019	83	57	26	68.67
Canale dell'Asso	2010	2019	10	10	0	100.00
Candela	2008	2019	12	11	1	91.67
Candelaro SS272	2018	2019	2	2	0	100.00
Canosa di Puglia	1952	2019	68	62	6	91.18
Carlantino	2010	2019	10	10	0	100.00
Carpino	2017	2019	3	3	0	100.00
Casalnuovo Monte-rotaro	2011	2019	9	9	0	100.00
Casamassima	1961	2019	59	53	6	89.83
Cassano Murge	1929	2019	91	72	19	79.12
Castel del Monte	1932	2019	88	58	30	65.91
Castellana Grotte	1961	2019	59	51	8	86.44

Castellaneta	1962	2019	58	58	0	100.00
Castelluccio dei Sauri	1935	2019	85	61	24	71.76
Ceglie Messapica	1962	2019	58	45	13	77.59
Celenza Valfortore	2010	2019	10	10	0	100.00
Cellino San Marco	2014	2019	6	6	0	100.00
Cerignola	1932	2019	88	79	9	89.77
Collepasso	1971	2019	49	37	12	75.51
Conversano	1968	2019	52	45	7	86.54
Copertino	1961	2019	59	51	8	86.44
Corato	1963	2019	57	55	2	96.49
Corigliano d’Otranto	1994	2019	26	24	2	92.31
Crispiano	1958	2019	62	49	13	79.03
Diga Locone	2017	2019	3	3	0	100.00
Diga Sul Celone	2008	2019	12	12	0	100.00
Diga sull’Osento	2010	2019	10	10	0	100.00
Diga sul Rendina	1962	2016	55	51	4	92.73
Faeto	1941	2019	79	44	35	55.70
Fasano	1937	2019	83	57	26	68.67
Foggia Ist_Agrario	1972	2019	48	39	9	81.25
Foggia Osservatorio	1934	2019	86	76	10	88.37
Fonte Rosa	1963	2019	57	50	7	87.72
Forenza	1957	2018	62	44	18	70.97
Galatina	1959	2019	61	56	5	91.80
Gallipoli	1934	2019	86	72	14	83.72
Ginosa Marina	1933	2019	87	64	23	73.56
Ginosa	1932	2019	88	76	12	86.36
Gioia del Colle	1961	2019	59	50	9	84.75
Giovinazzo	1960	2019	60	55	5	91.67

Grottaglie	1958	2019	62	54	8	87.10
Grumo Appula	1932	2019	88	63	25	71.59
Isole Tremiti	2014	2019	6	6	0	100.00
Lacedonia	1932	2010	79	40	39	50.63
Lagopesole	1929	2019	91	70	21	76.92
Laterza	2015	2019	5	5	0	100.00
Latiano	1958	2019	62	56	6	90.32
Lavello	1951	2019	69	58	11	84.06
Lecce	1932	2019	88	76	12	86.36
Lesina	1938	2019	82	76	6	92.68
Lizzano	1957	2019	63	50	13	79.37
Loconia	1971	2019	49	42	7	85.71
Locorotondo	1964	2019	56	54	2	96.43
Lucera	1938	2019	82	66	16	80.49
Maglie	1935	2019	85	68	17	80.00
Manduria	1962	2019	58	49	9	84.48
Manfredonia	1932	2019	88	65	23	73.86
Massafra	1958	2019	62	56	6	90.32
Masseria Monte-ruga	1967	2019	53	45	8	84.91
Masseria S. Chiara	1960	2019	60	53	7	88.33
Melendugno	1971	2019	49	34	15	69.39
Melfi	1932	2019	88	74	14	84.09
Mercadante	1967	2019	53	50	3	94.34
Minervino di Lecce	1949	2019	71	66	5	92.96
Minervino Murge	1960	2019	60	53	7	88.33
Monte Sant'Angelo	1933	2019	87	66	21	75.86
Monte Vulture	2008	2019	12	10	2	83.33
Monteleone di Pu-glia	1936	2019	84	66	18	78.57

Montemilone	1940	2019	80	56	24	70.00
Monticchio Bagni	1948	2019	72	57	15	79.17
Montursi	2008	2019	12	12	0	100.00
Nardò	1957	2019	63	54	9	85.71
Noci	1929	2019	91	87	4	95.60
Novoli	1959	2019	61	57	4	93.44
Nusco	1936	2019	84	64	20	76.19
Orsara di Puglia	1962	2019	58	50	8	86.21
Ortanova	1959	2019	61	46	15	75.41
Orto di Zolfo	1969	2019	51	44	7	86.27
Ostuni	1958	2019	62	59	3	95.16
Otranto	1934	2019	86	79	7	91.86
Palagiano	2010	2019	10	10	0	100.00
Palagianello	2015	2019	5	5	0	100.00
Peschici	2017	2019	3	3	0	100.00
Pescopagano	1964	2019	56	48	8	85.71
Pietramontecorvino A.Q.P.	1970	2012	43	39	4	90.70
Pietramontecorvino Paese	1951	2019	69	64	5	92.75
Poggio Imperiale	2014	2019	6	6	0	100.00
Polignano a Mare	1963	2019	57	56	1	98.25
Presicce	1954	2019	66	59	7	89.39
Quasano	1933	2019	87	41	46	47.13
Ripacandida	1940	2019	80	63	17	78.75
Ripalta	2017	2019	3	3	0	100.00
Rocchetta S.Antonio Paese	1961	2014	54	48	6	88.89

Rocchetta S.Antonio Scalo	1947	2016	70	52	18	74.29
Rodi Garganico	2017	2019	3	3	0	100.00
Ruffano	1943	2019	77	59	18	76.62
Ruvo di Puglia	1964	2019	56	46	10	82.14
San Fele	1941	2019	79	48	31	60.76
Saccione SS16ter	2018	2019	2	2	0	100.00
Salsola SS16	2018	2018	1	1	0	100.00
San Giorgio Jonico	1934	2019	86	47	39	54.65
San Giovanni Rotondo	1932	2019	88	55	33	62.50
San Marco in Lamis	1930	2019	90	74	16	82.22
San Nicandro Garganico	1967	2019	53	42	11	79.25
San Pancrazio Salentino	1957	2019	63	54	9	85.71
San Paolo Civitate	2010	2019	10	9	1	90.00
San Pietro Vernotico	1958	2019	62	52	10	83.87
San Samuele di Cafiero	2008	2019	12	11	1	91.67
San Severo	1932	2019	88	73	15	82.95
San Vito dei Normanni	1993	2019	27	26	1	96.30
Santa Maria di Leuca	1942	2019	78	68	10	87.18
Sant’Agata di Puglia	1932	2019	88	55	33	62.50
S. Angelo dei Lombardi	1932	2019	88	53	35	60.23
Santeramo in Colle	1963	2019	57	48	9	84.21

Savignano Irpino	1932	2019	88	50	38	56.82
Spinazzola	1936	2019	84	61	23	72.62
Talsano	1976	2019	44	43	1	97.73
Taranto	1935	2019	85	73	12	85.88
Taviano	1961	2019	59	54	5	91.53
Teora	1938	2019	82	62	20	75.61
Tertieveri	1969	2019	51	45	6	88.24
Torremaggiore	1940	2019	80	54	26	67.50
Troia	1932	2019	88	56	32	63.64
Turi	1960	2019	60	49	11	81.67
Venosa	1957	2019	63	48	15	76.19
Vico del Gargano	1967	2019	53	48	5	90.57
Vieste	1946	2018	73	62	11	84.93
Vignacastrisi	1959	2019	61	49	12	80.33
Volturara Appula	2010	2019	10	10	0	100.00
Volturino	1978	2019	42	30	12	71.43

12 APPENDIX C - The Weighted Least Squares (WLS) method

The principle of the WLS method is based on the minimization of the sums of the weighted square deviations of the observed and estimated moments, where the weights are the reciprocal of their expected values.

The first central moment is the expected value, known also as mean:

$$\sum WS_t^1 = \sum_{t=1}^{T} \gamma_t^{(1)} (x_t - \widehat{m_t})^2 \tag{C1}$$

where $\widehat{m_t} = f_1(\boldsymbol{g}, t)$ while the weight $\gamma_t^{(1)}$is:

$$\gamma_t^{(1)} = \frac{1}{E(x_t - \widehat{m_t})^2} = \frac{1}{\sigma^2(x_t)} \tag{C2}$$

Applying the WLS method in respect to the second central moment, we have:

$$\sum WS_t^{(2)} = \sum_{t=1}^{T} \gamma_t^{(2)} [\varepsilon_t^2 - \widehat{\mu_2}(x_t)]^2 \tag{C3}$$

where $\varepsilon_t = x_t - m_t$, $\widehat{\mu_2}(x,t) \equiv \widehat{\sigma^2}(x,t) = f_2(\boldsymbol{h}, t)$, and $\gamma_t^{(2)}$ which becames, in the case of time invariant skewness:

$$\gamma_t^{(2)} = \frac{1}{\sigma^4(x_t)[\varphi(c_s) - 1]} \tag{C4}$$

The minimum conditions of $(\sum WS_t^{(1)})$ of respect to the **g** vector of parameters are:

$$\sum_{t=1}^{T} \gamma_t^{(1)} (x_t - \widehat{m_t}) \frac{d\widehat{m_t}}{d\boldsymbol{g}} = 0 \tag{C5}$$

And for the weighted squares ($\sum WS_t^{(2)}$) with respect to **h** are:

$$\sum_{t=1}^{T} \frac{1}{\sigma_t^4} (\varepsilon_t^2 - \sigma_t^2) \frac{d\sigma_t^2}{d\boldsymbol{h}} = 0 \tag{C6}$$

The WLS method coincides with ML-method when data are normally distributed.

13 APPENDIX D - Method of L-Moments

Hosking (1986) introduced L-moments method as a linear function of the expected order statistics, as defined:

$$\lambda_r = \frac{1}{r}\sum_{i=0}^{r-1}(-1)^i \binom{r-1}{i} E\{X_{r-i:r}\} \tag{D1}$$

With r $\in \mathbb{Z}^+$.

E represents the expectation of an order statistic defined by:

$$E\{X_{j:r}\} = \frac{r!}{(r-j)!\,j!}\int_0^1 x\{F(X)\}^{j-1}\{1-F(X)\}^{r-j}\,dF(X) \tag{D2}$$

From combination of (D1) and (D2) is obtained:

$$\lambda_r = \int_0^1 x(F)P^*_{r-1}(F)\,dF \tag{D3}$$

Starting from equation (D3), the first four L-moments can be defined as:

$$\lambda_1 = E(X) = \int_0^1 x(F)\,dF \tag{D4}$$

$$\lambda_2 = \int_0^1 x(F)(2F-1)\,dF \tag{D5}$$

$$\lambda_3 = \int_0^1 x(F)(6F^2-6F+1)\,dF \tag{D6}$$

$$\lambda_4 = \int_0^1 x(F)(20F^3-30F^2+12F-1)\,dF \tag{D7}$$

λ_1 and λ_2 represent a measure of location and scale of the distribution respectively. This first four moments can be standardizes obtaining L-moments ratios, defined in general as:

$$\tau_r = \frac{\lambda_r}{\lambda_2} \tag{D8}$$

But usually are used the following quantities:

L-Coefficient of Variation $$\tau = \frac{\lambda_2}{\lambda_1} \tag{D9}$$

L-Skewness $$\tau_3 = \frac{\lambda_3}{\lambda_2} \tag{D10}$$

L-Kurtosis $$\tau = \frac{\lambda_4}{\lambda_2} \tag{D11}$$

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15 CURRICULUM

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- Lioi, B.; Gioia, A.; Totaro, V.; Balacco, G.; Iacobellis, V.; Chiaia, G. Coupled Use of Hydrologic-Hydraulic Model and Geomorphological Descriptors for Flood-Prone Areas Evaluation: A Case Study of Lama Lamasinata. In Proceedings of the International Conference on Computational Science and Its Applications, Cagliari, Italy, 1–4 July 2020; Springer: Cham, Switzerland, 2020; pp. 607–619.
- Gioia, A.; Lioi, B.; Totaro, V.; Molfetta, M.G.; Apollonio, C.; Bisantino, T.; Iacobellis, V. Estimation of Peak Discharges under Different Rainfall Depth–Duration–Frequency Formulations. *Hydrology* **2021**, *8*, 150.

Poster Presentation:

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