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Trend Analysis in the peak flows of the Meuse river and its tributaries through the use of series of ensemble forecasts events

Bachelor Thesis

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Abstract
Climate change is not a future issue. There is evidence that extreme events are changing in terms of frequency, intensity, duration, location, and timing due to climate change (Easterling et al., 2000 & IPCC, 2012, as cited by Rypkema & Tuljapurkar, 2021). Experts and decision-makers are concerned that these climate changes may be affecting extreme events on essential rivers such as the Meuse river. In addition to these changes in extreme events, it should be considered that a large part of the Netherlands is below water level and other areas are prone to flooding. That is why for Dutch water managers, finding a possible climate-induced trend in the probability of extreme discharges is a matter of great concern; because it could affect the design of the flood defense systems (Diermanse, et al., 2010).

Historical observations could have been an excellent tool to better understand what could happen in the future due to human-induced climate change (Villarini, et al., 2011). However, the problem when analyzing extreme events is that there is not enough historical data available, and the rarer the event, the more difficult it will be to identify changes (IPCC, 2012). According to van den Brink, et al. (2005), this dearth of data problem can be addressed through the use of ensemble weather forecasts obtained from the ECMWF (European Centre for Medium-Range Weather Forecasts). In previous research conducted by te Booij (2022), this ensemble re-forecasts technique was used to overcome the lack of data and increase the number of suitable extreme precipitation events to perform a trend analysis on these precipitation events of the Meuse catchment.

In this report, special attention was given to the extreme discharge events derived from a selection of extreme precipitation events identified from the reforecasts of the ECMWF in the previous research done by te Booij (2022). The selected extreme precipitation events for this investigation were the two most extreme events for each year (within a period of 20 years from 1996 until 2015) extracted from the list of 5-day accumulative rainfall volumes. These extreme precipitation extreme events served as input for a hydrological model (wflow model) to perform simulations for two possible scenarios (dry and wet) and to obtain the forecasted extreme discharge events. The initial conditions for both dry and wet scenarios and the historical simulated maximum annual discharges were determined using E-OBS gridded data as the main input in the wflow model. So, the three resulting datasets of discharge extremes that were used for the comparison and trend analysis are:

1. historical simulated maximum annual discharges
2. highest maximum annual discharges obtained with the dry initial states (forecasted dataset)
3. highest maximum annual discharges obtained with the wet initial states (Forecasted dataset)

The *historical simulated maximum annual discharges* were compared with both forecasted datasets. It turned out that there was a similarity between the *historical simulated maximum annual discharges* and the *highest maximum annual discharges obtained with the dry initial states*. On the contrary, the *highest maximum annual discharges obtained with the wet initial states* were different from *historical simulated maximum annual discharges*. Subsequently, an autocorrelation test was applied to the three datasets of discharge extremes to verify if the discharge extremes were independent. It turned out that all datasets of extreme events were independent. Once the autocorrelation on the extreme discharges was rejected, a graphical analysis started. Here, the maximum extreme discharges of each of the three datasets were plotted (y-axis) against the 20 years (x-axis) to obtain the best-fit line for each datasets. The resulting best-fit lines indicated a descending tendency for almost all datasets of the gauge stations. Finally, the veracity of these trend lines was inspected. For this, four statistical tests were applied to the three datasets of extreme discharges for each gauge station. The results of this statistical analysis showed that there was not enough evidence to indicate the presence of any ascending or descending trend in the maximum extreme annual discharges of the Meuse river and its tributaries.

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ECMWF: European Centre for Medium-Range Weather Forecasts

IPCC: Intergovernmental Panel on Climate Change

WWA: World Weather Attribution

1. Introduction

1.1. Problem Context

The Netherlands is a flood-prone country that started its battle against water about 1000 years ago (McVeigh, 2014). The first measures adopted in the past to protect the country from the sea and the rivers were ditches, dikes, windmills, mechanical pumping, polders, reclamation of lakes, and closing of sea inlets projects (Booij M. , 2019). According to Luijendijk (2012), all these water management interventions were mainly focused on avoiding flooding in low-lying areas. Nevertheless, van der Brugge, Rotmans, & Loorbach (2005) mention that this water management approach could face issues in the future due to continuous soil subsidence, rising sea levels, decreased retain water capacity, and an increase in population. But most importantly, because these threshold-against-water measures should now deal with climate change (Luijendijk, 2012).

Changes in extreme events are not a new topic. Previous reports delivered by the IPCC, like the "*AR4 Climate Change 2007-Synthesis Report"*, mention the increase of extreme events (droughts, heat waves, and floods) and the consequences produced by those changes since the AR3 report (IPCC, 2007). However, in recent years, scientists and experts have started attributing these changes in extreme events to climate change. The IPCC recently in its sixth assessment report states that climate change has been affecting extreme events, in terms of magnitude and frequency; and anticipates that as the climate continues to change, extreme events will be totally different not only in terms of frequency and intensity but also in location and duration (Adnan, et al., 2021). More extreme river discharges combined with an increase in rising air and water temperatures due to climate can cause impacts on the ecosystems of the rivers in the Netherlands (Rijksoverheid, 2022).

These changes in extreme river discharges do not seem to picture a promising future scenario for a low-lying country such as The Netherlands, where according to the PBL Netherlands Environmental Assessment Agency (n.d.) 26% of its territory is below sea level, 59% of the ground surface is prone to flooding, and 55% of the land needs to be protected by dikes, dams, and other protection structures. The Netherlands is aware of how devasting the consequences of flooding events could be; because throughout its history the country has been threatened by climatic events such as the Saint Elisabeth flood in 1421 or the storm disaster of February 1953 (See Figure 1), which resulted in a total of 2000 and 1836 casualties respectively (Olsthoorn, et al., 2008; Booij, 2019). Besides human losses and social damage, extreme weather events could also be responsible for significant economic losses (European Environment Agency , 2022). Hence, research should be conducted to understand how these extreme river discharge events are changing.

Figure 1: Storm disaster of February 1953 (Behre, 2018).

The focus of this thesis research is the Meuse catchment because due to climate change, considerable changes in the river discharges of the Meuse river could be witnessed (Sperna Weiland et al., 2015 as cited in de Rooij, 2020). On the one hand, the peak flows could be higher and appear more frequently; on the other hand, low flows could decrease much more and also increase their frequency (de Rooij, 2020). Examples of these types of unusual extreme events have been recorded in recent years. For instance, extremely low water levels were registered in Flanders during the years 2019 and 2020 (The Brussels Time, 2022). But also, heavy rains were recorded on July 14, 2021, resulting in noticeable increases in both water levels and discharges of the Meuse river, and beating its own historical records of water levels in the Netherlands (Rijkswaterstaat, 2021). These changes in river discharges, especially extreme higher river discharges, represent a significant threat to the Netherlands (Rijksoverheid, 2022). In case of finding trends or disproportional changes in the extreme discharge events of the Meuse river and its tributaries, the on-going flood risk management projects in the Netherlands will require adjustments and extra substantial investments (Diermanse, et al., 2010).

1.2. What has been done so far and is already available and what is going to be used for this thesis report?

The research findings of the thesis report entitled *"Trend analysis of extreme precipitation events in the Meuse catchment obtained with re-forecast from the ECMWF"* presented by Berend-Jan te Booij (a bachelor student at the University of Twente) will serve as input for the development of this thesis. Berend-Jan te Booij in his thesis aimed to use ensemble re-forecasts of the ECMWF to solve two main research questions. In the first research question, he had to identify and classify the extreme precipitation events from the ensemble prediction system over a 20-year period from 1996 to 2015 in the Meuse river basin. To solve this research question, he processed the re-forecast data provided by Deltares from March 1996 until March 2015 to obtain the extreme rainfall precipitation events for the red rectangle area in the Meuse catchment shown in Figure 2. Then, he classified the extreme precipitation events in lists as follows: 1-day, 3-days, 5-days, summer, and winter extreme events.

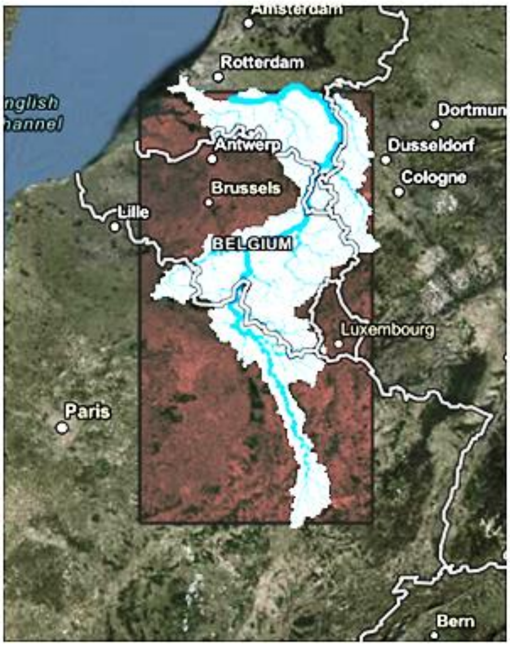


Figure 2: Study Area of previous thesis research (te Booij, 2022).

The second research question was about analyzing the existence of possible trends in the full set of ensemble forecasts combined over the period from 1996 until 2015. For this, he performed a trend analysis on each of the lists mentioned before. The results of this trend analysis showed that only for the one-day extreme events there was a trend with enough evidence, either when the extreme precipitation events were taken every year (annually) or during the summer (per season). Regarding the trend analysis applied to the 3-day and 5-day accumulative rainfall volume, the results suggest that a weaker trend can be observed graphically. However, statistical evidence for these trends was not found.

For this report, the five lists (1-day, 3-day, and 5-day, summer, and winter extreme precipitation events) were provided. In each of these lists, the ten most extreme events per year from a full set of ensembles starting in 1996 until 2015 (a total of 20 years) can be found. However, just the two most extreme events from the list of the 5-day accumulative rainfall volume have been filtered for further analysis about possible trends on the extreme discharges and to perform a comparison between historical and forecasted extreme discharge values. The decision to choose the 5-days cumulative volume events is based on the findings of Berghuijs, et al. (2019), who performed a study to determine the different flood-generating mechanisms in 4062 catchments of European rivers during the period from 1960 to 2010. According to Berghuijs, et al. (2019), 1-day precipitation events are not a predominant flood mechanism in Europe, while multi-day rainfall events are considered a fairly common flood-generating mechanism. Therefore, the 5-day precipitation events will be more useful for further analyses. This means that a total of 40 precipitation events will be converted into river discharges using a hydrological model (wflow), which is explained later in the Section 3. The list with the two most extreme precipitation events from the 5-day accumulative rainfall volume can be found in Appendix A.

1.3. Problem Statement

The encountered problem is that the world is changing rapidly due to global warming, and it is scientifically widely recognized that extreme events like precipitations and river discharge events could intensify in the future due to climate change. For a country like the Netherlands where 59% of its territory is prone to flooding either by rivers or by the sea, this scenario is of great concern to scientists, water managers, and decision-makers. Therefore, investigating the presence of trends in extreme events (precipitation and river discharges) is imperative to ensure the safety of the inhabitants.

The importance of analyzing these extreme events lies in the fact that these extreme events are usually applied within engineering practice to determine design standards for flood risk assessments and infrastructure designs where return periods and probability of occurrence of these extreme events are calculated (McPhillips, et al., 2018). For this, a stationary approach is usually adopted, where historic homogeneous series of discharges are required to classify them as annual maximum values (AM) or peaks over threshold values (POT); and so the design discharge values are calculated (Diermanse, et al., 2010). A time series can be considered stationary when it does not present any slow or abrupt changes or periodicities (Villarini, et al., 2011). However, Hounkpe, et al. (2015) mention that assuming stationarity could not be adequate for engineering practices anymore since the changes produced by climate change and trends are not being taken into account.

Nevertheless, analyzing extreme river discharge events could be challenging due to the lack of relevant historical records of these extreme events; because these types of events are rare and also do not occur within an optimal period that allows determining how the changes in the frequency and intensity of extreme events are happening (National Academies of Sciences, Engineering, and Medicine, 2016). Hence, other approaches like the use of extreme river discharges derived from precipitation series obtained from the reforecasts of the ECMWF are being explored. By doing this, the stationary assumption traditionally assumed for the extreme events in the water management practice can be assessed. This is with the aim of not underestimating or overestimating the possible presence of trends that would directly affect the decision-making process of the measures and protection mechanism in the Netherlands.

1.4. Research Objective and Research Questions

1.4.1. Research objective

This research project aims to identify of trends that can confirm how extreme discharges have been changing during the period from 1996 until 2015 in the River Meuse and its tributaries. In an ideal situation, this could have been done by using real-world observations. However, there is insufficient reliable data because extreme events are rare. Therefore, the next best option to compensate for this lack of data is to use extreme precipitation events derived from the ensemble forecast system. As explained before in Section 1.2, te Booij (2022) has already collected a set of precipitation events from the ECMWF for the Meuse catchment during a period of 20 years. The wflow model will use these extreme precipitation events to determine two forecasted datasets of extreme discharges:

- *highest maximum annual discharges obtained with the dry initial states (forecasted dataset)*
- *highest maximum annual discharges obtained with the wet initial states (forecasted dataset)*

However, the initial conditions and the dataset containing the *historical simulated maximum annual discharges* should be determined before obtaining these two forecasted datasets. For this, the w-flow model will make use of E-OBS gridded data. This high spatial resolution daily data grid provides daily values for mean, maximum, and minimum temperature, total daily precipitation, and mean sea level pressure (van der Schier, 2019). E-OBS gridded data has records from January 1950 to the present, and it is widely used because it allows monitoring of daily extreme events across Europe (van der Schier, 2019).

Hence, in this bachelor thesis, the aim is to perform a comparison of the forecasted simulated extreme discharges versus the historical simulated extreme discharges and a trend detection analysis in these three datasets of extreme discharges; to verify if it is true that noticeable changes or trends have been producing in the river discharges of the Meuse river and its tributaries.

1.4.2. Research questions

In order to fulfill the research objective and scope of this project, the following two main questions have been formulated:

1. ***In which way are the simulated forecasted extreme discharge values different from what we have seen in the simulated historical extreme discharge values?***
2. ***Is there enough evidence to confirm the presence of trends in the extreme discharge events of the Meuse river? And could the trend analysis results be different when considering the tributaries of the Meuse river?***

The first main question will compare the simulated forecasted extreme discharges obtained with the dry and wet initial conditions against the simulated historical discharges. This comparison will be performed to the three datasets of discharge extreme events of the Meuse river and some of its tributaries. If the difference between them is relatively small, it can be assumed that the forecasted and historical extreme discharges are reliable for the trend analysis.

For the second main question, the trend analysis will be first carried out for the three datasets of discharge extremes at the most important gauge station of the Meuse river (Borgharen). Then, other gauge stations of the river will be considered for the same trend analysis. The idea is to analyze the trend analysis results on the river discharges of the main river (Meuse). But also, to understand how the results of the same trend analysis could differ when considering the forecasted and historical simulated extreme discharge events of some tributaries of the river.

The following four sub-questions have been derived to answer these two main research questions.

a) **How can appropriate initial conditions/states be established to perform the simulations?**

This sub-question is related to the set-up of the simulations that will be conducted using the wflow model. In other words, the day zero for each extreme precipitation event that will be analyzed. As in any simulation, the initial conditions for the model are important because these are the base for such simulations. In the hydrological analysis of the Meuse river and its tributaries, the chosen initial conditions could strongly influence the resulting extreme discharges. Therefore, the initial states cannot be trivial. The problem is that the wflow model is a model that evaluates continuous data and produces continuous results as well. However, the interest of this research is to obtain the initial states for some specific dates (the first day of each extreme precipitation event). This could be a problem because the model can not be run until the starting date of each extreme precipitation event; it will take too much time. Therefore, other possibilities to find the initial states are explored and explained in more detail in Section 4.2.

b) **How different are the results of the trend analysis in extreme discharges when investigating some of the tributaries of the Meuse river instead of just analyzing the main river (Borgharen)?**

Borgharen is the point where the Meuse river enters the Netherlands and is widely used as a reference point in the Dutch flood protection system (Diermanse, et al., 2010). Therefore, it is a key location to start the comparison of historical versus forecasted discharges and the trend analysis.

Since the river Meuse crosses other countries besides the Netherlands, other tributaries will also be included to see how different the results for the trend analysis are. According to the International Meuse Commission (2021), some important tributaries are Chiers, Semois, Lesse, Sambre, Ourthe, and others. Therefore, the same comparison and trend analysis carried out for the three datasets of discharge extremes at Borgharen could be applied to the tributaries; to see how different their results are. The final list with the selected tributaries and the steps to perform the comparison between the simulated historical versus the simulated forecasted maximum discharge events obtained with the dry and wet conditions, as well as the steps for the trend analysis are explained in more detail in Section 4.

c) **Do the results obtained from the trend detection analysis depend on the methods and resources used during the analysis?**

The existing statistical tests for trend analysis will be applied to the three datasets of discharge extreme events obtained from the wflow model (*historical simulated maximum annual discharges, highest maximum annual discharges obtained with the dry initial states* & *highest maximum annual discharges obtained with the wet initial states*). Thereafter, each of the results obtained from these statistical tests should be analyzed and compared with each other. Based on the comparison of these statistical results, the existence of a trend on the river Meuse and its tributaries can be confirmed or rejected.

It is necessary to check the robustness of the statistical tests and measure the significance of the trend (in case of finding one). Because the statistical results could be affected for several reasons such as using data biased, choosing the wrong variables which leads to regression errors, misinterpreting p-values or other statistics, managing the data incorrectly (losing or mixing values), and forgetting the influence of the outliers (Bhatia, 2017). These reasons could be responsible for not finding consistent or logical answers. Hence, a sensitivity analysis should be performed on at least for one statistical test to check its strength/ robustness (te Booij, 2022).

2. Study Area

2.1. Basin Characteristics of the Meuse river

The Meuse river is the second largest river in The Netherlands, and it provides environmental services such as drinking water supply for about 6 million people (Reuber, Schielen, & Barneveld, 2005), navigation, ecology, leisure activities, and other socio-economical functions (de Rooij, 2020). The river originates in Langres (France) with an extension of approximately 950 km (Britannica, The Editors of Encyclopaedia, 2014). The total area of the catchment is approximately 33 000 km², and the river crosses the countries of France, Belgium, Luxemburg, Germany, and The Netherlands (Reuber, Schielen, & Barneveld, 2005), as can be seen in Figure 3. The Meuse river is a typical pluvial river with a partially low-middle mountainous catchment area and a subsoil that has a low storage index due to the type of soil, which causes the rainwater to flow quickly into the river (Reuber, Schielen, & Barneveld, 2005). The study area of this research is the upstream catchment area of the river. The reference point of this upstream area is the gauge station named Borgharen, which is located on the Dutch-Belgium border before entering the Netherlands.

Figure 3: Study Area - Meuse Catchment (Baris & Veenenbos, 2018).

2.2. Climate change and the River Meuse

The World Weather Attribution (2021) indicates that the Meuse river is one of the rivers where evidence has already been found about changes in the maximum discharges that may be ascribed to climate change. A study was carried out by several scientists where the alterations in the probability and intensity of the heavy rainfalls of July 2021 were analyzed to determine if human-induced climate change had had an important role in this rare and extreme event (World Weather Attribution, 2021). The results of this study suggested that evidence was found for significant trends at the regional scale, showing that climate change increased both the probability and the intensity of the flood event (World Weather Attribution, 2021). More details of this flood disaster of July 2021 are explained in the next section.

It is estimated that future discharges of the Meuse river will continue to change, resulting in possibly higher and more frequent discharges (de Rooij, 2020). In the same way, the low discharge values will fall even more during the summer and autumn seasons, all of this due to the effects of climate change and human intervention (de Rooij, 2020).

2.3. The flood of July 2021 in the Meuse Basin

There was a heavy rainfall event that took place in the year 2021 (from 12 to 15 July 2021); where states from Germany were the most severely affected, followed by other regions in the countries of Belgium, Luxembourg, and The Netherlands (World Weather Attribution, 2021). This event has been classified as an extreme and unprecedented event because an event of such magnitude is expected to occur only once every 100 to 1000 years (van Ruiten, 2021). Furthermore, this extreme precipitation event occurred during the summer when high water levels in the Meuse river were not expected at all and that is why it is considered an exceptional extreme event (Boon & Kaspersma, n.d.); This extreme event broke its own record of highest discharges recorded for the third time (Boon & Kaspersma, n.d.), as can be seen in Figure 4, where the daily precipitation from 1950 until 2021 has been plotted for the border between Belgium and Germany (Copernicus Climate Change Service (C3S), n.d.).

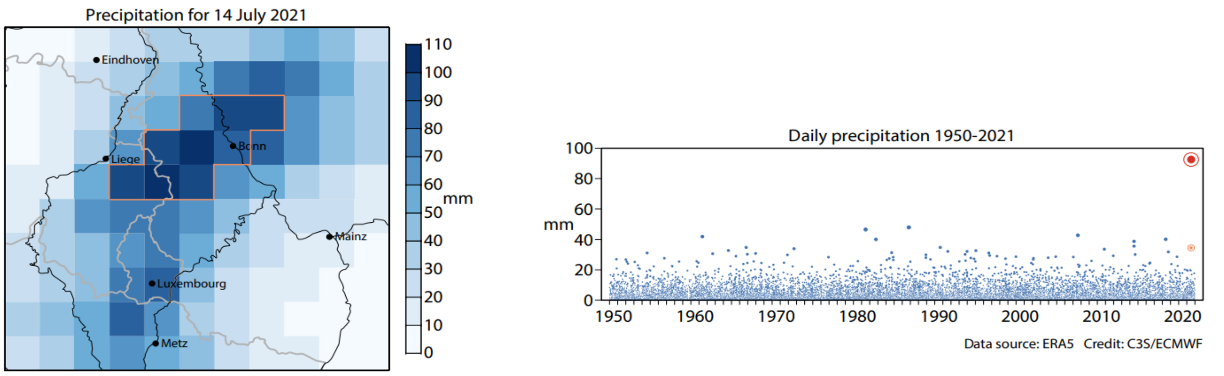


Figure 4: The left figure is shows the precipitation in the most affected countries, being the orange-bounded region the most affected. The figure on the right shows the daily average precipitation of the orange-bounded region. The orange and red circles on this right.

It was not only the water from the Meuse river that contributed to this event; other rivers like the Geul and Roer, which converge into the Meuse also had a significant increment in their discharges during July 2021 (Boon & Kaspersma, n.d.). For example, the Roer River registered a discharge of 300 m³/s, when normally it should just have a discharge of approximately 12 m³/s (Boon & Kaspersma, n.d.). Besides, Kreienkamp, et al. (n.d.) point out that other factors also contributed to this event like hydrological factors, pedological and topographical characteristics, and others characteristics such as different land uses, water management measures (dams and dikes), and level of development near the river.

The consequences of the extreme event of July 2021 were incredibly tragic. There were deaths in Germany and Belgium, damage to infrastructure, disruption of some livelihoods and local businesses, shortages, and cuts in the supply of water and electricity, and road closures that tremendously affected the evacuation measures and emergency responses (Kreienkamp, et al., n.d.). The economic loss was also tremendous, and raised a total of 350 to 600 million euros, more than previous flood events of the Meuse river in 1993 and 1995 (van Ruiten, 2021).

This extreme event of July 2021 has alarmed several universities and research institutions like the Delft University of Technology, HKV Line in Water, Deltares, and others (van Ruiten, 2021). They believe that this type of unusual extreme events could happen again in the foreseeable future, and depending on the location where these events occur, the impacts could be worse (Deltares, 2022). Therefore, experts from Deltares conducted a study to analyze how catastrophic the situation could be if an event of such magnitude and intensity occur in a location further northwest in the Netherlands. The results of such a study show that the floods would have lasted more than a week, causing the polder-drainage systems, secondary dikes, pumping stations, and dams to reach their limits, and the economic damage would have easily reached more than billions of euros (Deltares, 2022). In Figure 5, the actual rainfall event of July 2021 (left picture) considered for this study can be seen, as well as the simulated scenario (right picture) developed at Deltares to analyze the impacts in the Netherlands in case of experimenting with an extreme event like the one of July 2021.

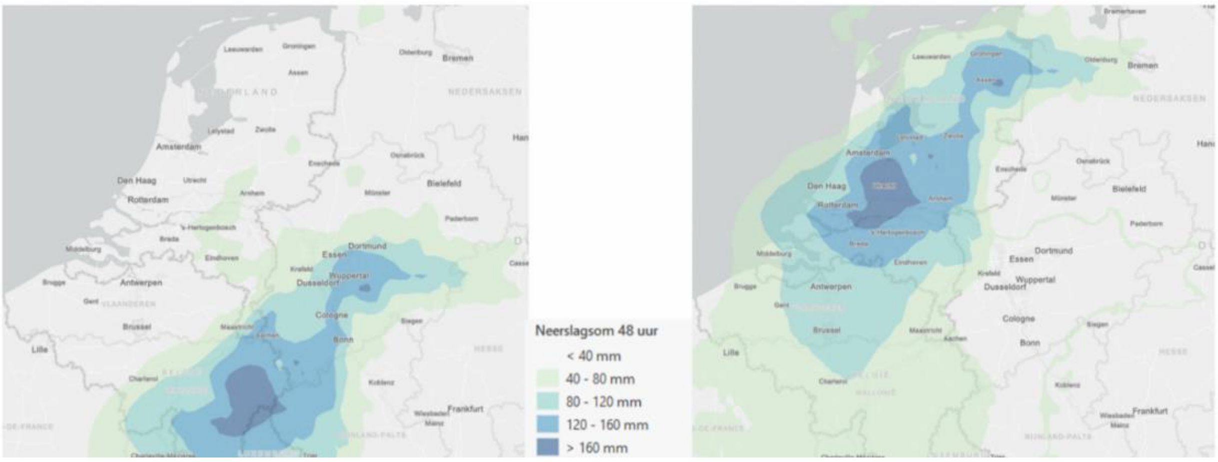


Figure 5: Left figure shows the flood event of July 2021, while the right figure corresponds to the simulation of a 48-hour precipitation event like the one of July 2021 in a different location in the Netherlands (Deltares, 2022).

Extreme events like this one point to the importance of investigating the possible presence of trends in the Meuse river and its tributaries. New approaches in the field of water management can be considered in the case of finding trends in the river discharges of the Meuse river or its tributaries. The adverse impacts caused by extreme events can also be avoided if water management authorities and decision-makers can anticipate and respond appropriately to these types of extreme events (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2015).

3. Theoretical framework

In this chapter, an introductory background will be provided regarding the topics that are important for the approach taken in this thesis project. First, a brief explanation of the ensemble forecasting system is given. Followed by a discussion about hydrological models and the reasons for using the wflow model. Finally, the available resources to analyze the wflow simulation results (three datasets of discharge extreme events) are explained.

3.1. What is the ensemble forecasting system and why may this be an alternative for observations?

In the past, weather forecasts used to be predicted by means of a deterministic system where a single prediction was based on the best guess set for the initial conditions and the best deterministic computational representation (Palmer, 2018). However, to create a more reliable prediction system, a new approach known as ECMWF Ensemble Prediction System was introduced, which is based on a probabilistic approach (Palmer, 2018). According to Dutton (2021), an ensemble forecast system is a set of different members, where each member represents a single weather forecast that has been produced from a unique set of initial conditions; and each ensemble member is a possible prediction of the behaviour of the climate at a specific moment. Figure 6 provides a graphical explanation of how ensemble forecast estimation looks like.

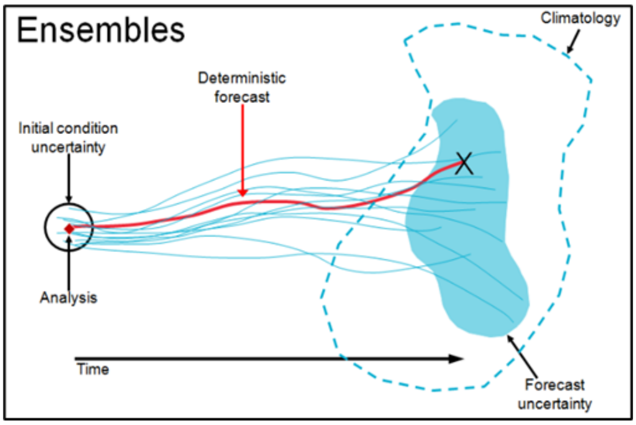


Figure 6: Graphical explanation of how ensemble forecasts are produced (Met Office, n.d.)

In Figure 6, it can be observed that the initial conditions (circle on the left) are slightly different among each ensemble member; but as time elapses each ensemble member disperses and follows a different path than the others members (Dutton, 2021). This results in the creation of "spaghetti plots", wich are common to see in weather ensemble forecasts (Department of Meteorology and Atmospheric Science, n.d.). These "spaghetti plots" expose the dispersion range of all possible ensemble members and could also provide information on the uncertainty of the forecast (Dutton, 2021).

The advantage of using ensemble data from the ECMWF forecasting prediction system is that a forecast derived from the average of all these ensemble members will be much more skillful when compared with a traditional and single forecast (Dutton, 2021). Furthermore, many possible outcomes can be explored and filtered according to specific criteria such as maximum or minimum values and extremes with low occurrence (te Booij, 2022). Additionally, using the ensemble forecasting system is a suitable method to investigate the extremes of weather-related variables, such as extreme precipitation events and river discharges, especially in cases where there is not enough relevant data for the analysis (van den Brink, et al., 2005).

3.2. What are hydrological models and why is the hydrological model wflow used here?

According to Devia, Ganasri, & Dwarakish (2015), hydrological models can be defined as the construction to represent a real-world system in a simplified version. They are applied within a wide range of expertise areas like planning of water resources, water management, flood forecasting, and the assessment of climate impact (Hasan & Elshamy, 2009). The hydrological model selected for this research is the wflow model developed at Deltares. This wflow model has been used in several places worldwide; because it can model various situations such as droughts, changes in land use, flood risks, and consequences of climate change (Deltares, n.d.).

There is already a wflow model for the Meuse river, which has been used for the analysis of the catchment area of the Meuse river. Hence, this wflow model of the Meuse river will be used to transform the ensemble forecast precipitation data provided by te Booij (2022) into forecasted simulated discharges for two scenarios: dry and wet. But before getting these simulated forecasted discharges, the wflow model will determine the initial conditions needed for the simulations, and it will also provide the historical simulated discharges from 1996 until 2015; for these the model will make use of E-OBS gridded data.

The wflow model of the Meuse river is already calibrated. However, it requires some specific types of data and they are:

- **Static Data:** contains a set of static maps describing the study area. For instance, the topography, land use, river maps, sub-catchment map, soil properties, and model parameters. A file named ***staticmaps_hydrodem_ksh.nc*** which contains this static data was provided by Deltares. This static date will not be changed during the 80 simulations, because the characteristics of the basin are the same for each simulation.
- **Dynamic Data:** contains information such as precipitation, temperature, and potential evapotranspiration for the study area. This information can be presented in different time formats: per day, per hour. This dynamic data should be changed depending on the situation:
    - For initial states calculation: the file named ***eobs_v24.0e_1980_2020.nc*** contains the E-OBS gridded data with continuous information about the precipitation, temperature, and potential evapotranspiration and other variables for each day since January 1st, 1980 until December 31st, 2020 for the whole Meuse catchment (the French, Dutch and Belgian part).
    - For simulations: the inmaps obtained from the ECMWF forecasted precipitation events should be used instead of the file used to calculate the initial states.

All this data is processed by a setting toml text file named ***wflow_sbm_eobs.toml,*** which is responsible for all the configurations in the model. With this information, the wflow model should be able to calculate the hydrological fluxes (like interception, evaporation, snow accumulation, melt, discharges, and others) of a specific point within the area of interest and at a given moment in time (Deltares, n.d.).

3.3. What are the means to analyze the wflow results

Three types of datasets can be extracted from the wflow model. The first dataset of discharge extremes contains the historical discharge values. In other words, the daily maximum discharge values from January 1st, 1995, until December 31st, 2015. These historical discharges are calculated together with the initial state conditions for the wflow simulations. Only the most extreme historical discharge value per year is filtered from these historical results. The second and third datasets of discharge extremes correspond to the forecasted simulation results (40 runs for the dry and 40 for the wet scenario) when the extreme precipitation events are used as the main input for the wflow model. From these resulting forecasted dry and forecasted wet datasets, just the first highest extreme discharge values per year are selected. Therefore, for the comparison and statistical analysis, there are three datasets of extreme discharge values for each gauge station and they were named as follows:

- Historical simulated maximum annual discharges
- First highest maximum annual discharges with the dry initial states (forecasted dataset)
- First highest maximum annual discharges with the wet initial states (forecasted dataset)

A more detailed explanation of how these three datasets of discharge extremes are obtained can be found in Section 4. In the following paragraphs the available resources for the comparison and trend analysis are explained.

3.3.1. Comparison of historical discharge values vs forecasted discharge values

The first thing that can be done with these datasets is a graphical comparison. First, the *historical simulated maximum annual discharges* versus the *first highest maximum annual discharges with the dry initial states*. Then, the *historical simulated maximum annual discharges* will be compared again, but this time against the *first highest maximum annual discharges with the wet initial states*. These graphical comparisons are made to see how big the difference is between the values predicted by means of the forecasted data (extreme precipitation events) when compared with the historical simulated values. If the difference is not significantly large, then the three datasets of discharge extremes can be used for trend analysis.

3.3.2. Autocorrelation test

Another test that is necessary to apply to these three datasets of discharge extremes before performing the trend analysis is the autocorrelation test. This test seeks to identify if the discharge values for each of these datasets are not autocorrelated with each other. In other words, analyze if each discharge value of these three lists does not depend on the previous values. If the independence in the data (in this case the three datasets) cannot be demonstrated, the trend analysis results may not be reliable because common trend analysis methods may not be most appropriate for the analysis (Villarini, et al., 2011).

Autocorrelated data is usually found on daily values (like daily discharge extreme values). But that is not the case in this research because only the highest extreme discharge values per year are being taken into account. However, just to verify that there are no autocorrelated values, this autocorrelation test will be applied to each of the three datasets of extreme discharges. For this, the function *autocorr* from Matlab will be used.

3.3.3. Best-fit line (linear trend line)

Now that the three data sets have been tested to demonstrate that they are not autocorrelated, the analysis of the river discharges can start to investigate the existence of any trend on the extreme flows. A graphical analysis of each of the three datasets of discharge extremes seems to be a good start before applying numerical analysis (Meals, et al., 2011). Hence, all the extreme discharge values of the three datasets should be plotted individually, and then the best-fit line that goes through these extreme discharge values can be drawn. This line should be plotted in such a way that the extreme discharge values are as close as possible to this line. For this, the command *fit* from Matlab can be used. This command will estimate the best-fit line of the discharges, and it can also provide the coefficients with a 95% of confidence for the linear equation of this trend line.

3.3.4. Standard statistical trend tests to show the significance of a possible trend

The previous graphs showing the best-fit line for the datasets are a necessary tool to get a first impression of the possible trends in the extreme discharges. However, more than this visualization of trends is needed to determine the veracity of an existing or non-existing trend in the extreme discharges; because simple visualization has some limitations (Meals, et al., 2011). Hence, a more rigorous analysis is required before it can be affirmed or denied that such trends exist in the extreme discharges of the Meuse river and its tributaries. According to Diermanse, et al. (2010), applying some standard statistical tests can help to identify a trend in the discharge values.

For this research, a null hypothesis (H_o) and an alternative hypothesis (H_1) have been defined as follows:

> ***H_o: There is no trend in the extreme discharges derived from extreme precipitation events that were obtained through the ensemble forecast system.***
>
> ***H_1: There is a trend in the extreme discharges derived from extreme precipitation events.***

The two hypotheses complement each other, meaning that if one is accepted, the other hypothesis should be rejected (Dåsvand, 2022). Two types of tests can be applied to determine if the Null hypothesis is rejected: one-sided test and two-sided test. For the one-sided test there is a directional hypothesis trend, because here the idea is to reject the null hypothesis by means of evidence in a specific direction (Diermanse, et al., 2010). Hence, for this one-sided test, it is important to determine whether a positive or negative trend is searched in the data. The two-sided test on the contrary, is a non-directional test where the direction of departures from the null hypothesis is unimportant or can not be determined (Booij D. , 2017). Since it is unclear what type of trend (positive or negative) could be present in the datasets of discharge extremes, it has been decided to perform a two-tailed test.

The p-value is the probability value and will be used to determine if the Null hypothesis can be rejected or not (Diermanse, et al., 2010). This p-value is a value between 0 and 1; but by itself it is not enough to reject the Null hypothesis because it needs to be compared with an α-value known as significance level (Dåsvand, 2022). Statistical significance is usually accepted for a p-value of 5%, meaning that any statistical test result below 5% will reject the null hypothesis with a confidence of more than 95% (Diermanse, et al., 2010). Other common α-values are 0.10 and 0.01 (Dåsvand, 2022). For this research, the p-values will be tested against the following significance levels: $\alpha = 0.01$, $\alpha = 0.05$, $\alpha = 0.10$, $\alpha = 0.25$.

Both parametric and non-parametric statistical tests can be applied to detect significant trends over a period of time in hydrological series (Önöz & Bayazit, 2002). In the following paragraphs, the statistical tests selected for this investigation are explained in more detail.

Pearson t-test (linear trend test)

This is a parametric test where it is assumed that Pearson's correlation coefficient "r" fits a Student's t distribution (Diermanse, et al., 2010). This Pearson correlation-coefficient r also known as the linear correlation coefficient and the p-value are calculated using the following Matlab function:

```
[RHO,p_value] = corr(variable1, variable2, 'Type','Pearson');
```

This function asks as input two different variables and it also asks to define the type of statistical test. The discharge values (y) are assigned to the first variable "variable1" and the years (x) starting from 1996 until 2015 are assigned to the second variable "variable2". Then, this Matlab function will take these inputs and it will deliver the rho coefficient and the p-value. The formula behind this function to calculate the rho coefficient is displayed bellow.

Equation 1: Pearson correlation-coefficient "rho"

$$rho(a,b) = \frac{\sum_{i=1}^{n}\left(X_{a,i} - \overline{X_a}\right)\left(Y_{b,i} - \overline{Y_b}\right)}{\left\{\sum_{i=1}^{n}(X_{a,i} - \overline{X_a})^2 \ \sum_{j=1}^{n}\left(Y_{b,i} - \overline{Y_b}\right)^2\right\}^{1/2}}$$

Where:

n: number of elements or discharge values
$\overline{X_a}$ and $\overline{Y_b}$: are the means of x and y

According to Neideen & Brasel (2007) and Helsel, et al. (2020), a positive slope means that r equals 1 and the variables are positively and completely correlated; but if the value of r is zero, it can be inferred that there is no correlation and the variables are completely random; and finally in the case of having a negative slope, it means that r equals -1 and the variables are completely and negatively correlated.

Spearman's rank correlation test

In this non-parametric test, which is analogous to the Pearson t-test; the correlation between the two variables (extreme discharges and years) will be determined using the Spearman rank correlation coefficient (Ahmad, et al., 2015). It is not necessary to assume some sort of distribution to determine the sampling distribution because ranges are being used instead of absolute values (Diermanse, et al., 2010). According to Ahmad, et al. (2015) one important requirement for this test is that the data should be independent and identically distributed. The Matlab function used to calculate both the Spearman rank correlation coefficient and the p-value for this statistical test is kind of similar to the function used before for the Pearson correlation coefficient. The only difference is that the type of test should be changed from "Pearson" to "Sperman" as shown below:

```
[RHO, p_value] = corr(variable1, variable2, 'Type','Spearman');
```

For this statistical test the spearman rank correlation coefficient is calculated using the following formula:

Equation 2: Spearman rank correlation coefficient

$$rho(a,b) = 1 - \frac{6\sum d^2}{n(n^2-1)}$$

Where:

d: the resulting difference from the rank value of the first variable minus the rank value of the second variable

n: the number of discharges or years

Here again the output of this Matlab function is the rho value (Spearman rank coefficient) and the p-value, which by default has been calculated for a two-tailed test.

Mann-Kendall test

This non-parametric test is commonly used for trend evaluation in hydro-meteorological time series (Xiong, et al., 2013). Since the statistic is based on the sign of differences instead of considering the actual values of the random variable, it is expected that this test would not be affected by unusual values also called outliers (Önöz & Bayazit, 2002). This test basically evaluates two variables x (years) and y (discharge values), to determine if the y values tend to increase or decrease with respect to the variable x, which is the time as explained by Booij D. (2017). According to Booij D. (2017) and Juahir, et al. (2010) the Mann-Kendall statistic "S" is the result obtained from the positive differences (number of pairs where y increases as x increases) minus the negative differences (number of pairs where y decreases as x increases). There is a function available in Matlab to perform this statistical test and it is displayed bellow:

```
function[p_value]=Mann_Kendall_ORIGINAL(V,alpha)
```

The input for this function is a vector V containing the discharge values and the significance level α. As output this function returns the p-value which will be compared with different significance levels. The equations behind this function have been taken from the documentation provided by this Matlab function and are displayed below:

Equation 3: Mann-Kendall Statistics "S"

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sig(X_j - X_i)$$

Equation 4: The sign for equation 5.

$$sig\left(X_j - X_i\right) = \begin{cases} +1 & if\ (X_j - X_i) > 0 \\ 0 & if\ (X_j - X_i) = 0 \\ -1 & if\ (X_j - X_i) < 0 \end{cases}$$

Equation 5: Variance "VAR(S)" without considering ties

$$VAR(S) = \frac{1}{18}[n(n-1)(2n+5)\,]$$

Equation 6: standardized test statistics "Z"

$$Z = \begin{cases} if\ S \geq 0 & \dfrac{S-1}{\sqrt{VAR(S)}} * (S\sim = 0) \\ if\ S < 0 & \dfrac{S+1}{\sqrt{VAR(S)}} \end{cases}$$

Where:

X_i and X_j are the discharge values in chronological order

"n" value is the number of observations

It is important to mention that ties are not considered by this Matlab function. This means that it is assumed there are no repeated values among the discharge values. The results can be analyzed in the following way: for a positive Z, it can be said there is a positive trend and vice versa (Ali, et al., 2019). This Z-value is used to calculate the p-value.

Wilcoxon-Mann-Whitney test

It is a non-parametric test, sometimes referred as the Wilcoxon ranks sum test or the Mann-Whitney U test; where the principle is to split the data sets into two independent samples (Diermanse, et al., 2010). The test is aimed to determine for a certain level of significance if there is a significant difference between the two split groups (Helsel, et al., 2020). A possible approach to apply this test could be to divide the 20-year data into quinquennial periods to compare the pairs of two consecutive periods, as explained by Mozetič, et al. (2009). By doing this it would be easy to detect when abrupt changes occur.

However, since the period analyzed for this thesis research is just 20 years; it would be more convenient to just split the data into a first and second half (Booij D. , 2017). This results on having two groups of data: the first one is Group A with a sample size length of “n” and the second one is B with a sample size length of “m” (Booij D. , 2017). There is also a Matlab function that can be used to apply this statistical test and is formulated as follows:

```
[p_value]= ranksum(GroupA,GroupB,'tail','both','method','exact');
```

The input variables for this function are the two groups containing the discharge values (Group A and Group B). Then, the type of test should be specified because this function can perform a two-sided test but also the one-sided test. Then, the words `'tail','both'` should be specified, so the program knows that a two-tailed test should be executed. The last two words in the code `'method'`,`'exact'`, are asking the code to calculate the p-value as precise as possible.

4. Approach

In this section, the steps to achieve the research objective and answer the research questions are explained in detail. This approach section is divided into 5 sub-sections which are as follows:

4.1. Method outline

A workflow has been created (See Figure 7) to explain the steps that will be followed to perform the comparison of historical vs forecasted extremes discharge values and the trend analysis.

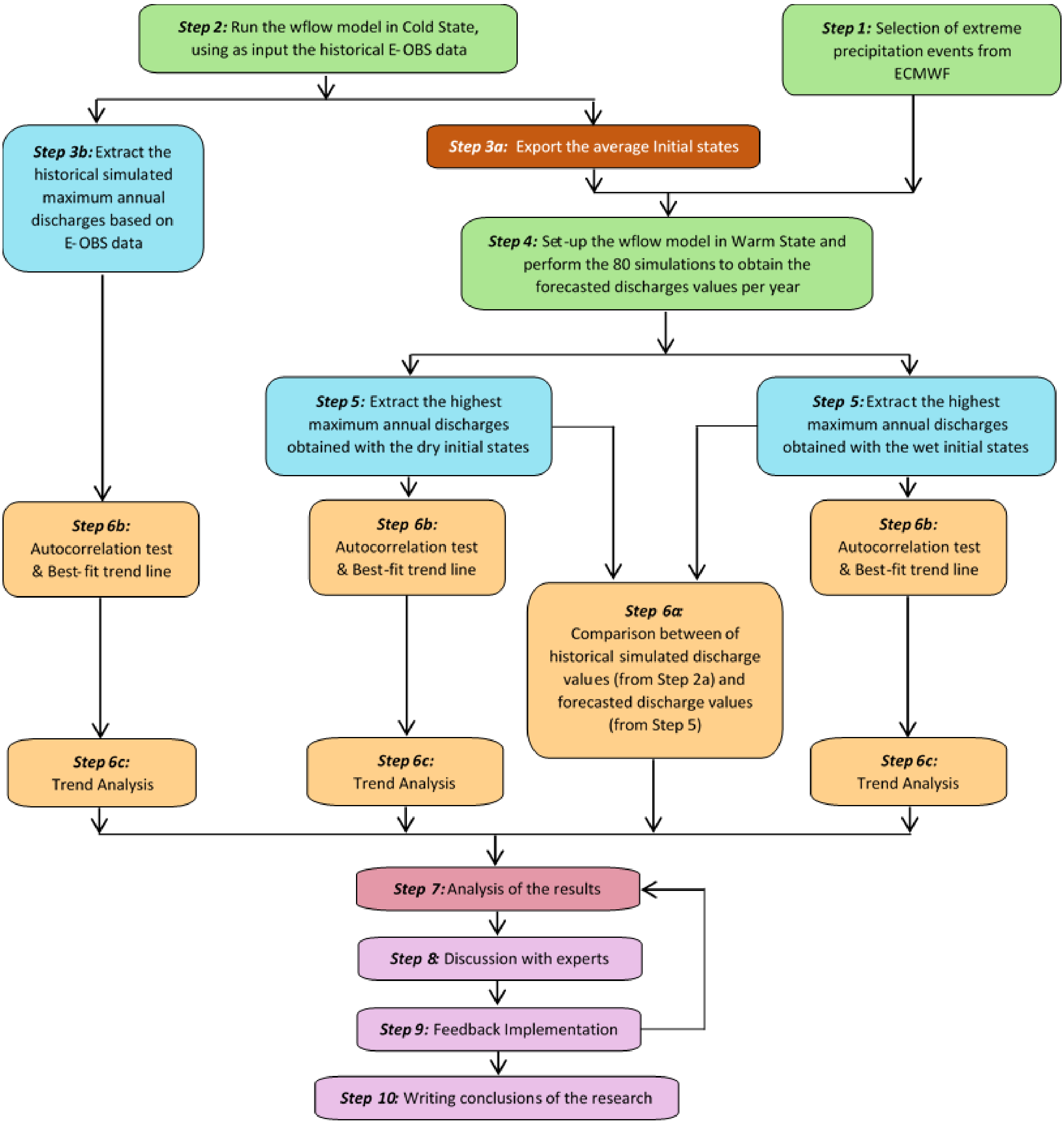


Figure 7: Workflow diagram for this thesis research.

4.2. Determining the Initial States for the 80 experiments (Steps 2 & 3a)

The first step shown in Figure 7, consists on the selection process of the extreme precipitation events that will serve as input during the wflow simulations. This step has already been explained in Section 1.2. Now, it is time to determine the initial states that will be used for the wflow model during the 80 simulations.

Soil moisture excess is the main flood-generating mechanism in European rivers (Berghuijs, et al., 2019). An excellent example of this fact is the flood in the Meuse river that took place in July 2021. Because according to (Kreienkamp, et al., n.d.) the heavy rainfall event was not the only cause of the flooding. It was discovered that the soils in some regions of the Meuse basin almost reached saturation limits due to the intense and long-lasting rains registered three weeks before the extreme precipitation event occurred (Kreienkamp, et al., n.d.). Then, after considering this soil moisture excess condition, two possible scenarios have been defined to perform the simulations: wet and dry. For these two scenarios (dry & wet), the initial states should be defined.

The ideal and more realistic way to determine these initial states would be to find the average initial conditions of the day in which each ensemble forecast was produced. For instance, if the ensemble forecast of one extreme precipitation event starts on July 1st, the average initial conditions should be taken from the wflow model on that specific day (July 1st). However, this approach would take too much time. Therefore, other options to determine these initial states have been considered, and these are:

Option 1: Assuming values:

For instance, for wet scenario an 80% of full groundwater storage capacity and soil moisture conditions can be assumed and for the dry scenario just the 20%.

Option 2: Referring to previous trend analysis

Literature from other authors can be searched where trend analysis similar to the one intended for the Meuse river has been carried out. Those papers may contain information about what initial conditions can be assumed for the Meuse river.

Option 3: Using averages per seasons

For this, the wflow model is run in cold state. In this way, the default values are used without considering initial states. The dynamic input in this case is E-OBS gridded data starting on 01-01-1980 until 31-12-2020, a total of 40 years. But the period for this research is just 20 years (from 01-01-1996 until 31-12-2015); which is the period for which the forecasted precipitation data is available. So, the wflow model can be run for these two periods (40 and 20 years). Then the results can be compared to decide which initial states are the most appropriate.

Before the simulation to calculate the initial states starts, the *start and end dates* for each period of time (20 and 40 years) should be adjusted in the wflow model. The *Timestepsec* variable should be set to 86400 seconds because the results should be obtained on a daily basis. The variable *reinit* should be set to "true". After applying these configurations, the wflow model is run, and the outcomes are classified per season (winter for the wet scenario and summer for the dry scenario), and the averages are calculated as follows:

- <u>For wet scenario:</u> the results obtained for December, January and February are used to calculate the averages of each variable that make up the initial conditions and these averages will be the final initial states for the wet simulations.
- <u>For dry scenario:</u> the results obtained for June, July, and August are used to calculate the averages of each variable that make up the initial conditions and these will be the final initial states for the wet simulations.

The chosen approach for the calculation of the initial states is Option 3. This method is a bit more realistic than the others, because during winter higher soil moisture content is expected. On the other side, during summer, the soil moisture content is expected be low. The outcomes delivered by the wflow model should be four nc files containing the final initial states: ***DRY_instate_20yrs.nc*** and ***WET_instate_20yrs.nc*** for the initial states of the 20-year period; and ***DRY_instate_40yrs.nc*** and ***WET_instate_40yrs.nc*** for the initial states of the 40-year period. A comparison between the resulting nc files for the 20-year period and the resulting nc files for the 40-year period can be found Appendix B. Here, the decision to choose the ***DRY_instate_20yrs.nc*** and ***WET_instate_20yrs.nc*** as the final initial states for the 80 simulations is explained in more detail.

4.3. Extracting the historical simulated maximum annual discharge values (Step 3b)

When the initial states are being calculated using the wflow model in cold state; the historical simulated maximum annual discharges for the 20 years from 1996 until 2015 can also be obtained for each gauge station of the Meuse basin. A gauge station is a point in the river where there is a measuring station, from which the discharge values can be retrieved. The gauge stations of the Meuse catchment are shown in Figure 8 (red triangles).

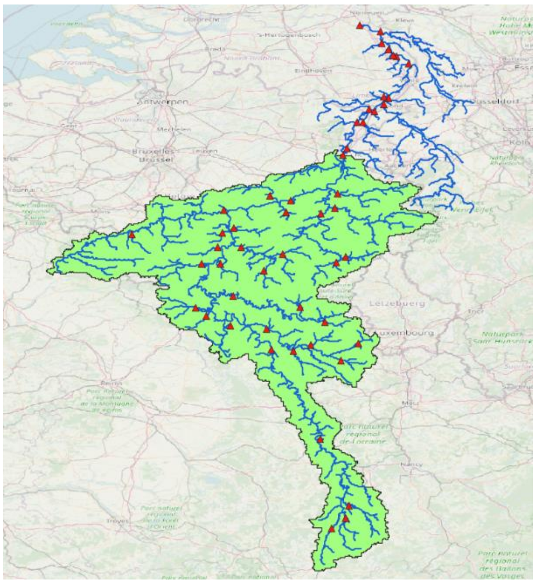


Figure 8: Meuse catchment (green area) where the river network (blue lines) and the gauge stations (red small triangles) can be observed.

Figure 9: Borgharen Gauge station retrieved from QGIS model.

At the Beginning the investigation will be focused on the Gauge station named Borgharen (see Figure 9). However, other gauge stations (which represents the tributaries of the Meuse river) have also been selected to perform the same trend analysis and comparison between historical and forecasted extreme discharge values. The list with the names of all the gauge stations that are being investigated in this report can be found in Table 1.

Table 1: List with the names and IDs of the gauge stations.

	Name of the gauge station	ID
1	Borgharen	16
2	Chooz	6221102
3	Chaudfontaine	6221200
4	Moligne at Warnant	703
5	Hermeton at Hastiere	701
6	Ourthe at Tabreux	10
7	Sambre at Salzinnes	9
8	Meuse at Saint-Mihiel	101
9	Semois at Membre Pont	5
10	Lesse at Gendron	801
11	Chiers at Carignan	201
12	Bar at Cheveuges	41

4.4. Performing the 80 Experiments using the wflow model and selecting the highest forecasted discharge values per year (Steps 4 & 5)

Once the initial state conditions have been determined for both scenarios (wet and dry), simulations can start to determine the modelled forecasted discharges for each of the 40 events. The wflow model should be run again, after applying the following changes:

- **Initial states:** First and most importantly, the wflow model is now programmed to run in warm state. For this, the already calculated initial states (one for the dry instate conditions and one for the wet instate conditions) should be read by the model during these 80 simulations.
- **The dynamic data:** instead of using the E-OBS gridded historical data that was used for the calculation of the initial states, the two most extreme 5-day precipitation events provided by te Booij (2022) will be entered into the wflow model. For each of the 5-day precipitation events one inmap has been created, which are going to be read by the wflow model during the 80 simulations.
- **start time and end time for simulation:** It is not necessary to adjust these variables in the wflow model, because each of the inmaps has been configured with the specific start and end dates for each event simulation.
- **Timestepsecs:** for the 80 simulations this should be set to 21600 seconds. which equals 6 hours. This is because the extreme precipitation events are set to a 6-hour format.
- **reinit:** this variable should be set to "false" for simulations

Some predefined parameters and the static data do no need to be changed. Then, after applying these changes, the wflow model can be run again. Once the simulations are finished, 80 folders containing the results are created, 40 for the dry scenario and 40 for the wet scenario. These folders contain the extreme discharge values in a 6-hour basis for the 15 days duration of each event. However, for the comparison of historical simulated and forecasted simulated discharge extremes as well as for the statistical analysis, these forecasted extreme discharge results have been converted from a 6-hour basis to a daily basis. In Table 2, the results of this conversion from a 6-hour basis to a daily basis are shown. These discharge values shown in Table 2, correspond to the two extreme events of the year 1996 in Borgharen, and they are the result of the simulation with the Dry Initial conditions.

Table 2: Two Dry events for the year 1996 at Borgahren.

DRY 25	
time	Q_16
'27-Jun-1996 00'	131,185927
'28-Jun-1996 00'	127,702001
'29-Jun-1996 00'	125,400666
'30-Jun-1996 00'	119,046309
'01-Jul-1996 00'	112,586138
'02-Jul-1996 00'	105,110411
'03-Jul-1996 00'	99,1194781
'04-Jul-1996 00'	108,466804
'05-Jul-1996 00'	127,481684
'06-Jul-1996 00'	129,232716
'07-Jul-1996 00'	124,549453
'08-Jul-1996 00'	145,603851
'09-Jul-1996 00'	145,843849
'10-Jul-1996 00'	134,91741
'11-Jul-1996 00'	130,257655
MAXIMUM	**145,84**

DRY 18	
time	Q_16
'24-Nov-1996 00'	131,588513
'25-Nov-1996 00'	132,773757
'26-Nov-1996 00'	130,547798
'27-Nov-1996 00'	126,935092
'28-Nov-1996 00'	123,168378
'29-Nov-1996 00'	126,4814
'30-Nov-1996 00'	128,152621
'01-Dec-1996 00'	138,474382
'02-Dec-1996 00'	151,237722
'03-Dec-1996 00'	174,427407
'04-Dec-1996 00'	191,527731
'05-Dec-1996 00'	203,596451
'06-Dec-1996 00'	205,280991
'07-Dec-1996 00'	190,945005
'08-Dec-1996 00'	178,524626
MAXIMUM	**205,28**

Each of the 80 events resulting from the simulations with Dry and Wet Initial conditions ended up like the lists shown in Table 2. Then, the next step was to extract the maximum discharge value from each list of 15 daily discharges, as shown in Table 2. This resulted in a total of 40 maximum discharges for the dry scenario and 40 maximum discharges for the wet scenario, because there were two extreme events per year. For instance, in Table 2, the two maximum forecasted discharge values for the year 1996 resulting from the simulation with Dry Initial States are 145.84 and 205.28 m^3/s per day. Since a single value per year was needed for the statistical analysis, only the first highest maximum discharge value was extracted for each year. In this case, the first highest value is 205.28 m^3/s per day, corresponding to the year 1996 for a Dry Scenario at Borgharen. The same selection process of the first highest maximum annual discharge values per year has been applied to the forecasted discharge values resulting from the simulation with the Dry and Wet Initial Conditions. This process of selecting the first highest maximum annual discharge values has been applied to all the 12 Gauge stations mentioned before in Table 1.

It is important to mention that during the selection process of the forecasted highest maximum annual discharge values, it was noticed that sometimes the maximum discharge value of the 15-day list was an acceptable value. An example of an event with an acceptable maximum discharge value can be found in Figure 10a, where the maximum discharge value is the outermost point of the graph with a discharge value of Q= 146.09 m^3/s per day. However, for some events, the maximum discharge value was not clearly defined, and those situations are explained hereafter:

- *Figure 10b:* There is no noticeable peak discharge in the figure. it is not known if there will be a maximum discharge value after 15 days or if there was a maximum discharge value before the beginning of the event. In this case, the maximum discharge value corresponds to the initial condition, Q= 275.64 m^3/s per day. But this value is not the most appropriate for statistical analysis because it is not a real peak
- *Figure 10c:* In this case, the maximum discharge value of the 15 days corresponds to the initial condition (Q= 275.64 m^3/s per day). However, the real peak discharge value that should be used is the discharge corresponding to the 13th day, which has a value of Q= 261.23 m^3/s per day.

- *Figure 10d:* Here even though there is a maximum peak, it is not very clear if this maximum peak discharge is valid because it is almost at the end of the 15-day period. It is not known if a maximum peak discharge could be found in the following days.

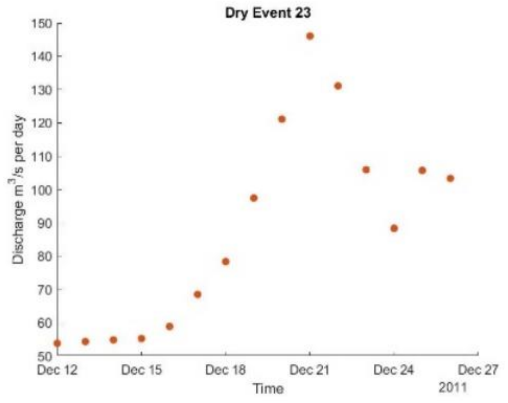


Figure 10a: Dry event at Chooz

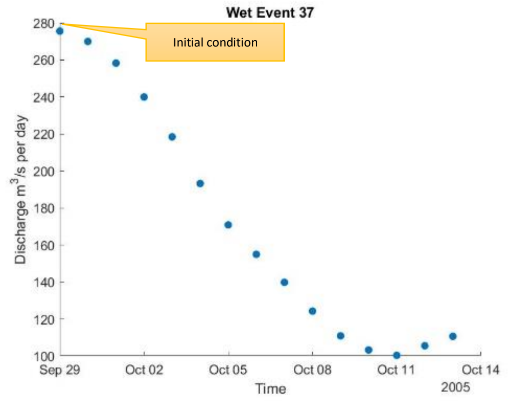


Figure 10b: Wet event at Chooz

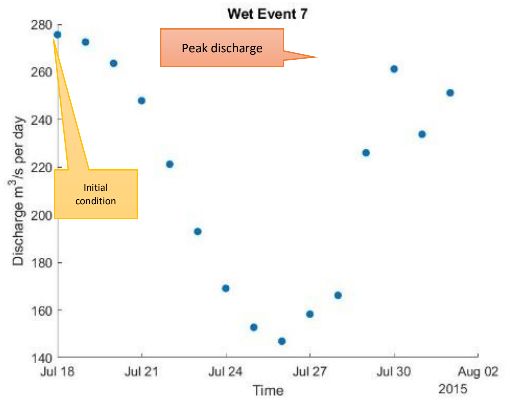


Figure 10c: Wet event at Chooz

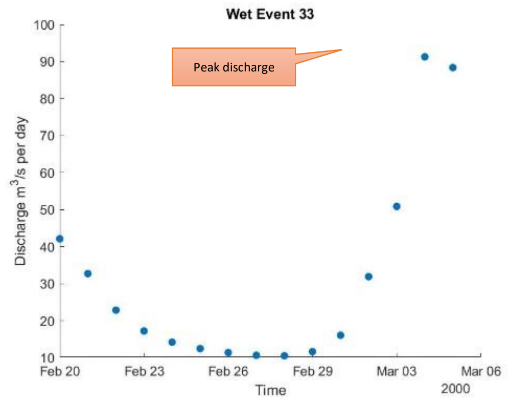


Figure 10d: Wet event at Ourthe

Figure 10: Different possible simulation outcomes.

4.5. Performing the comparison (Step 6a), autocorrelation test (Step 6b), finding the best-fit trend line (Step 6b), and trend analysis for the extreme discharges (Step 6c)

The theory explained in Section 3.3 (means to analyze the wflow results) will be applied here. For that, a Matlab script has been created where the three different data sets of extreme discharges of each gauge station will be analyzed. This code produces the graphs needed to compare the historical versus forecasted discharge extremes. It also performs the autocorrelation test and shows the best trend line for the datasets of discharge extremes. Finally, the code performs the statistical analysis, for which the p-values of each statistical test are calculated. This Matlab code can be found in the Appendix E.

5. Results

In this section, the results achieved in the comparison of historical versus forecasted extreme discharge values are analyzed. Followed by the explanation of the results obtained with the autocorrelation test and best-fit line. Finally, the results for the trend analysis on the extreme discharge values are also described. Due to the lack of space, only the results and graphs obtained Borgharen will be displayed in this section. The remaining graphs for the other gauge stations can be found in the Appendix C.

5.1. Results of the comparison of historical versus forecasted extreme discharge values

The first thing to do with the resulting annual extreme discharges from the wflow model is a comparison between the historical simulated and forecasted simulated extreme values. This with the aim to check if the difference between them is small. In that case these extreme discharge values can be appropriate for further statistical analysis. This comparison was be done by plotting the forecasted annual extreme events together with the historical annual extreme events for each gauge station. In Figure 11 and Figure 12, the comparison between historical and forecasted extremes discharges for the gauge station *Borgharen* are displayed.

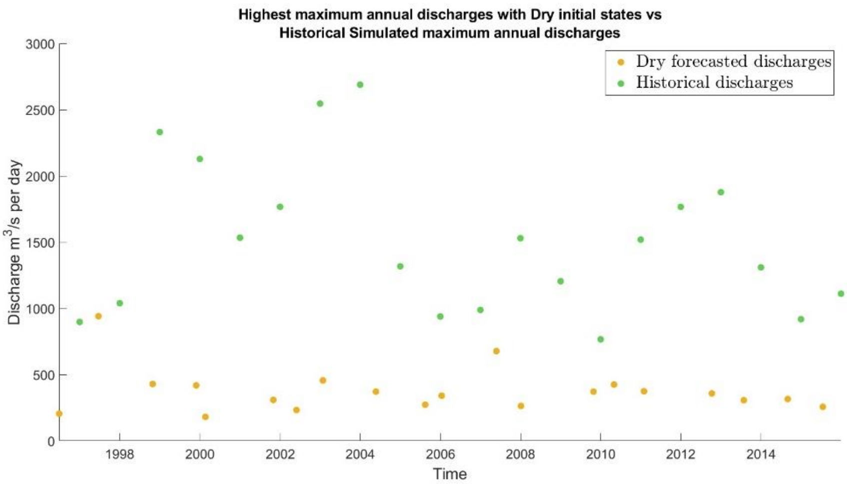


Figure 11: Comparison of historical simulated maximum annual discharges vs highest maximum annual discharge with dry initial states.

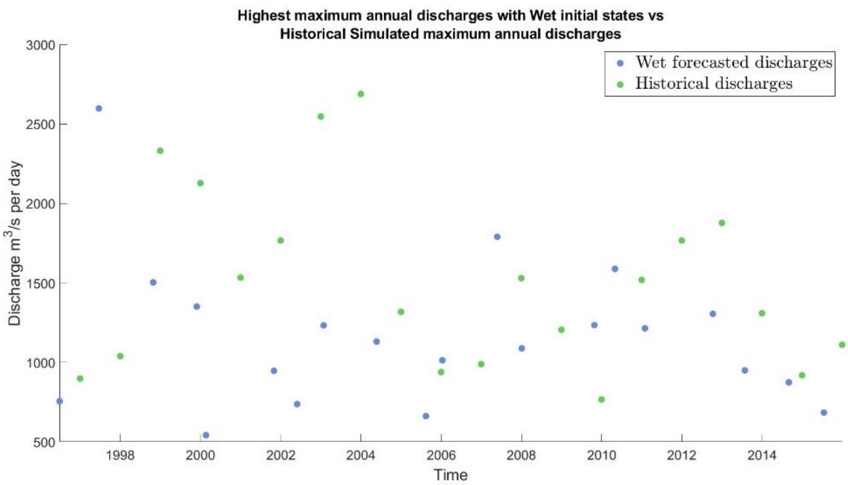


Figure 12: Comparison of historical simulated maximum annual discharges vs highest maximum annual discharge with wet initial states.

Figure 11 shows the comparison results between the *historical simulated maximum annual discharges* and *the highest maximum annual discharges with the <u>dry initial states</u>*. There is a considerable difference between the dry forecasted and historical data in mostly all discharge values. Figure 12, on the other hand, compares the *historical simulated maximum annual discharges* and *the highest maximum annual discharges with the <u>wet initial states</u>*. In this case, the results are different because the forecasted discharge values are similar to the historical values.

The resulting graphs of the comparison between historical simulated discharges and forecasted simulated discharges for the remaining gauge stations can be found Appendix C. For the dry scenario, in the majority of the gauge stations, the *highest maximum annual discharges with the <u>dry initial states</u>* were far away from *historical simulated maximum annual discharge values*. In contrast, for the wet scenario results, the *highest maximum annual discharges with the <u>wet initial states</u>* in most cases were quite similar and close to the *historical simulated maximum annual discharges*. Therefore, it could be said that the extreme discharges obtained through the simulations with dry initial states are not very reliable. This could be due to several reasons, such as the initial conditions of the dry scenario and other reasons that are explained in the conclusions section.

5.2. Results of the autocorrelation test applied to the historical dataset and forecasted data sets of extreme discharges

In this section the autocorrelation results for the extreme discharge values of Borgharen are displayed. It is important to remember that there were three data sets of discharge extremes for each gauge station and they are named as follows:

1. historical simulated maximum annual discharges
2. highest maximum annual discharges obtained with the dry initial states (forecasted dataset)
3. highest maximum annual discharges obtained with the wet initial states (Forecasted dataset)

Then, the autocorrelation test was applied on each of these datasets and the results are displayed in Figure 13.

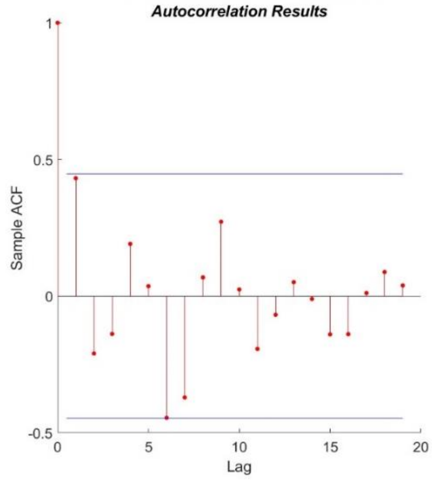


Figure 13a: *autocorrelation results for historical simulated maximum annual discharges*

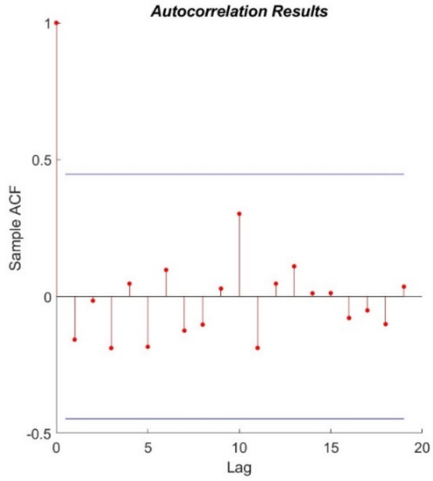


Figure 13b: *autocorrelation results for the highest maximum annual discharges obtained with the dry initial states*

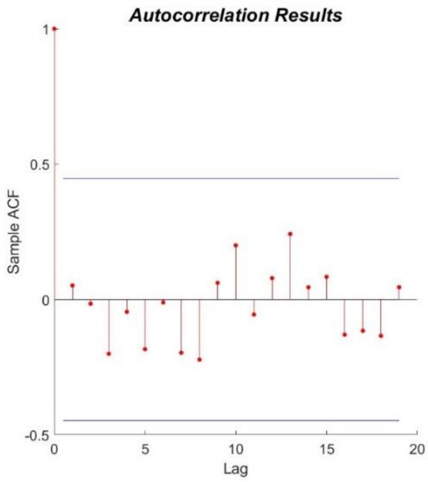


Figure 13c: *autocorrelation results for the highest maximum annual discharges obtained with the wet initial states*

Figure 13: Autocorrelation results for the extreme discharges at Borgharen. In the x-axis, the lags considered for this autocorrelation can be found. In the y-axis, the autocorrelation coefficients for each corresponding lag are displayed.

In these graphs, it can be seen that the ACF value for lag zero is the highest value in the three figures. This is because for lag zero the data is compared to itself. Then, it makes sense that the ACF value is one. Meaning that the data is autocorrelated to itself. The autocorrelation coefficients for lag 1, lag 2, lag 3, and so on are also displayed in the graphs and those are lower than one. Those autocorrelation results are more realistic than the result for lag zero and can be either positive or negative. The blue lines in the graph are the 95.4 % confidence bounds. These two blue lines form a critical range in this plot. Because when the ACF coefficients exceed these any of these two boundary lines, there is a strong autocorrelation in the data. For the datasets of discharge extremes at Borgharen, it can be said that the extreme discharges are not autocorrelated.

The results of the autocorrelation test for the three datasets of extreme discharges for the remaining gauge stations can be found in Appendix C. Based on all these autocorrelation graphs, it can be said that the three datasets of extreme discharges of each gauge station from the Meuse river and its tributaries are not autocorrelated. There were very few cases where the ACF coefficients were too close to the confidence bound, but they did not cross the boundary lines. Therefore, it can be affirmed that the extreme discharge values of each dataset are independent and can be used for statistical analysis.

5.3. Results for the best-fit lines of the historical dataset and forecasted data sets of extreme discharges

In Figure 14 the resulting trend lines for the three datasets of extreme discharges at Borgharen are displayed. The upper left figure (Figure 14a) shows the trend line of the historical simulated maximum annual discharges at Borgharen over 20 years. The upper right (Figure 14b) figure indicates the trend line for the highest maximum annual discharges obtained with the dry initial states. Figure 14c shows the trend line for the highest maximum annual discharges obtained with the wet initial states. Based on these graphs, it can be said that the three trend lines indicate a descending trend on the maximum extreme discharges at Borgharen from 1996 until 2015.

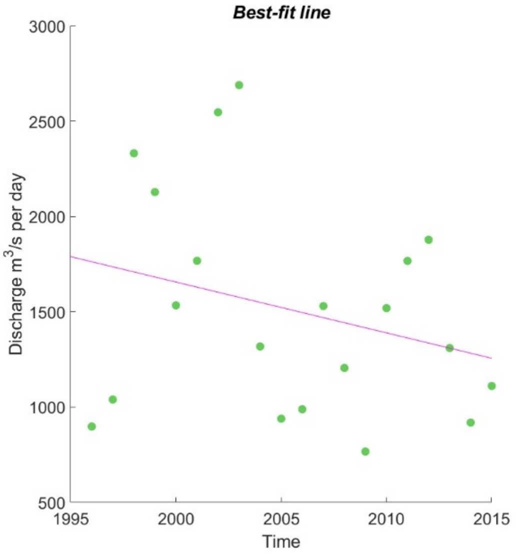


Figure 14a: *best-fit line for historical simulated maximum annual discharges*

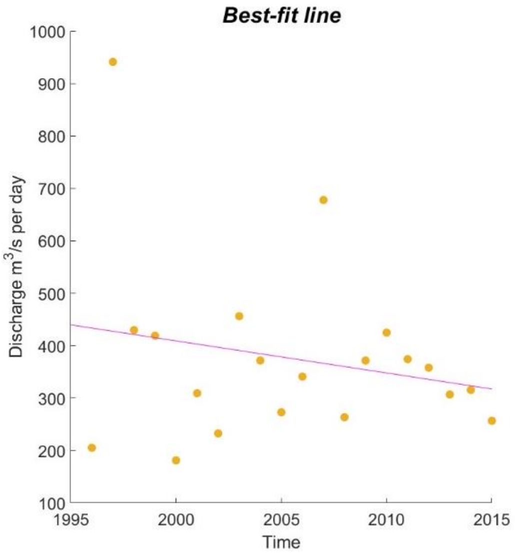


Figure 14b: *best-fit line for the highest maximum annual discharges obtained with the dry initial states*

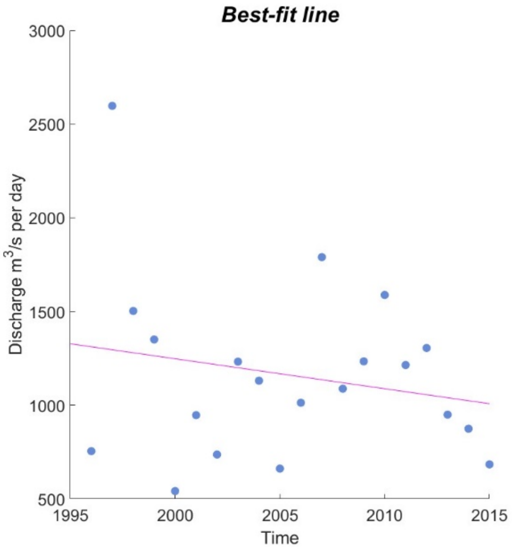


Figure 14c: *best-fit line for the highest maximum annual discharges obtained with the wet initial states*

Figure 14: Trend lines for the extreme annual discharges at Borgharen.

Graphs showing each dataset of extreme discharges (*historical simulated maximum annual discharges*, *highest maximum annual discharges with the dry initial states* & *highest maximum annual discharges with the wet initial states*) together with their respective trend lines can be found in Appendix C. The graphs generally show a downward trend/tendency in most gauge stations. Only two gauge stations (Molignee & Sambre) showed an ascending tendency in their forecasted highest maximum annual discharges obtained with the dry and wet initial states. There were also two gauge stations (Sambre and Semois) where there is no trend for their historical simulated maximum annual discharges. In Table 3, the type of trend present for all the datasets of discharge extremes for all the gauge stations can be found.

Table 3: Graphical analysis of the historical and forecasted data of all the gauge stations.

	Gauge Station	Historical simulated maximum annual discharges	Highest maximum annual discharges obtained with the DRY initial states	Highest maximum annual discharges obtained with the WET initial states
1	Borgharen	descending tendency	descending tendency	descending tendency
2	Chooz	descending tendency	descending tendency	descending tendency
3	Chaudfontaine	descending tendency	descending tendency	descending tendency
4	Molignee at Warnant	descending tendency	ascending tendency	ascending tendency
5	Hermeton at Hastiere	descending tendency	descending tendency	descending tendency
6	Ourthe at Tabreux	descending tendency	descending tendency	descending tendency
7	Sambre at Salzinnes	no trend	ascending tendency	ascending tendency
8	Mause at Saint-Mihiel	descending tendency	descending tendency	descending tendency
9	Semois at Membre Pont	no trend	descending tendency	descending tendency
10	Lesse at Gendron	descending tendency	descending tendency	descending tendency
11	Chiers at Carignan	descending tendency	descending tendency	descending tendency
12	Bar at Cheveuges	descending tendency	descending tendency	descending tendency

5.4. Results for the trend analysis of the maximum annual historical and maximum annual forecasted datasets of discharge extremes

The statistical tests mentioned in the Section 3.3.4. have been applied to the three datasets of extreme discharge events (*historical simulated maximum annual discharges, highest maximum annual discharges with the dry initial states* & *highest maximum annual discharges with the wet initial states*). When carrying out these statistical tests, the different p-values for each statistical test were calculated. Several significance levels (α-values) have been established to be compared with these p-values and approve or reject the null hypothesis.

The results for the trend analysis in the maximum annual extreme discharges of Borgharen are displayed in the following tables. Table 4 contains the trend analysis results for the *historical simulated maximum annual discharges* over the 20 years period at Borgharen. In Table 5, the results for *highest maximum annual discharges obtained with the dry initial states* are shown. Finally, in Table 6, the trend analysis results for the *highest maximum annual discharges obtained with the wet initial states* can be found. The green boxes in the tables indicate that a trend/tendency has been detected in the maximum extreme annual discharges when applying a specific statistical test with a determined significance level. Whether the statistical test results show trends in the maximum extreme annual discharges depends not only on the type of statistical test applied but also on the significance levels with which the p-values are being compared.

Table 4: Statistical results for the trend analysis in the historical simulated maximum annual discharges at Borgharen.

Results for the historical discharge values at Borgharen					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,23932	No Trend	No Trend	No Trend	descending trend
Spearman's rank correlation test	0,32439	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,34676	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,16549	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,05619	No Trend	No Trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,04735	No Trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,80005	No Trend	No Trend	No Trend	No Trend

Table 5: Statistical results for the trend analysis in the highest maximum annual discharges with the dry initial states at Borgharen.

Results for the first highest dry maximum discharge values at Borgharen					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,37396	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,71434	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,58125	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,91180	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,88198	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	1,00000	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,55315	No Trend	No Trend	No Trend	No Trend

Table 6: Statistical results for the trend analysis in the highest maximum annual discharges with the wet initial states at Borgharen.

Results for the first highest wet maximum discharge values at Borgharen					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,39691	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,70958	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,62650	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,52885	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	1,00000	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,96993	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,49729	No Trend	No Trend	No Trend	No Trend

The rest of the tables containing the results of this statistical analysis for the other gauge stations can be found in Appendix C. This statistical analysis answers the second sub-question of this research. In general, it can be said that results of this statistical analysis did not show noteworthy findings in terms of trends. Although in the trend line graphs (displayed in the Appendix C) there seemed to be mostly negative trends; there is not enough evidence to say that there are trends in the historical simulated maximum annual discharges, or the highest maximum annual discharges obtained with the dry initial states or the highest maximum annual discharges obtained with the wet initial states. In very few gauge stations, the statistical test results show a trend on the extreme discharges. But this just happens for significance levels higher than the typical value of $\alpha = 0.05$. The problem is that when increasing the significance level from 0.05 to 0.10 or even 0.25 the credibility of the statistical results decreases, making these results not so reliable.

Regarding the parametric and non-parametric statistical tests applied, the amount of maximum extreme annual discharge (one extreme discharge value for each year during a period of 20 years) could have affected the trend analysis results. Specially, when applying the Wilcoxon-Mann-Whitney test. This test consists of dividing the available data (20 maximum extreme annual discharges) into two subgroups and comparing them to detect the presence of some type of trend. However, the results obtained in this trend may not be consistent in all cases. For example, with the aim to compare the discharges in the past versus the discharges in the last 5 years, the 20 discharge values were split into two subgroups (*Group nI* containing the first 15 discharge values and *Group nK* containing the last 5 discharge values). However, the results after applying the Wilcoxon-Mann-Whitney test to these two subgroups (Group nI and nK) could not be considered acceptable because a subgroup containing just 5 discharge values is not adequate to applied a statistical test and establish a trend. In Table 4, it can be seen how the results differ depending on how the data is divided for this Wilcoxon-Mann-Whitney test. The p-values when the data is split in (nA= 10 and nB=10), (nC=9 and nD=11) and (nE=8 and nH=12) are lower. But when the data is split in (nI=15 and nK=5) the p-value is higher than the previous results.

This answers the last sub-question formulated in the Section 1.4.2. The results of the trend analysis do depend somewhat on the statistical tests used. But the greatest influence is caused by the amount and type of data (maximum extreme annual discharge values) available for analysis. For this research project, the most important input were the extreme precipitation events. However, as mentioned before in the Section 4.4, the maximum extreme annual discharge events obtained after the wflow simulations were not the most optimal results for comparison and statistical analysis. By closely inspecting the hydrographs of each extreme discharge event obtained with the dry and wet initial conditions, it was possible to determine the percentage of events that can be considered adequate for the study of trends. In the case of Borgharen (See Table 7), only 70% of the Dry and 70% of the Wet extreme discharge events present a real maximum peak that can be considered optimal for statistical analysis. These hydrographs for the gauge station Borgharen can be found in Appendix D. For other gauge stations, the percentage of acceptable peaks may be even lower. For instance, for the gauge station named Chooz the percentage of acceptable peaks for dry extreme discharge events is only 40% and 50% for Wet extreme discharge events (See Table 8).

Table 7: Percentage of events with an optimal peak for Borgharen.

Gauge Station: Borgharen			
Scenario	**Peak**	**No peak**	**Percentage of events with a peak**
Dry	14	6	70
Wet	14	6	70

Table 8: Percentage of events with an optimal peak for Chooz.

Gauge Station: Chooz			
Scenario	**Peak**	**No peak**	**Percentage of events with a peak**
Dry	8	12	40
Wet	10	10	50

6. Conclusions

In this study, the maximum extreme annual discharges of the Meuse river and its tributaries were analyzed to investigate whether possible trends can be found on these discharges derived from ensembles of precipitation extremes. This research investigation was carried out because some well-known sources like the World Weather Attribution (who has been analyzing the possible relationship between climate change and extreme events to provide robust assessments after an event takes place) indicated that changes in the maximum discharges of the Meuse river were found. That is why this investigation was carried out to verify if there is sufficient evidence to demonstrate the presence of trends in the extreme discharge values of the Meuse river and its tributaries during the period starting on 1996 until 2015. Two main questions were formulated to carry out this investigation and these are:

1. ***In which way are the simulated forecasted extremes discharge values different from what we have seen in the simulated historical extreme discharge values?***
2. ***Is there enough evidence to confirm the presence of trends in the extreme discharge events of the Meuse river? And could the trend analysis results be different when considering the tributaries of the Meuse river?***

From these two main questions, 3 sub-questions were created that have already been answered in the previous section. From such results the following conclusions can be derived:

a. **How can appropriate initial conditions/states be established to perform the simulations?**

The initial states could have affected in a certain way the results obtained in the trend analysis of the extreme discharges. First, the averages per season were calculated for the variables that make up the initial conditions of the dry and wet scenario. This means that the same average values were used for each of the 40 events to calculate the discharge annual extreme values. This could generate some type of error because the initial conditions for each precipitation event should have been different.

Second, two sets of initial conditions were analyzed (20-year initial states & 40-year initial states). It was shown that there was not much difference in using the initial conditions of the 40-year period or the initial conditions of the 20-year period. However, the results could have been different depending on the chosen initial conditions. This is because the initial conditions play an extremely important role for each of the maximum extreme annual discharges. Each forecasted extreme discharge event is made up of 15 days, for which the wflow model provides the discharge values after using the initial conditions and the extreme precipitation events as input. Therefore, if the initial conditions are not adequate, the discharge values resulting from the wflow simulations can not be considered optimal for the trend analysis.

b. **How different are the results of the trend analysis in extreme discharges when investigating some of the tributaries of the Meuse river instead of just analyzing the main river (Borgharen)?**

Based on the graphs showing the tendencies present in the maximum extreme annual discharges for the period of 20 years and the statistical results for the trend analysis, which can be found in Appendix C; it can be said that graphically the 12 gauge stations analyzed show a descending tendency on the extreme river discharges (for both historical and forecasted simulated discharge extremes) during the 20 years period. However, when the statistical tests were applied to these data sets of extreme discharges, the results obtained were not the same obtained graphically. The statistical analysis started by investigating the possible presence of trends in the extreme discharges for a significance level of $\alpha = 0.01$. But trends were not identified at any of the gauge stations. Then the significance level was increased for significance levels of $\alpha = 0.05$, $\alpha = 0.10$, and $\alpha = 0.25$. Gauge stations such as Meuse at Saint-

Mihiel and Chiers showed signs of trends on their historical simulated extreme discharges with significance levels of $\alpha = 0.05$ and $\alpha = 0.10$ respectively. However, these statistical results fail to reject the null hypothesis.

The conclusion is that, despite finding changes in the discharges of the Meuse river (as mentioned by the World Weather Attribution); it can hardly be demonstrated that there is any ascending or descending trend on the maximum extreme annual discharge values of the Meuse river and its tributaries over the 20 years period.

c. Do the results obtained from the trend detection analysis depend on the methods and resources used for during the analysis?

Statistical tests and the amount of data available for statistical analysis also influenced the results. First, the period of time is very short. Therefore, it cannot be assured with certainty that the trend lines plotted for each gauge station are reasonable results. it is true that these lines show trends on the historical and forecasted simulated maximum annual discharges. However, these trends could be completely different if the same trend analysis had been carried out for a period of time greater than 20 years. It is possible that for longer periods of time, there is no trend at all on the river extreme discharges, or the trend lines could be totally different from the trend lines that have been obtained for the 12 gauge stations analyzed in this report. But the main question of this research was to analyze if there were trends in recent years. Therefore, a longer period of time for the trend analysis was not an option. Additionally, even for longer periods, it could be the case that there is not enough extreme river discharges available for the trend analysis because those events are rare.

The initial conditions used for simulations together with the extreme precipitation data used for the wflow simulations strongly influenced the trend results. First, the initial conditions were the most appropriate and realistic conditions. Second, the information received for each extreme precipitation event that was used for the wflow simulations was not the most optimal. Because the extreme discharge events derived from these precipitation events did not always have a real and acceptable maximum discharge value (among the 15 discharge values of each event as explained before in Section 4.4.). However, at the end those incorrect values were included in the trend analysis. This undoubtedly generates uncertainty in the results obtained when applying the statistical tests to these maximum discharge values.

Nevertheless, despite the data limitations due to the short period of time and the way the set-up for the experiments was prepared, it is a good approach to start investigating the possible presence of trends in the extreme discharges of the Meuse river and its tributaries.

7. Recommendations

Some recommendations for future trend research analysis of the Meuse river could be:

First, try to find a more optimal way to determine the initial conditions. Various options for determining these initial conditions were explained in the Approach Section of this report. However, none of these options could give initial conditions that are 100% real. This notably influences the results obtained for the trend analysis and that is why it is recommended to find other approaches to determine these initial conditions. A possible solution would be instead of calculating the averages per season, to find the real values of the initial date for each extreme precipitation event.

Secondly, the selection process for extreme precipitation events should be more rigorous. As seen in the previous section, there are gauge stations where a high percentage of hydrographs did not present an peak maximum discharge that is appropriate for the statistical analysis. Therefore, some type of constraint could be established where the events to be used for the wflow model simulations clearly present a maximum peak in at least 95% of cases. Then it would be sound to compare and analyze them.

The last recommendation is that another approach could be tried when analysing the maximum discharge values. Other statistical methods could be attempted to determine trends, especially in cases where there is not sufficient data available. For example, you could start looking for the points where an abrupt change in the extreme discharges occurs and then the trend analysis of the extreme discharges before and after this abrupt change could be performed by means of more suitable statistical tests.

Appendix

Appendix A: Extreme precipitation events taken from the ECMWF

Table 9: List of the two most extreme precipitation events for the 5-day accumulative volume.

Year (NC-file)	Month (NC-file)	Day (NC-file)	Days since 0-0-0000 of Extreme Event	Ensemble Member	Day in Ensemble member	Precipitation (in m/m^2)
1996	11	24	729359	5	6	0,05418635
1996	6	27	729211	6	8	0,051123032
1997	6	20	729567	8	6	0,084769083
1997	12	22	729756	7	10	0,063082745
1998	11	14	730082	10	9	0,076477233
1998	10	27	730057	9	2	0,065055393
1999	11	28	730460	7	8	0,075757613
1999	12	22	730479	9	3	0,070958103
2000	2	20	730546	8	10	0,063091355
2000	9	19	730756	6	8	0,063002583
2001	12	12	731208	2	11	0,063604238
2001	10	31	731162	8	7	0,061849158
2002	5	30	731371	8	5	0,067404074
2002	10	31	731523	3	3	0,062473238
2003	1	26	731618	3	11	0,062618942
2003	9	29	731860	10	7	0,056609952
2004	5	23	732101	8	11	0,069349706
2004	11	10	732270	10	9	0,06436794
2005	9	29	732595	8	11	0,054313162
2005	8	15	732548	6	9	0,054139883
2006	12	29	733049	5	9	0,063166825
2006	1	12	732696	3	7	0,057212579
2007	5	26	733189	2	1	0,073515444
2007	12	1	733383	2	6	0,065379457
2008	2	9	733458	1	11	0,059205818
2008	1	5	733421	5	9	0,058050861
2009	10	27	734081	5	8	0,055914513
2009	12	19	734132	5	6	0,051287732
2010	5	2	734271	6	11	0,067371233
2010	8	15	734366	4	1	0,066536986
2011	1	30	734540	10	7	0,070451097
2011	12	12	734850	5	1	0,066173368
2012	12	15	735226	6	8	0,071123387
2012	10	10	735162	3	10	0,064368567
2013	7	28	735453	3	10	0,065824103
2013	12	12	735590	3	10	0,063032796
2014	10	13	735893	8	8	0,060761081
2014	9	1	735854	1	11	0,058141972
2015	7	18	736170	1	7	0,065203742
2015	8	18	736203	5	9	0,058863953

Appendix B: Final initial states to perform the experiments

The approach to determine the initial states was already explained in section 4.3. Deltares has provided continuous historical data (E-OBS gridded data) from 1980-01-01 until 2020-12-31 (a total of 40 years). However, the period of interest for this report is from the year 1996 until 2015 (a period of 20 years). Therefore, the model has been run in cold state with the continuous historical data as input for both periods (40 and 20 years) to compare the results and determine which initial condition results are more appropriate for the subsequent simulations. The resulting initial states are a set of variables for which the average per season (winter and summer) has been calculated. These variables are explained in the following table:

Table 10: Variables that are present in the initial conditions.

Variable	Name in the wflow model	Units
Volume	volume_reservoir	m^3
Surface flow	ssf	m^3/d
River water level	h_river	m
Saturated storage	satwaterdepth	mm
Overland flow	q_land	m^3/s
Depth of overland flow	h_land	m
Average water level	h_av_river	m
Top soil temperature	tsoil	ºC
River discharge	q_river	m^3/s
Canopy storage	canopystorage	mm
Snow storage	snow	mm
Liquid water content in the snow	snowwater	mm
Average water level	h_av_land	m
Amount of water in the unsaturated store, per layer	ustorelayerdepth	mm

Comparison of the resulting initial states for a 20-year period versus the initial states for a 40-year period

As a result of the simulation of the wflow model in cold state, nc files were created containing the results of both the simulation for the 20-year period and for the 40-year period. For each time period (20-year & 40-year), two nc files were created, one containing the initial conditions for the dry scenario and another with the initial conditions for the wet scenario (in total 4 nc fles). However, it was necessary to define what results were more convenient to be used in the simulations of the precipitation events. That is why the initial condition results of the 20-year period were compared with the initial condition results of the 40-year period.

For instance, the corresponding plots for the 20-year and 40-year period of the variable *surface flow (ssf)* for the dry scenario can be seen in Figure 15. The figure in the upper left corner (Figure 15a) represents the surface flow variable for the dry scenario as a result of the 20-year simulation, while the figure in the upper right corner (Figure 15b) shows the same variable but for a 40-year period simulation. The two graphs have been adjusted to show results on the same scale, being the minimum value: 0 m^3/d and the maximum value: 60 000 m^3/d. When visually inspecting the two graphs, it can be seen that there is not much difference between them. This is confirmed in Figure 15c, which is the graph resulting from the difference between Figures 15a and Figure 15b. As can be seen in Figure 15c, the values resulting from the difference between the graphs vary between zero and close to 1000 m^3/d, which compared to the maximum values of Figures 15a and 15b, are much lower values. Therefore, for this variable (*surface flow*) it can be said that there is not a large difference between the results for the 20-year period versus the results of the 40-year period.

Dry Scenario for 20 years Period	Dry Scenario for 40 years Period

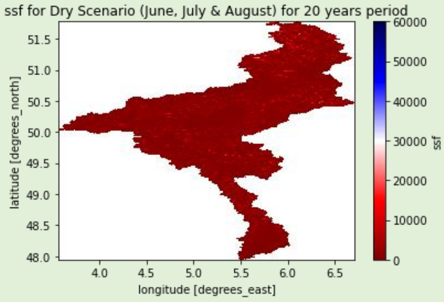
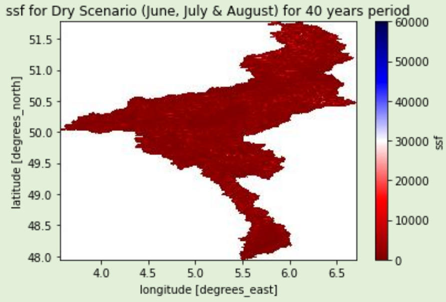

	

Figure 15a	***Figure 15b***

Difference

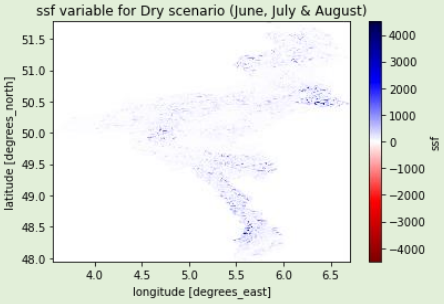


Figure 15c

Figure 15: Comparison of the DRY initial states for the 20-year period versus the 40-year period.

The same analysis was done one of the the variables of the wet scenario. In this case, Figure 16a is displaying the results of the variable named *saturated* storage *(satwaterdepth)* resulting from the simulation of a 20-year period, while Figure 16b is showing the results obtained with the 40-year period. Again, the figures have been set to the same scale for comparison. At first glance the two figures, Figure 16a and Figure 16b look very similar. Figure 16c shows the difference between these two figures, and again the values in this last graph are very small and in some cases zero.

Wet Scenario for 20 years Period	Wet Scenario for 40 years Period

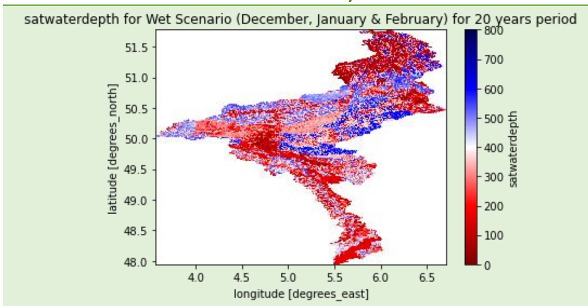
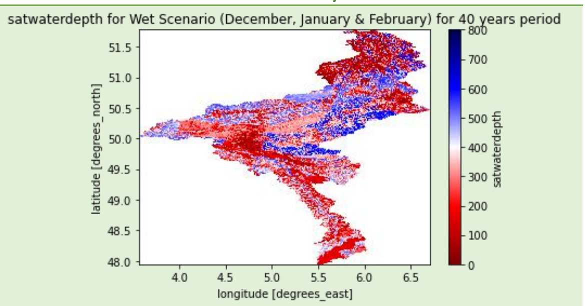

	

Figure 16a	***Figure 16b***

Difference

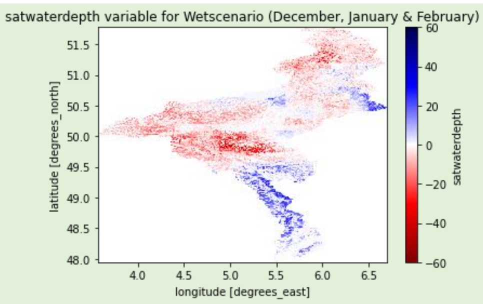


Figure 16c

Figure 16: Comparison of the WET initial states for the 20-year period versus the 40-year period.

The initial states resulting from the 20-year simulation have been chosen instead of the initial states of the 40-year period. Because after comparing the averages per season of each variable of the initial states for both the 20-year period and the 40-year period, it was noted that there was not a considerable difference in the averages of each variable for the two time periods (40 and 20 years). Therefore, it is assumed that if the initial conditions calculated for the 20-year period are used for the simulations, the resulting forecasted discharge values would not be so different from the values that can be obtained by performing the same simulations but with the initial conditions corresponding to the period of 40 years.

Checking if the 20-year initial states for the dry and wet scenario are appropriate and logical

Before using these initial states (from the 20-year run) it is necessary to analyze whether these variables are suitable for the simulations of the extreme precipitation events. For this, a comparison has been done for the variables of the dry scenario versus the variables of the wet scenario. For the dry scenario, the average of the results for the months of June, July, and August has been calculated, while for the wet variables the months taken into account are December, January, and February. Therefore, the variables of the dry scenario should be different from the variables of the wet scenario. To check if this is true, two of these variables have been plotted for two dates that fall within the period of the Dry scenario and Wet scenario respectively (See Figure 17).

Saturated storage for dry scenario	Saturated storage for wet scenario

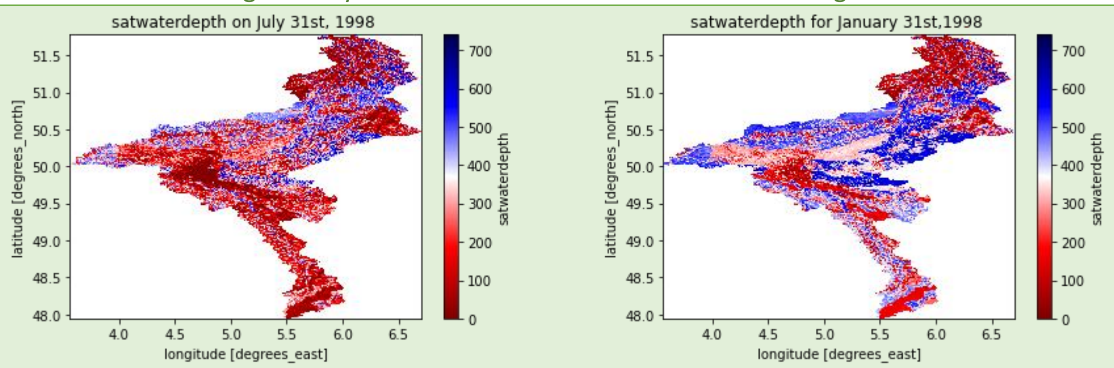


Figure 17a ***Figure 17b***

Figure 17: Comparison of the Dry and Wet final initial states.

The difference in the two graphs is very clear. In the graph for the dry scenario (date: July 31st, 1998), the *saturates storage variable* presents very low values, with places where it could even be said to be zero (dark red colour); while for the graph of the wet scenario (date: January 31st, 1998), this same variable mostly shows values above 400 mm.

Remaining graphs for the comparison of the Initial states for summer versus winter

In this section, the remaining graphs for all the variables that make up the initial states of both the dry and wet scenarios can be found; except the graphs of the variables *Volume* and *canopy storage* because the graphs were empty. The variables where the difference between the dry and wet states was most noticeable were: saturated storage (*satwaterdepth*), overland flow (*q_land*), depth of overland flow (*h_land*), top soil temperature (*tsoil*), river discharge (*q_river*), snow (*Snow storage*), liquid water content in the snow (*snowwater*), average water level (*h_av_land*), amount of water in the unsaturated store in the four layers (*ustorelayerdepth*).

Based on this comparison between dry and wet initial conditions for the 20 years simulation results, it can be said that the 20-year period initial conditions are acceptable to carry out the 80 wflow simulations. In this way, the first sub-question mentioned in the Section 1.4 has been answered.

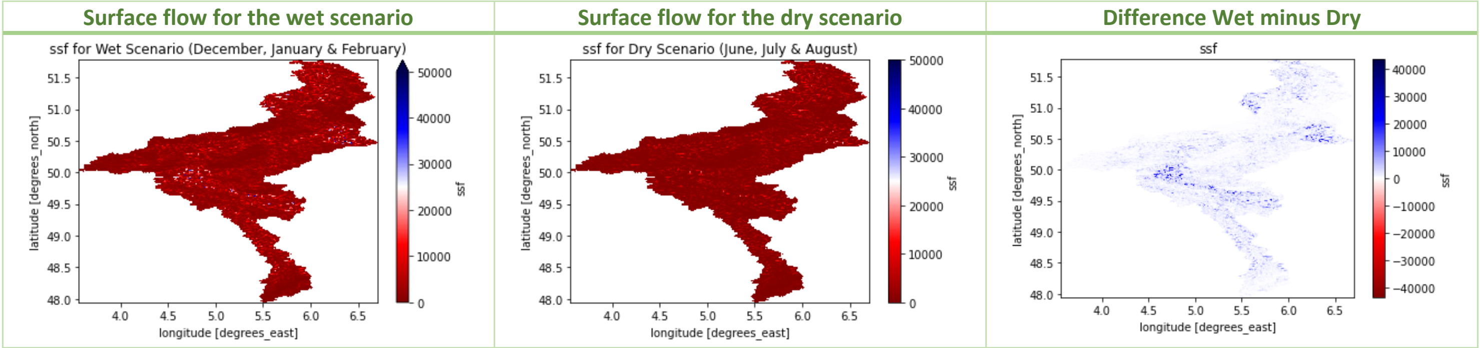


Figure 18: Graphs for the variable "Surface flow for the wet scenario"

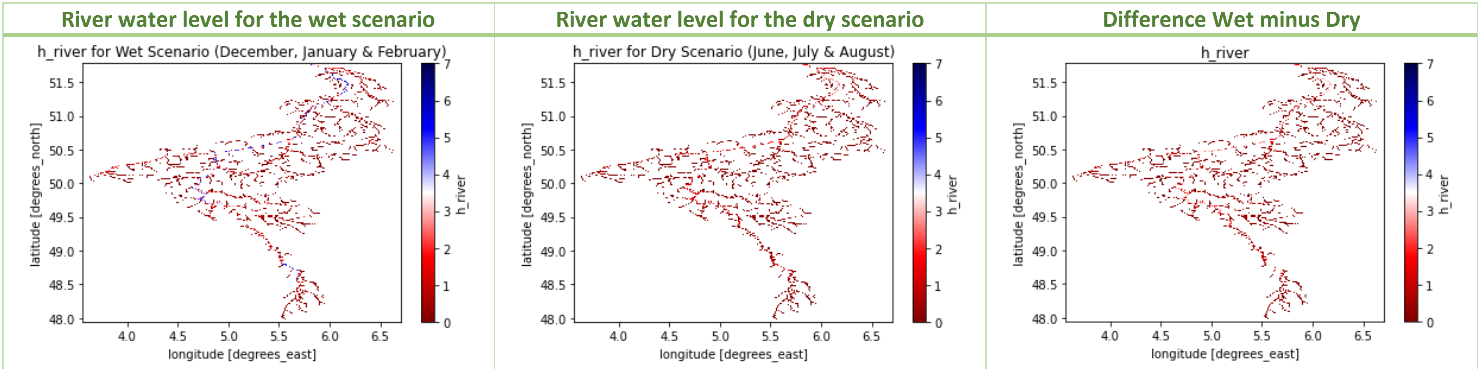


Figure 19: Graphs for the variable "River water level"

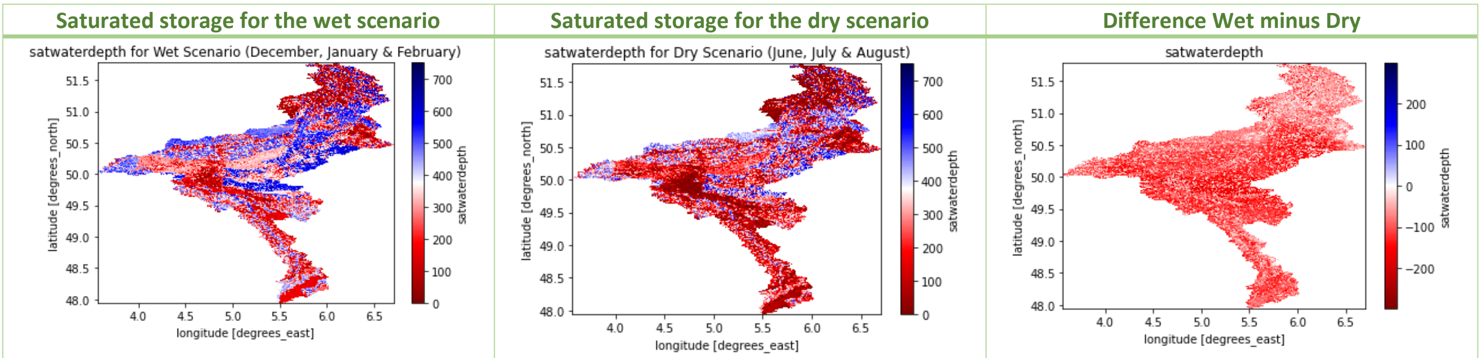


Figure 20: Graphs for the variable "Saturated storage"

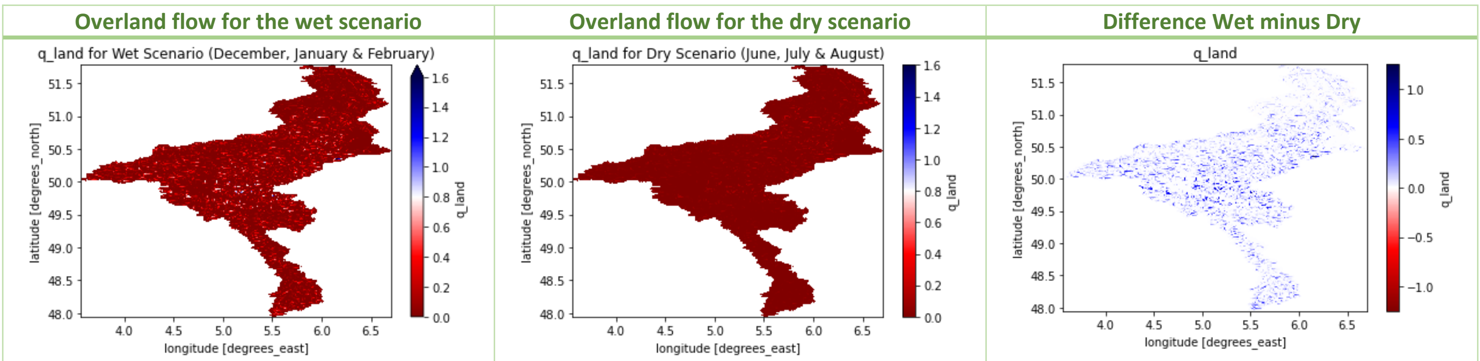


Figure 21: Graphs for the variable "Overland flow"

Depth of overland flow for the wet scenario	Depth of overland flow for the dry scenario	Difference Wet minus Dry

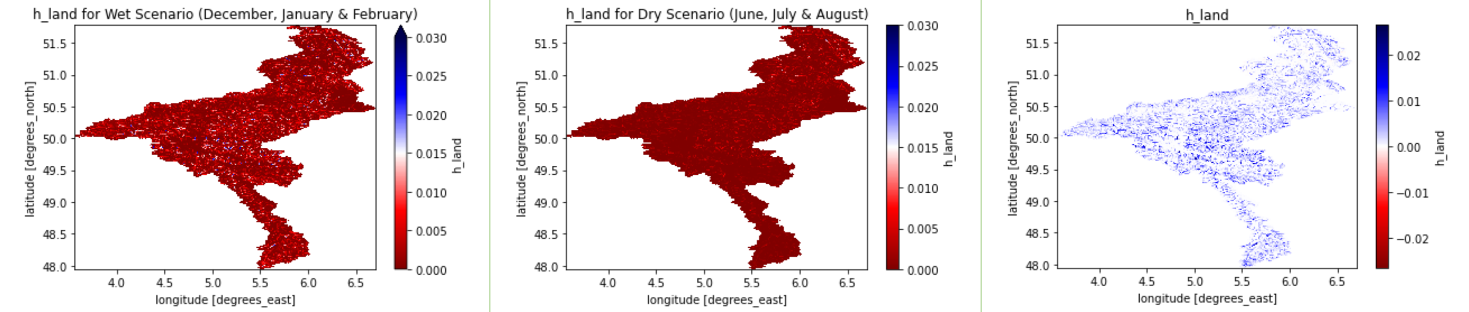


Figure 22: Graphs for the variable "Depth of overland flow"

Average water level for the wet scenario	Average water level for the dry scenario	Difference Wet minus Dry

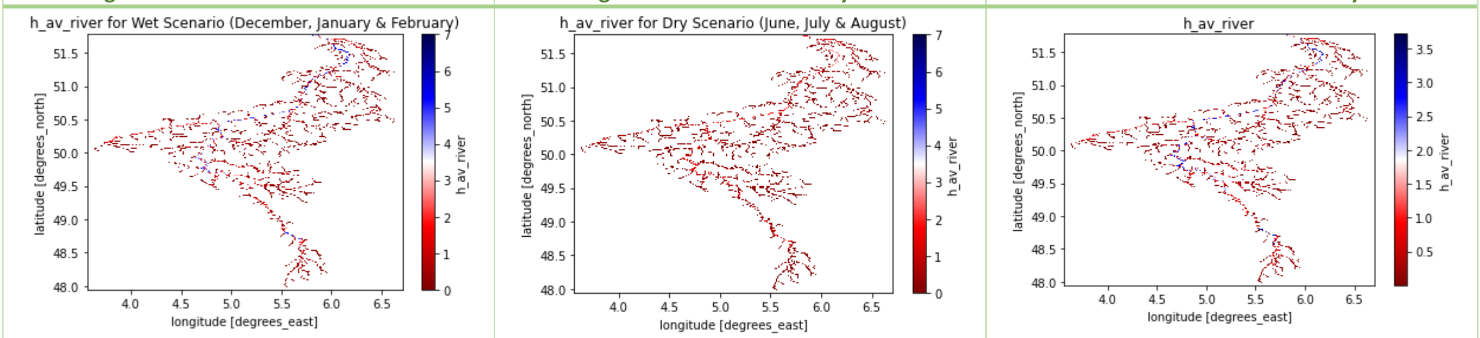


Figure 23: Graphs for the variable "Average water level"

Top soil temperature for the wet scenario	Top soil temperature for the dry scenario	Difference Wet minus Dry

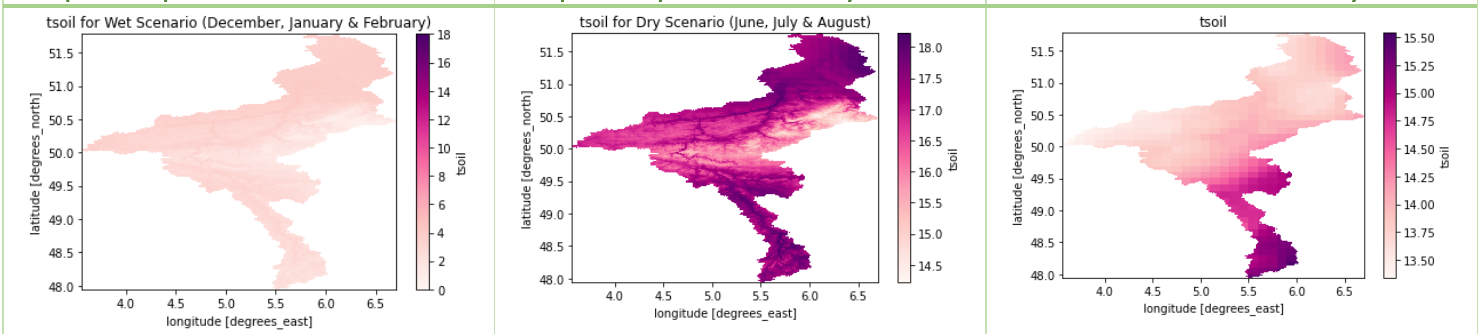


Figure 24: Graphs for the variable "Top soil temperature"

River discharge for the wet scenario	River discharge for the dry scenario	Difference Wet minus Dry

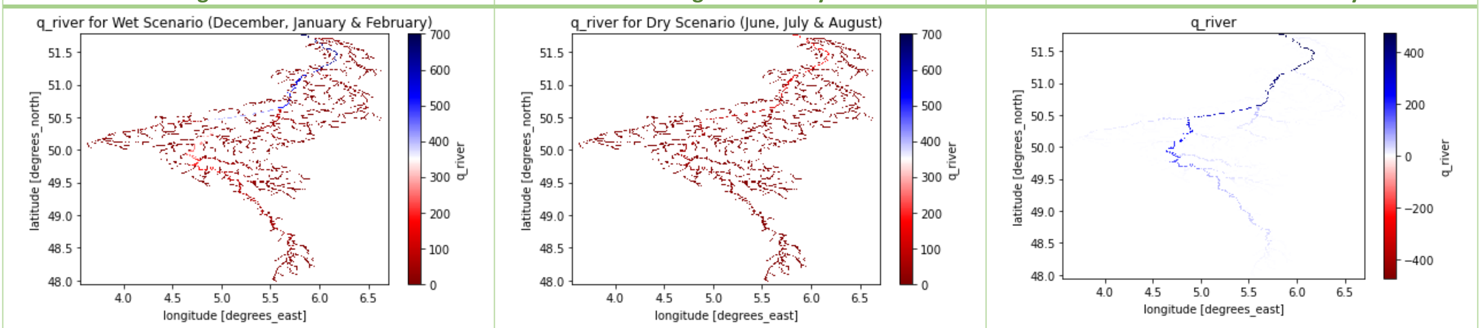


Figure 25: Graphs for the variable "River discharge"

Snow storage for the wet scenario	Snow storage for the dry scenario	Difference Wet minus Dry

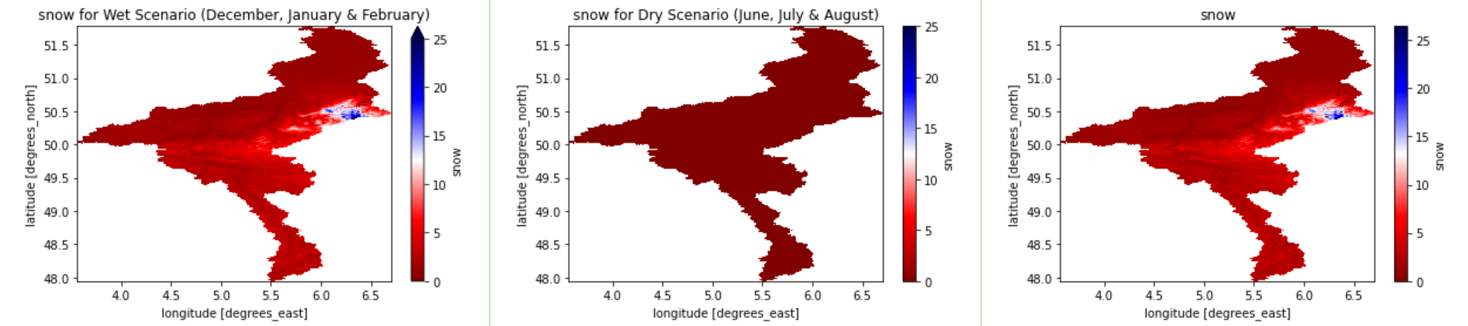


Figure 26: graphs for the variable "Snow storage"

Liquid water content in the snow for the wet scenario	Liquid water content in the snow for the dry scenario	Difference Wet minus Dry

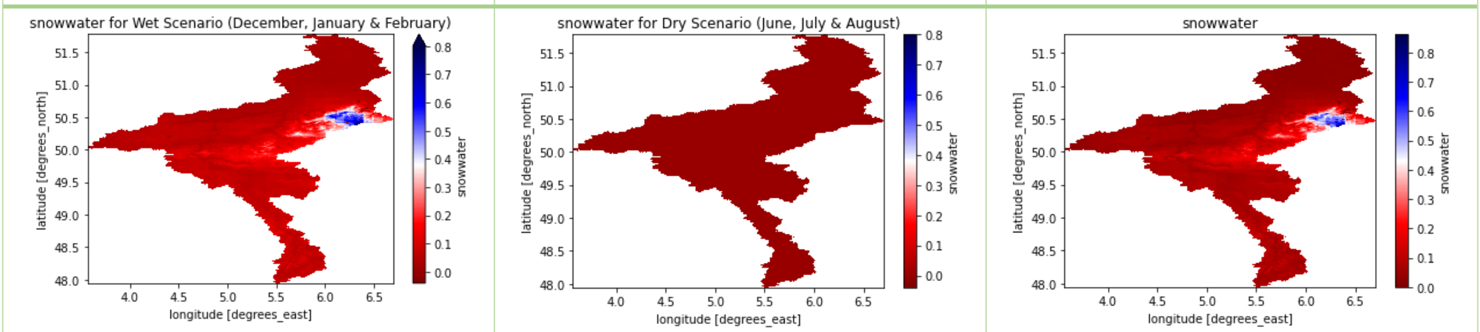


Figure 27: Graphs for the variable "Liquid water content in the snow"

Average water level for the wet scenario	Average water level for the dry scenario	Difference Wet minus Dry

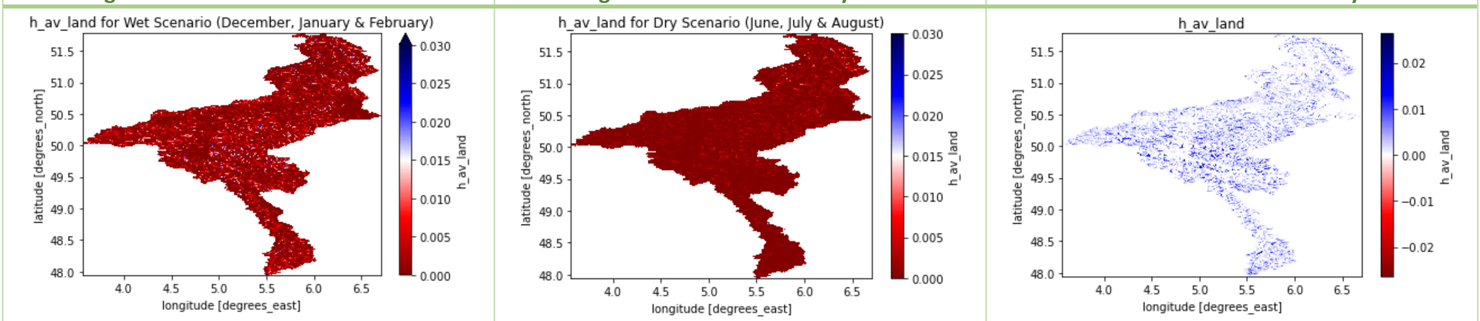


Figure 28: Graphs for the variable "Average water level"

Amount of water in the unsaturated store (layer 1) for the wet scenario	Amount of water in the unsaturated store (layer 1) for the dry scenario	Difference Wet minus Dry

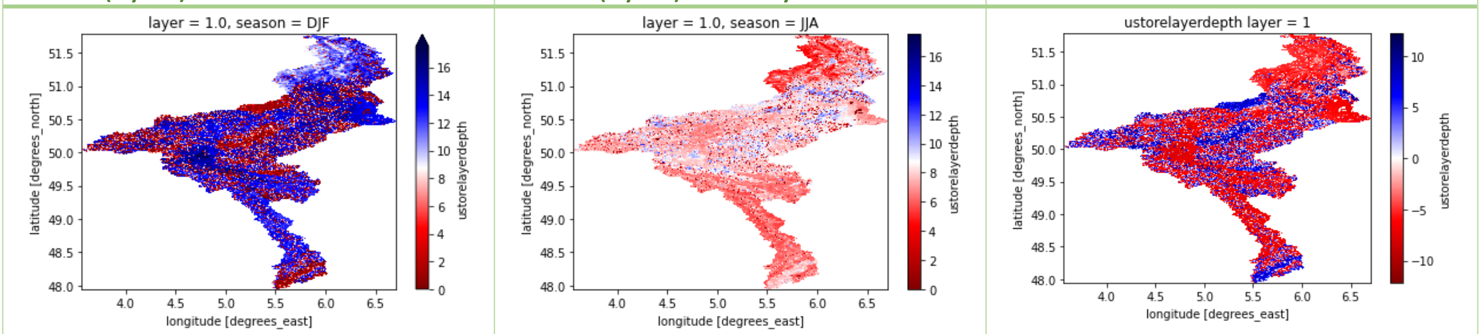


Figure 29: Graphs for the variable "Amount of water in the unsaturated store - Layer 1"

Amount of water in the unsaturated store (layer 2) for the wet scenario	Amount of water in the unsaturated store (layer 2) for the dry scenario	Difference Wet minus Dry

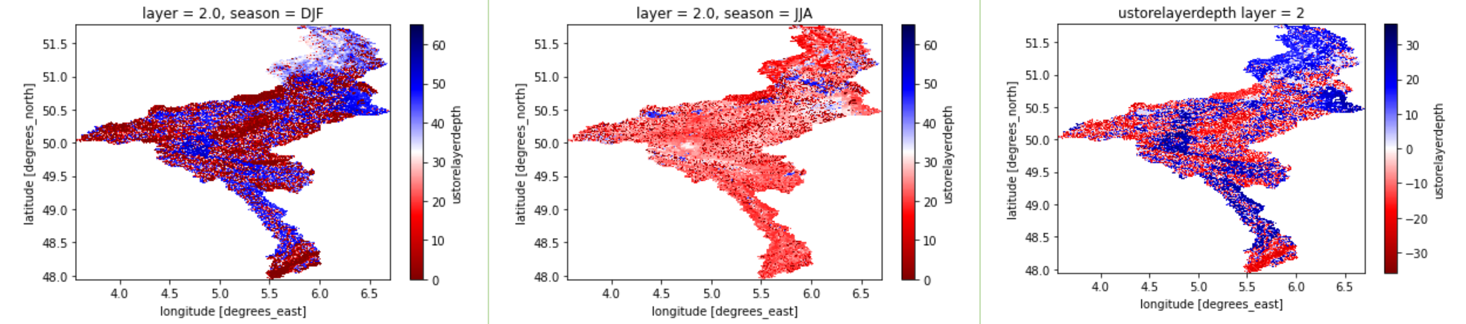


Figure 30: Graphs for the variable "Amount of water in the unsaturated store - Layer 2"

Amount of water in the unsaturated store (layer 3) for the wet scenario	Amount of water in the unsaturated store (layer 3) for the dry scenario	Difference Wet minus Dry

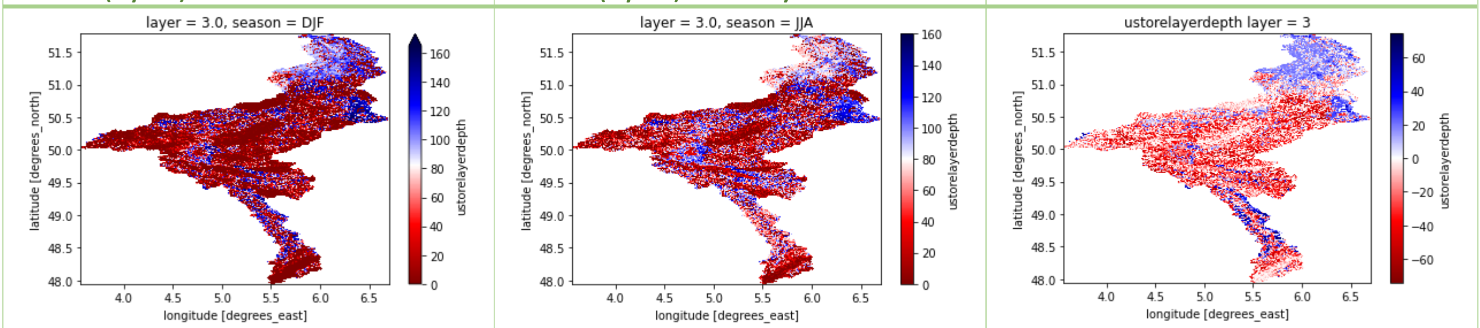


Figure 31: Graphs for the variable "Amount of water in the unsaturated store - Layer 3"

Amount of water in the unsaturated store (layer 4) for the wet scenario	Amount of water in the unsaturated store (layer 4) for the dry scenario	Difference Wet minus Dry

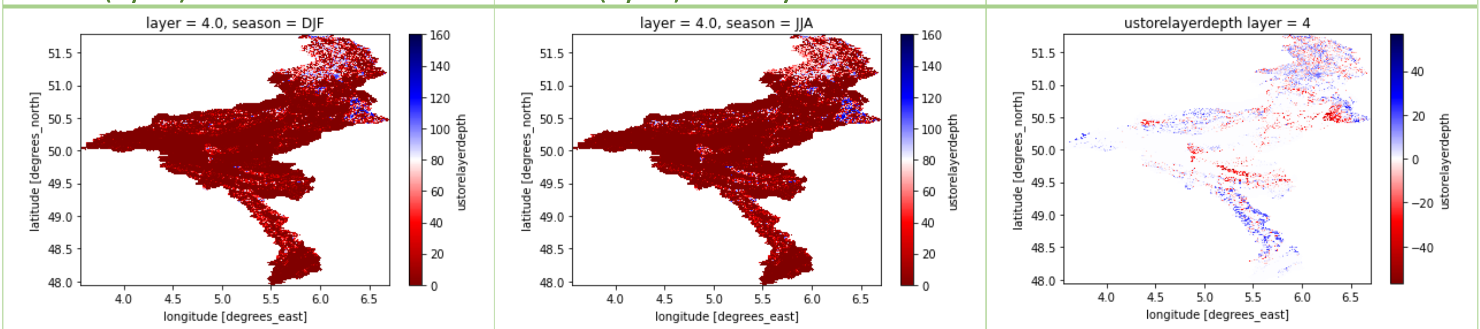


Figure 32: Graphs for the variable "Amount of water in the unsaturated store - Layer 4"

Appendix C: Comparison plots & Trend analysis results for the remaining gauge stations

Chooz

Comparison of historical vs forecasted extreme discharge values

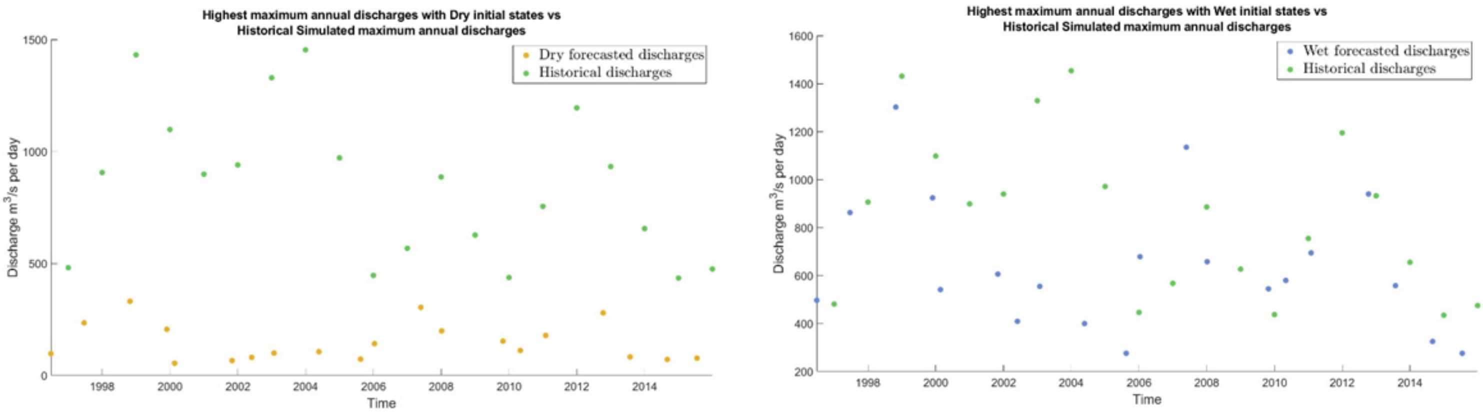


Figure 33: Comparison of historical vs forecasted extreme discharges at Chooz.

Statistical analysis for historical simulated maximum annual discharges

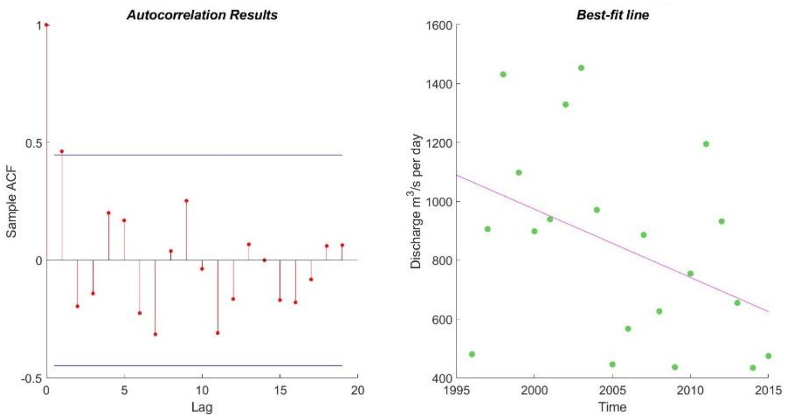


Figure 34: Graphs for the historical simulated maximum annual discharges (Chooz).

Table 11: Statistical results of the historical simulated maximum annual discharges at Chooz.

Results for the historical discharge values at Chooz					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,07121	No Trend	No Trend	descending trend	descending trend
Spearman's rank correlation test	0,05692	No Trend	No Trend	descending trend	descending trend
Mann-Kendall test	0,07435	No Trend	No Trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,03546	No Trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,00566	descending trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,01586	No Trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,44453	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

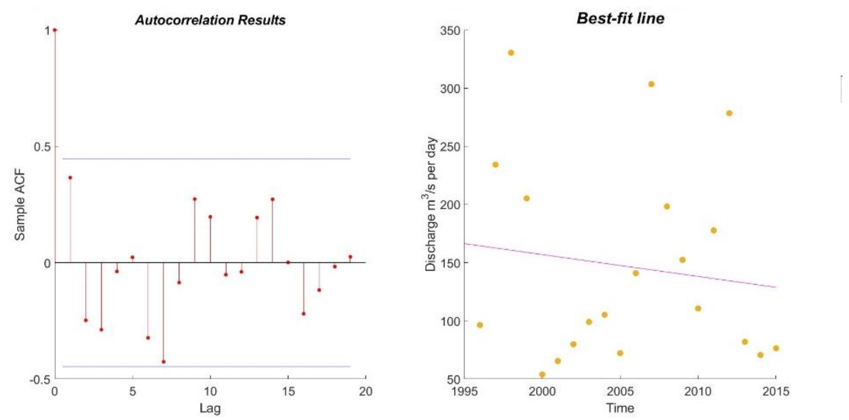


Figure 35: Graphs for the highest maximum annual discharges with the dry initial states (Chooz).

Table 12: Statistical results of the highest maximum annual discharges with the dry initial states at Chooz.

Results for the first highest dry maximum discharge values at Chooz					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,58458	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,69066	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,87113	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,39305	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,71030	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,73449	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,67247	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

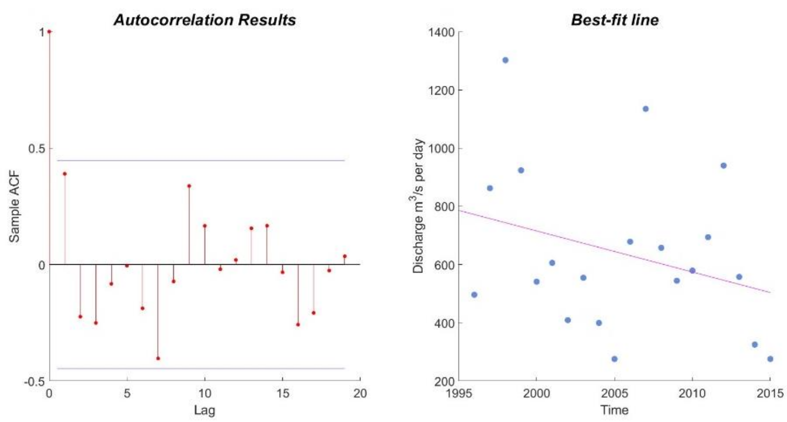


Figure 36: Graphs for the highest maximum annual discharges with the wet initial states (Chooz).

Table 13: Statistical results of the highest maximum annual discharges with the wet initial states at Chooz.

Results for the first highest wet maximum discharge values at Chooz					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,19398	No Trend	No Trend	No Trend	descending trend
Spearman's rank correlation test	0,37831	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,34676	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,63053	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,94084	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,57136	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,67247	No Trend	No Trend	No Trend	No Trend

Chaudfontaine

Comparison of historical vs forecasted extreme discharge values

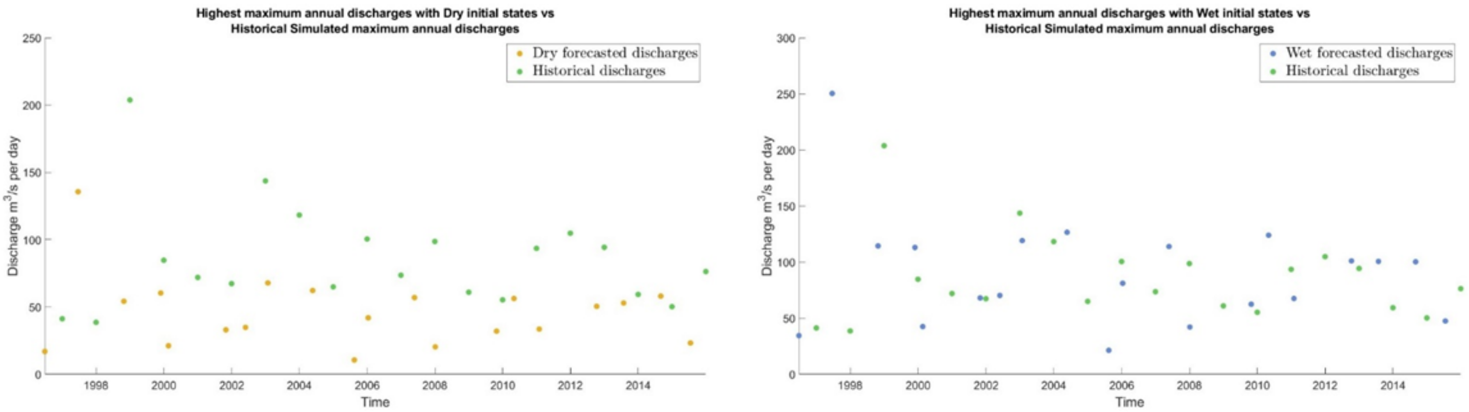


Figure 37: Comparison of historical vs forecasted extreme discharges at Chaudfontaine.

Statistical analysis for historical simulated maximum annual discharges

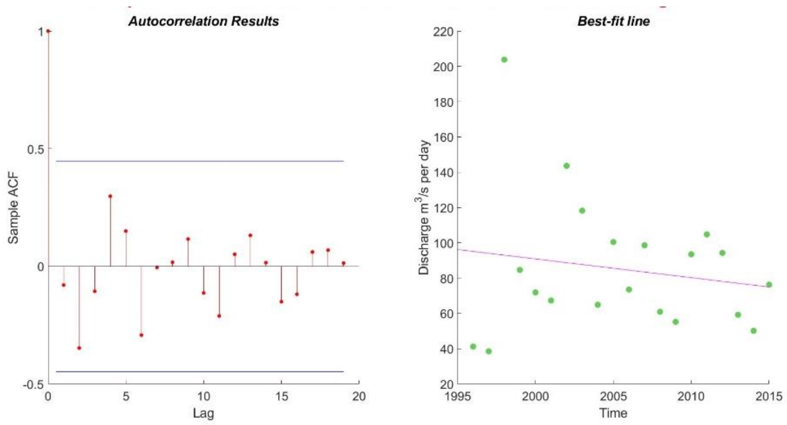


Figure 38: Graphs for the historical simulated maximum annual discharges (Chaudfontaine).

Table 14: Statistical results of the historical simulated maximum annual discharges at Chaudfontaine.

Results for the historical discharge values at Chaudfontaine					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,49170	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,98225	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,67319	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,63053	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,94084	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,73449	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,86597	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

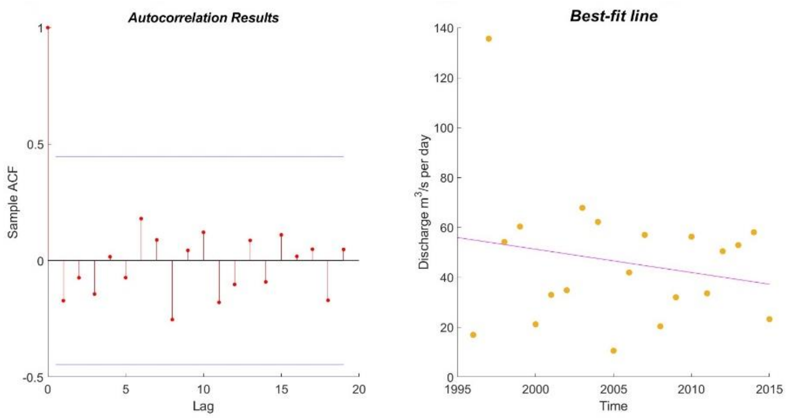


Figure 39: Graphs for the highest maximum annual discharges with the dry initial states (Chaudfontaine).

Table 15: Statistical results of the highest maximum annual discharges with the dry initial states at Chaudfontaine.

Results for the first highest dry maximum discharge values at Chaudfontaine					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,38975	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,75761	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,87113	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,73936	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,29472	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,62388	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	1,00000	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

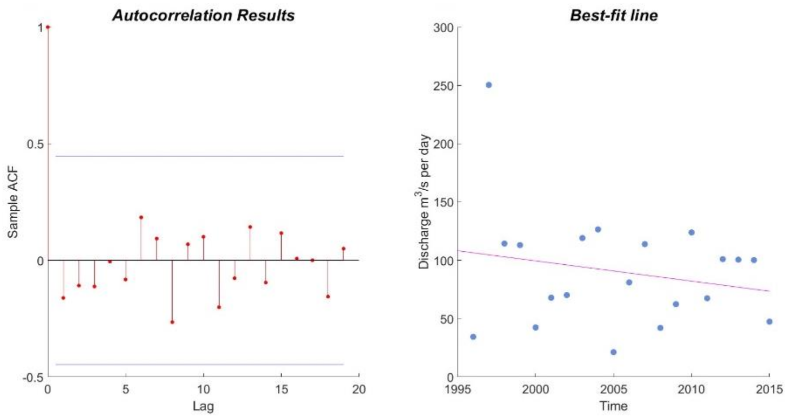


Figure 40: Graphs for the highest maximum annual discharges with the wet initial states (Chaudfontaine).

Table 16: Statistical results of the highest maximum annual discharges with the wet initial states at Chaudfontaine.

Results for the first highest wet maximum discharge values at Chaudfontaine					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,38504	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,65799	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,67319	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,73936	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,29472	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,67843	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,73542	No Trend	No Trend	No Trend	No Trend

Molignee at Warnant

Comparison of historical vs forecasted extreme discharge values

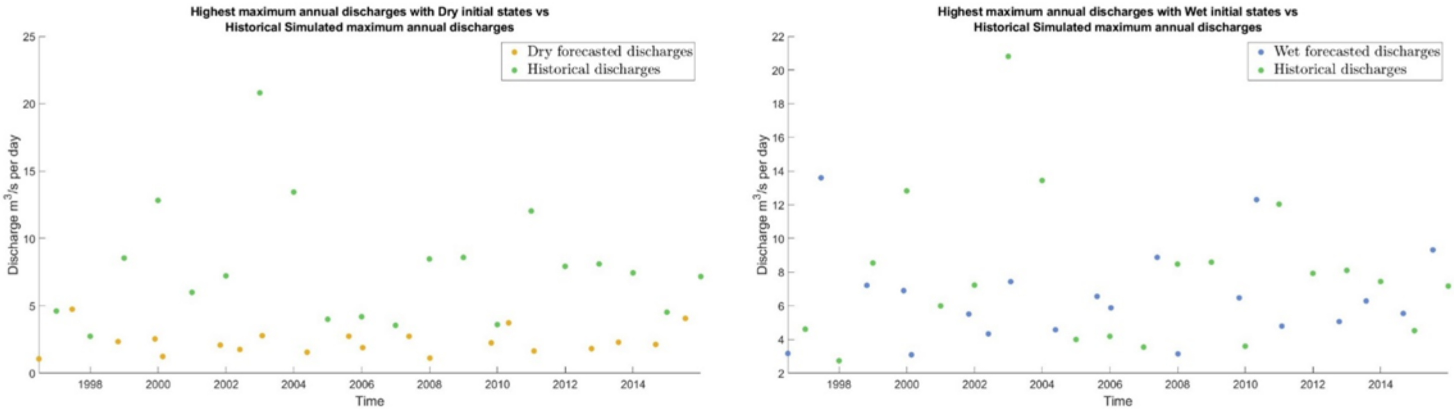


Figure 41: Comparison of historical vs forecasted extreme discharges at Molignee at Warnant.

Statistical analysis for historical simulated maximum annual discharges

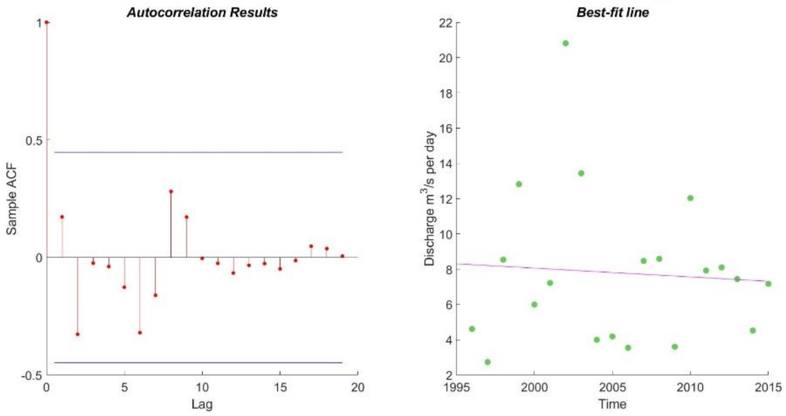


Figure 42: Graphs for the historical simulated maximum annual discharges (Moligne at Warnant).

Table 17: Statistical results of the historical simulated maximum annual discharges at Moligne at Warnant.

Results for the historical discharge values at Molignee					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,77675	No Trend	No Trend	No Trend	No Trend
Spearman’s rank correlation test	0,99746	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,92246	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,91180	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,60268	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,30539	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,93279	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

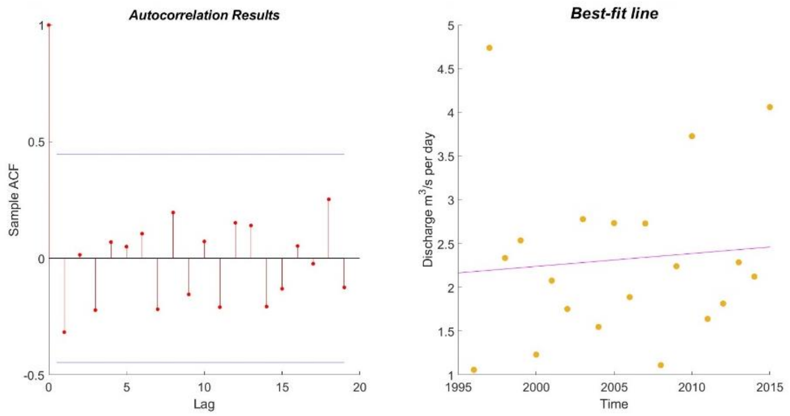


Figure 43: Graphs for the highest maximum annual discharges with the dry initial states (Moligne at Warnant).

Table 18: Statistical results of the highest maximum annual discharges with the dry initial states at Moligne at Warnant.

Results for the first highest dry maximum discharge values at Molignee					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,70352	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,62591	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,58125	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,91180	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,60268	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,96993	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	1,00000	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

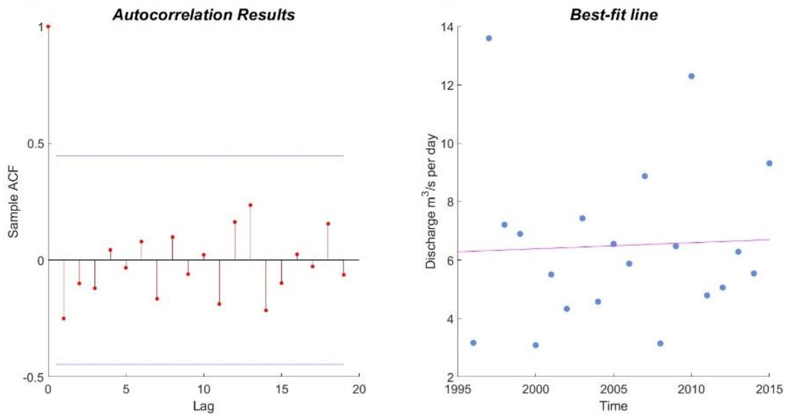


Figure 44: Graphs for the highest maximum annual discharges with the wet initial states (Moligne at Warnant).

Table 19: Statistical results of the highest maximum annual discharges with the wet initial states at Moligne at Warnant.

Results for the first highest wet maximum discharge values at Molignee					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,85350	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,70484	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,67319	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,68421	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,55163	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,85063	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,93279	No Trend	No Trend	No Trend	No Trend

Hermeton at Hastiere

Comparison of historical vs forecasted extreme discharge values

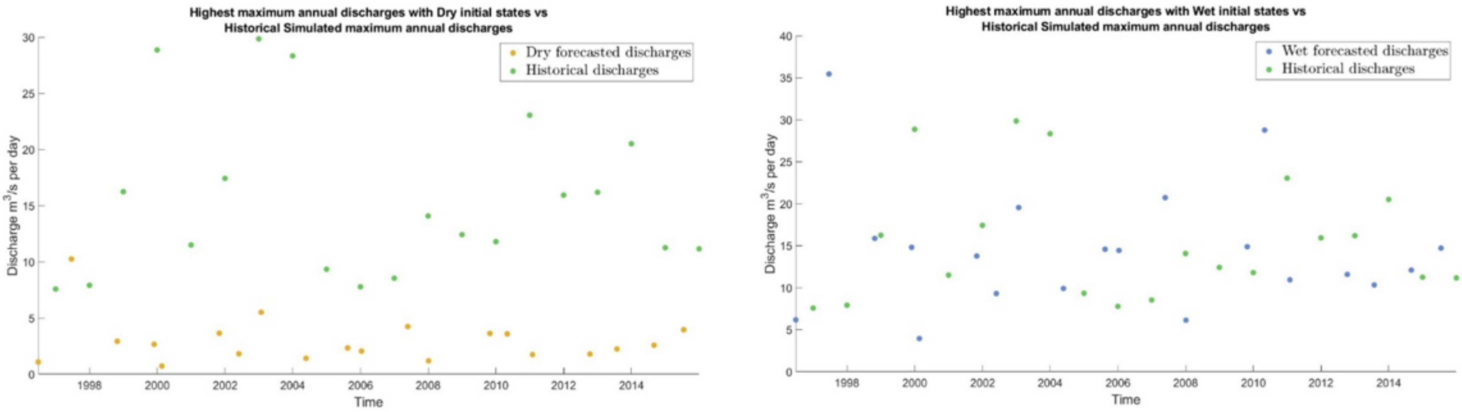


Figure 45: Comparison of historical vs forecasted extreme discharges at Hermeton at Hastiere.

Statistical analysis for historical simulated maximum annual discharges

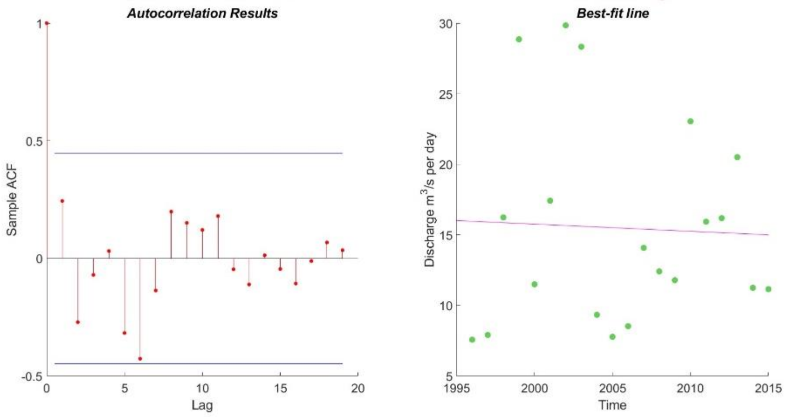


Figure 46: Graphs for the historical simulated maximum annual discharges (Hermeton at Hastiere).

Table 20: Statistical results of the historical simulated maximum annual discharges at Hermeton at Hastiere.

Results for the historical discharge values at Hermeton					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,86123	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,80161	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,77029	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	1,00000	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,55163	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,30539	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,93279	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

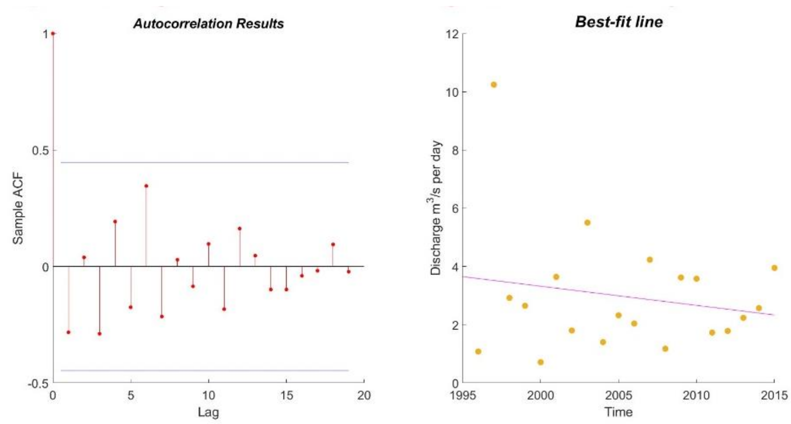


Figure 47: Graphs for the highest maximum annual discharges with the dry initial states (Hermeton at Hastiere).

Table 21: Statistical results of the highest maximum annual discharges with the dry initial states at Hermeton at Hastiere.

Results for the first highest dry maximum discharge values at Hermeton					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,43408	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,91141	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,92246	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,97051	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	1,00000	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,67843	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,73542	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

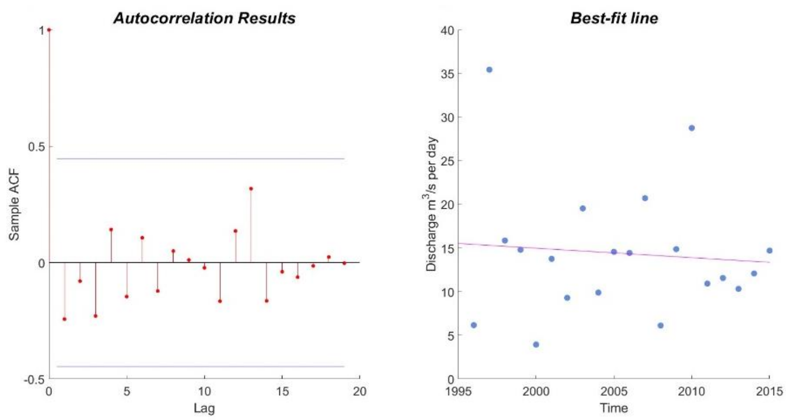


Figure 48: Graphs for the highest maximum annual discharges with the wet initial states (Hermeton at Hastiere).

Table 22: Statistical results of the highest maximum annual discharges with the wet initial states at Hermeton at Hastiere.

Results for the first highest wet maximum discharge values at Hermeton					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,71857	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,90637	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	1,00000	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,85343	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,76643	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,96993	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,44453	No Trend	No Trend	No Trend	No Trend

Ourthe at Tabreux

Comparison of historical vs forecasted extreme discharge values

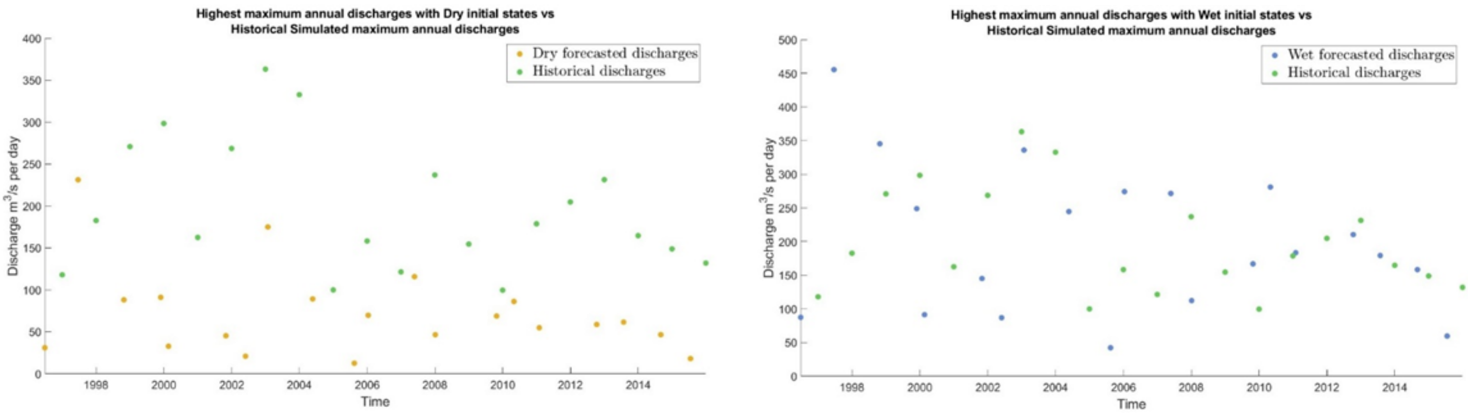


Figure 49: Comparison of historical vs forecasted extreme discharges at Ourthe at Tabreux.

Statistical analysis for historical simulated maximum annual discharges

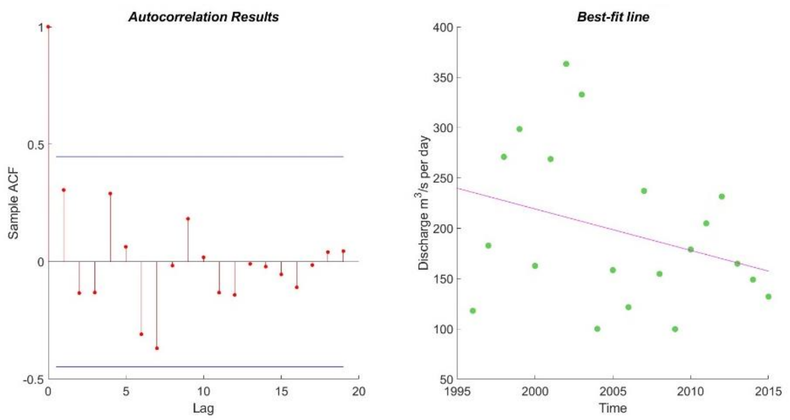


Figure 50: Graphs for the historical simulated maximum annual discharges (Ourthe at Tabreux).

Table 23: Statistical results of the historical simulated maximum annual discharges at Ourthe at Tabreux.

Results for the historical discharge values at Ourthe					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,17525	No Trend	No Trend	No Trend	descending trend
Spearman’s rank correlation test	0,22127	No Trend	No Trend	No Trend	descending trend
Mann-Kendall test	0,22997	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,16549	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,11194	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,02013	No Trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,73542	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

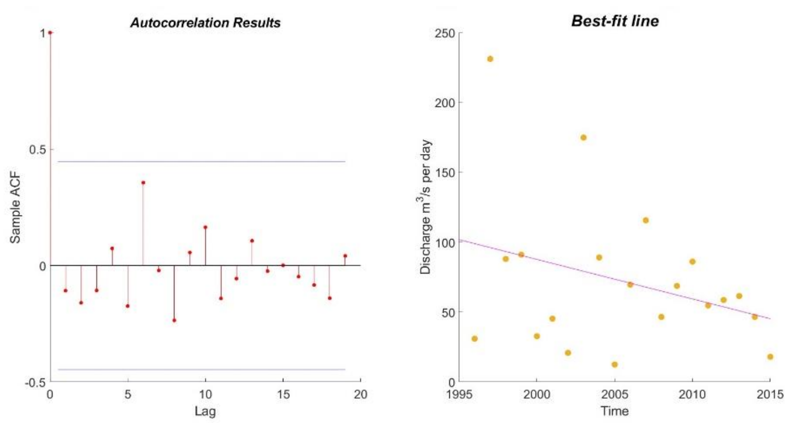


Figure 51: Graphs for the highest maximum annual discharges with the dry initial states (Ourthe at Tabreux).

Table 24: Statistical results of highest maximum annual discharges with the dry initial states at Ourthe at Tabreux.

Results for the first highest dry maximum discharge values at Ourthe					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,17698	No Trend	No Trend	No Trend	descending trend
Spearman's rank correlation test	0,41449	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,31452	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,97051	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,45610	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,73449	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,30560	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

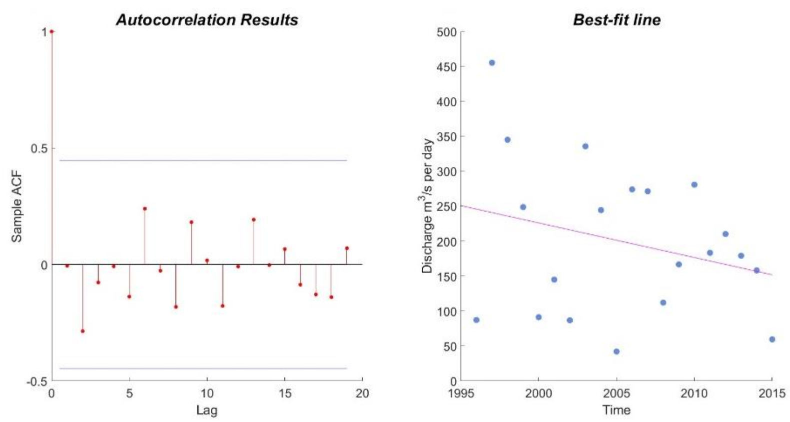


Figure 52: Graphs for the highest maximum annual discharges with the wet initial states (Ourthe at Tabreux).

Table 25: Statistical results of the highest maximum annual discharges with the wet initial states at Ourthe at Tabreux.

Results for the first highest wet maximum discharge values at Ourthe					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,24887	No Trend	No Trend	No Trend	descending trend
Spearman's rank correlation test	0,43708	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,31452	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,97051	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,55163	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,67843	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,44453	No Trend	No Trend	No Trend	No Trend

Sambre at Salzinnes

Comparison of historical vs forecasted extreme discharge values

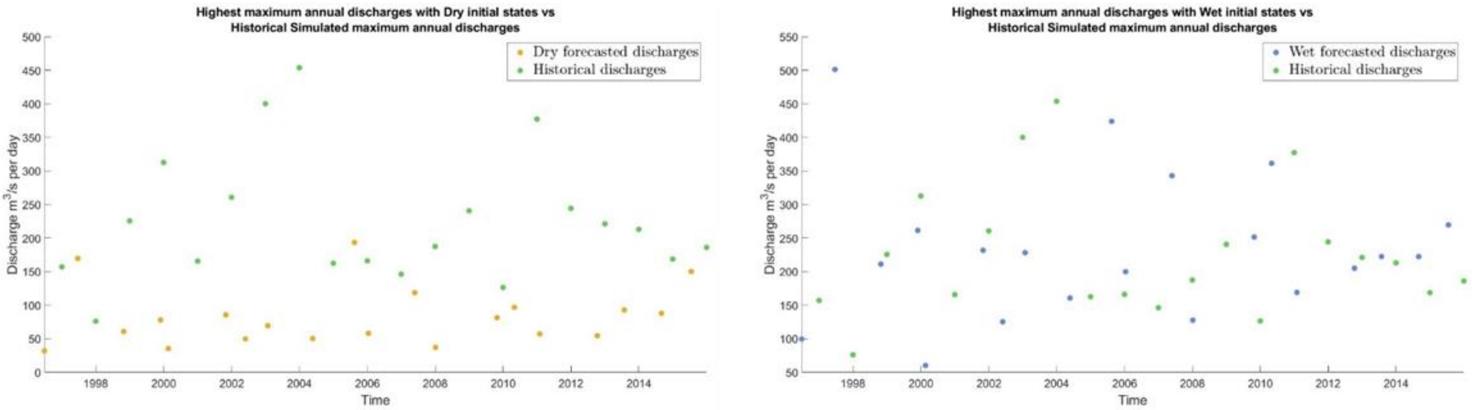


Figure 53: Comparison of historical vs forecasted extreme discharges at Sambre at Salzinnes.

Statistical analysis for historical simulated maximum annual discharges

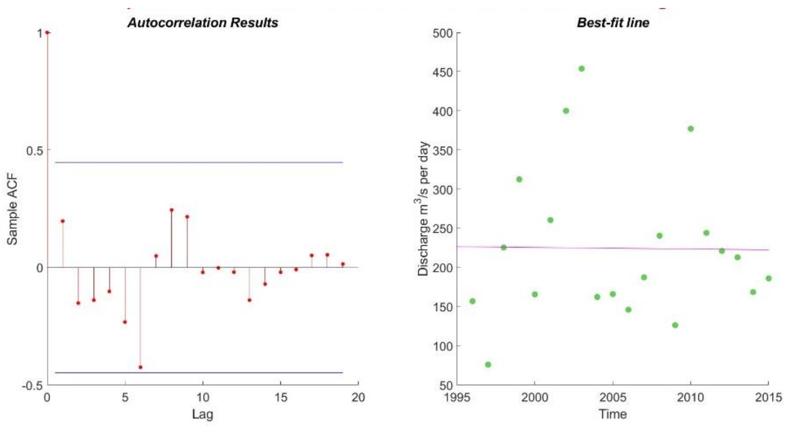


Figure 54: Graphs for the historical simulated maximum annual discharges (Sambre at Salzinnes).

Table 26: Statistical results of the historical simulated maximum annual discharges at Sambre at Salzinnes.

Results for the historical discharge values at Sambre					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,95914	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,75761	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,82034	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,85343	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,65563	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,38374	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,86597	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

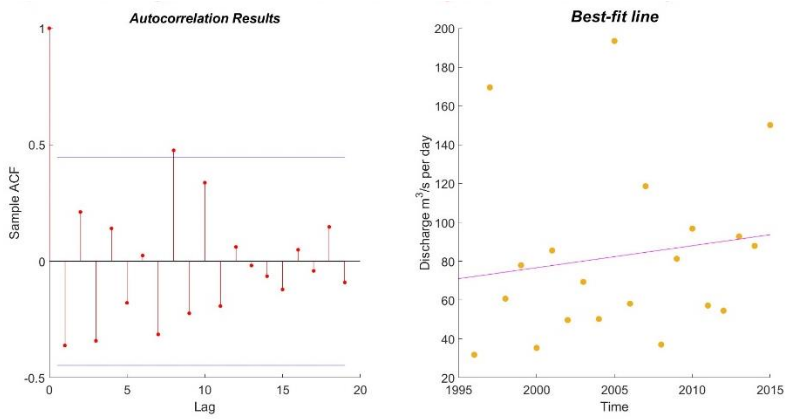


Figure 55: Graphs for the highest maximum annual discharges with the dry initial states (Sambre at Salzinnes).

Table 27: Statistical results of the highest maximum annual discharges with the dry initial states at Sambre at Salzinnes.

Results for the first highest dry maximum discharge values at Sambre					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,52710	No Trend	No Trend	No Trend	No Trend
Spearman’s rank correlation test	0,20893	No Trend	No Trend	No Trend	ascending trend
Mann-Kendall test	0,20575	No Trend	No Trend	No Trend	ascending trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,43587	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,13080	No Trend	No Trend	No Trend	ascending trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,27027	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,55315	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

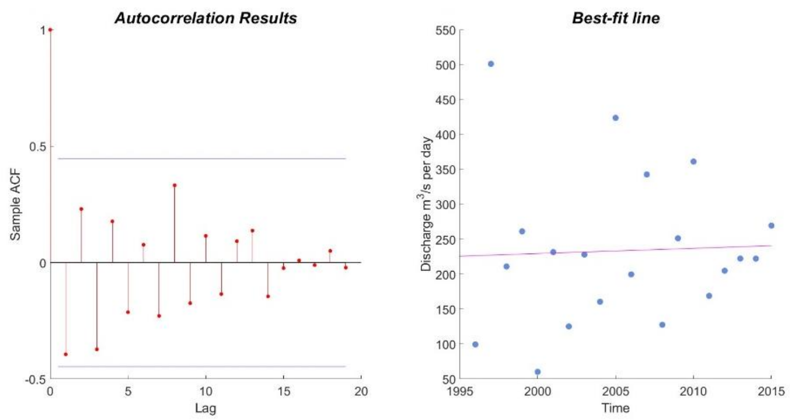


Figure 56: Graphs for the highest maximum annual discharges with the wet initial states (Sambre at Salzinnes).

Table 28: Statistical results of the highest maximum annual discharges with the wet initial states at Sambre at Salzinnes.

Results for the first highest wet maximum discharge values at Sambre					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,86360	No Trend	No Trend	No Trend	No Trend
Spearman’s rank correlation test	0,53378	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,49566	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,68421	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,29472	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,52081	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,93279	No Trend	No Trend	No Trend	No Trend

Meuse at Saint-Mihiel

Comparison of historical vs forecasted extreme discharge values

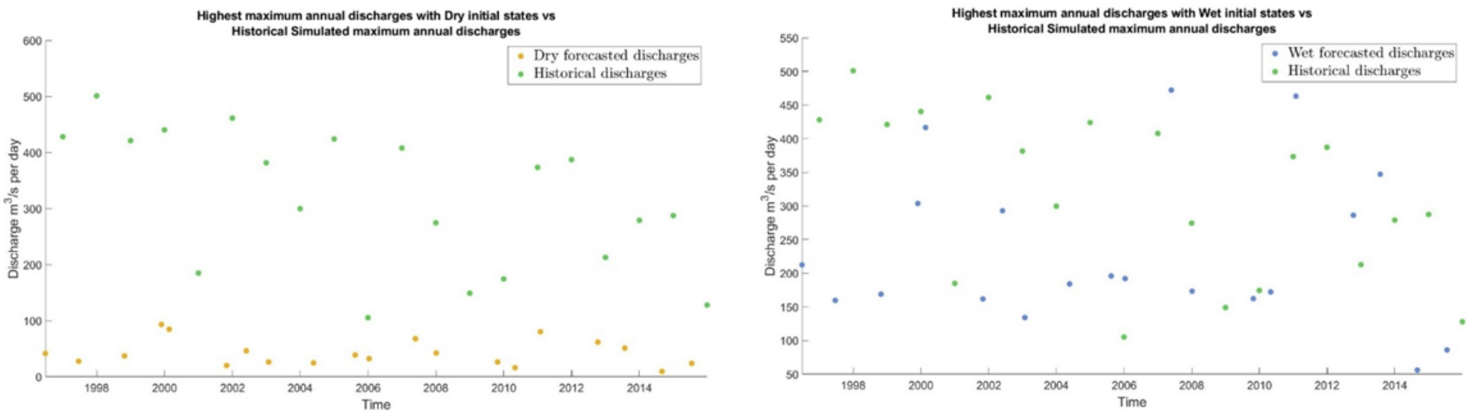


Figure 57: Comparison of historical vs forecasted extreme discharges at Meuse at Saint-Mihiel.

Statistical analysis for historical simulated maximum annual discharges

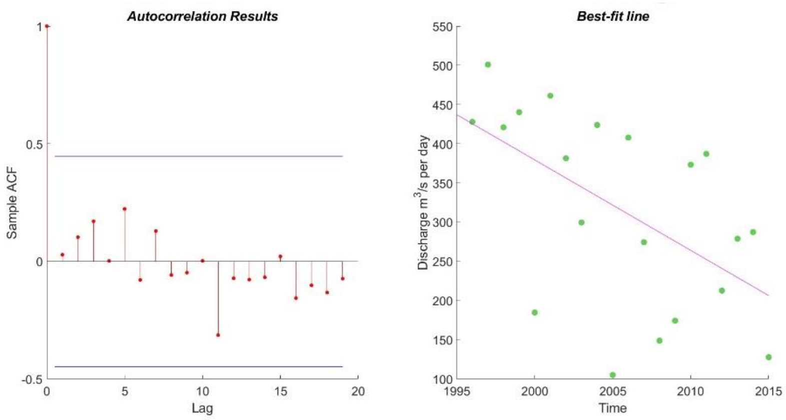


Figure 58: Graphs for the historical simulated maximum annual discharges (Meuse at Saint-Mihiel).

Table 29: Statistical results of the historical simulated maximum annual discharges at Meuse at Saint-Mihiel.

Results for the historical discharge values at Meuse at Saint-Mihiel					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,01104	No Trend	descending trend	descending trend	descending trend
Spearman’s rank correlation test	0,00445	descending trend	descending trend	descending trend	descending trend
Mann-Kendall test	0,00859	descending trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,03546	No Trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,00314	descending trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,01240	No Trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,23001	No Trend	No Trend	No Trend	descending trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

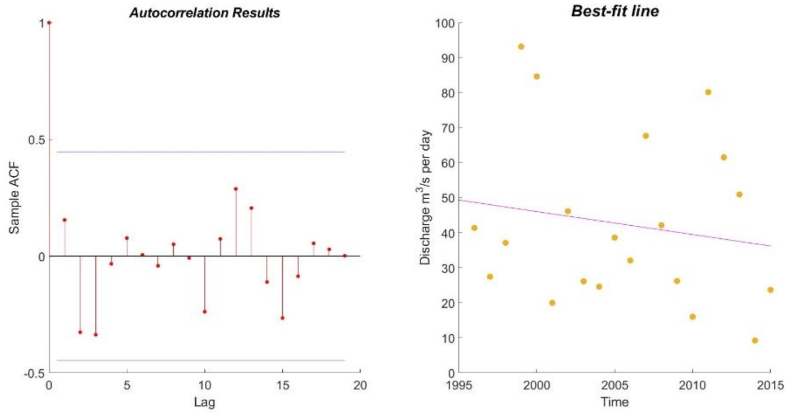


Figure 59: Graphs for the highest maximum annual discharges with the dry initial states (Meuse at Saint-Mihiel).

Table 30: Statistical results of the highest maximum annual discharges with the dry initial states at Meuse at Saint-Mihiel.

Results for the first highest dry maximum discharge values at Meuse at Saint-Mihiel					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,49189	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,42948	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,41730	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,85343	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,88198	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,57136	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,93279	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

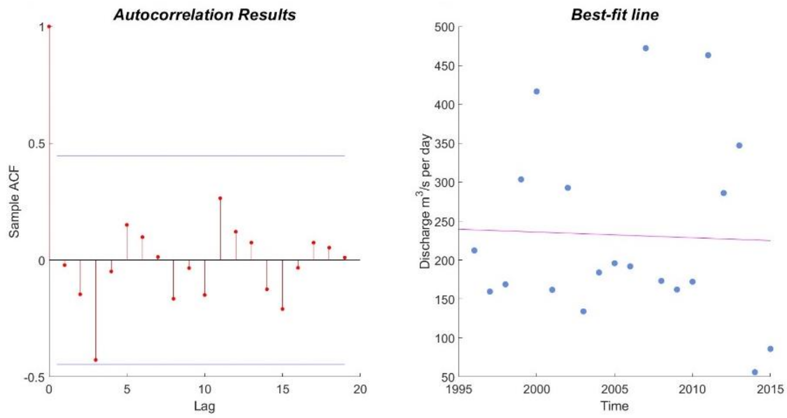


Figure 60: Graphs for the highest maximum annual discharges with the wet initial states (Meuse at Saint-Mihiel).

Table 31: Statistical results of the highest maximum annual discharges with the wet initial states at Meuse at Saint-Mihiel

Results for the first highest wet maximum discharge values at Meuse at Saint-Mihiel					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,87849	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,74793	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,77029	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,91180	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,82376	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,85063	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	1,00000	No Trend	No Trend	No Trend	No Trend

Semois at Membre Pont

Comparison of historical vs forecasted extreme discharge values

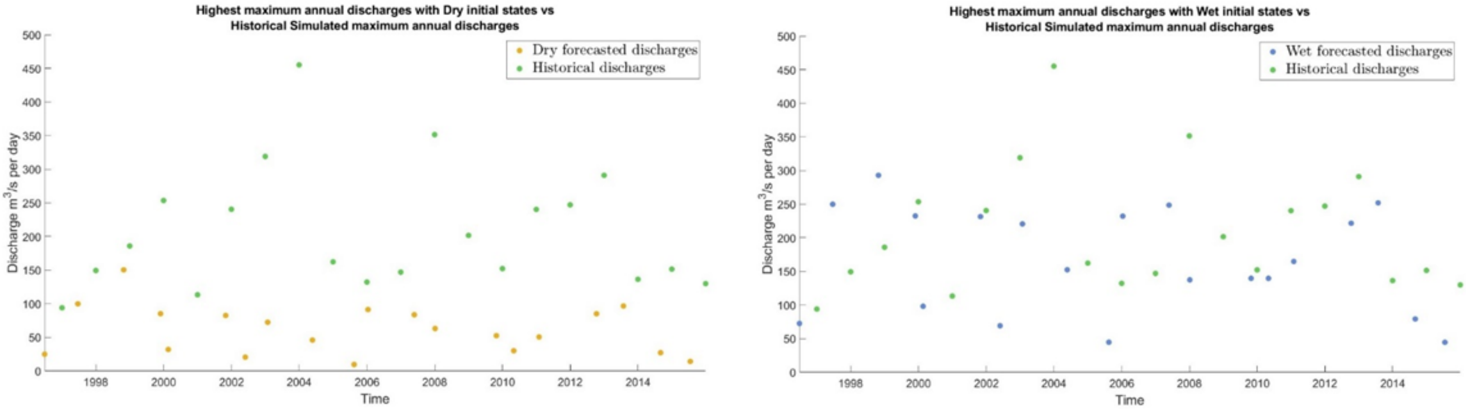


Figure 61: Comparison of historical vs forecasted extreme discharges at Semois at Membre Pont.

Statistical analysis for historical simulated maximum annual discharges

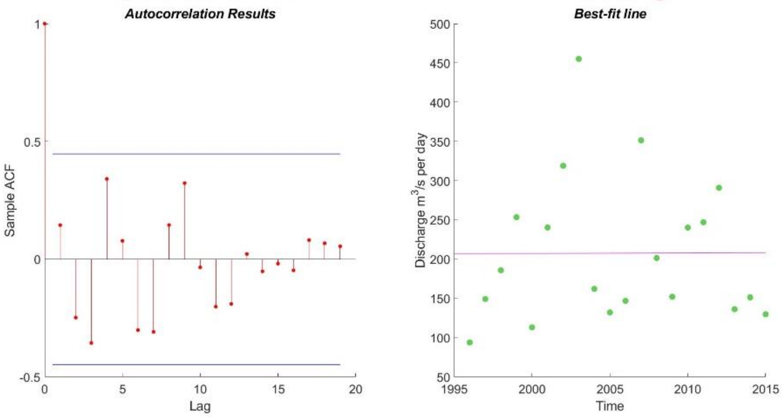


Figure 62: Graphs for the historical simulated maximum annual discharges (Semois at Membre Pont).

Table 32: Statistical results of the historical simulated maximum annual discharges at Semois at Membre Pont.

Results for the historical discharge values at Semois					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,98725	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,90637	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,87113	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,91180	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,76643	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,73449	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,73542	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

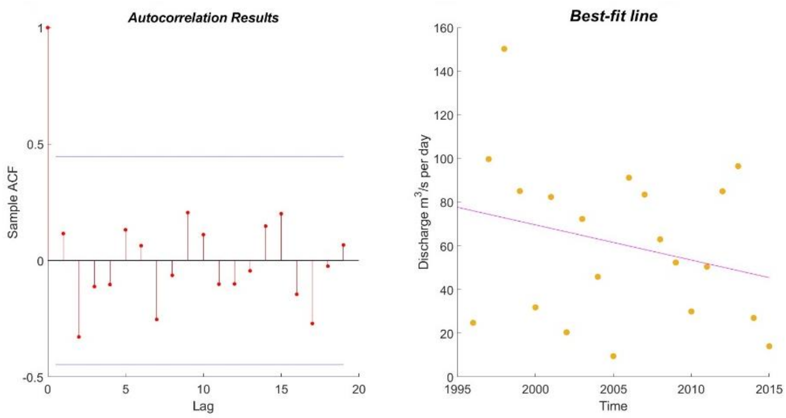


Figure 63: Graphs for the highest maximum annual discharges with the dry initial states (Semois at Membre Pont).

Table 33: Statistical results of the highest maximum annual discharges with the dry initial states at Semois at Membre Pont.

Results for the first highest dry maximum discharge values at Semois					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,26380	No Trend	No Trend	No Trend	No Trend
Spearman’s rank correlation test	0,36783	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,28432	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,91180	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,60268	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,47267	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,80005	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

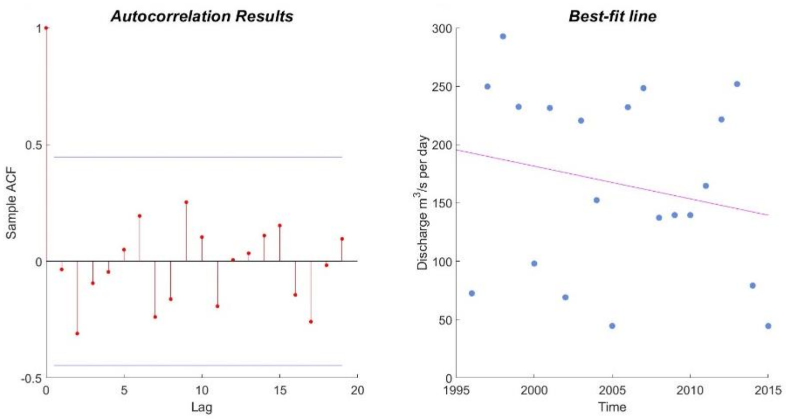


Figure 64: Graphs for the highest maximum annual discharges with the wet initial states (Semois at Membre Pont).

Table 34: Statistical results of the highest maximum annual discharges with the wet initial states at Semois at Membre Pont.

Results for the first highest wet maximum discharge values at Semois					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,37451	No Trend	No Trend	No Trend	No Trend
Spearman’s rank correlation test	0,37131	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,34676	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	1,00000	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,55163	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,52081	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,80005	No Trend	No Trend	No Trend	No Trend

Lesse at Gendron

Comparison of historical vs forecasted extreme discharge values

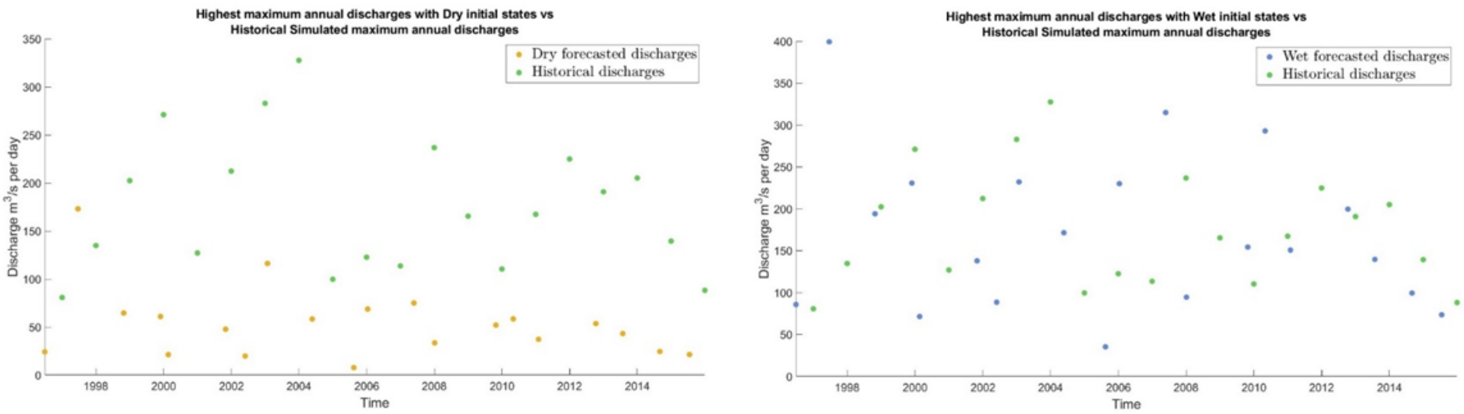


Figure 65: Comparison of historical vs forecasted extreme discharges at Lesse at Gendron.

Statistical analysis for historical simulated maximum annual discharges

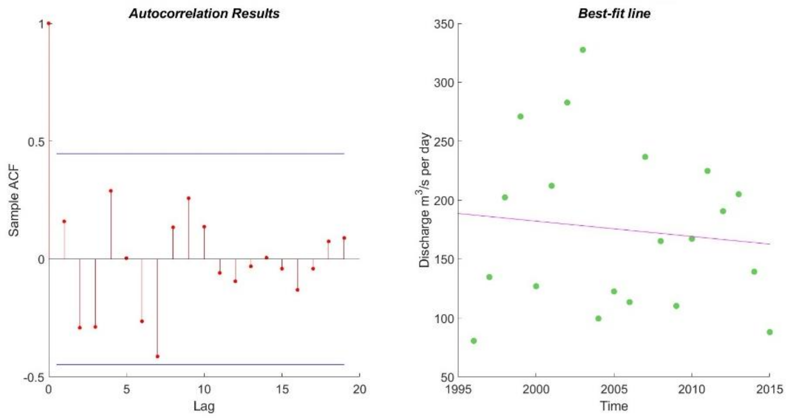


Figure 66: Graphs for the historical simulated maximum annual discharges (Lesse at Gendron).

Table 35: Statistical results of the historical simulated maximum annual discharges at Lesse at Gendron.

Results for the historical discharge values at Lesse					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,64257	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,80653	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,87113	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,73936	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,50273	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,20829	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	1,00000	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

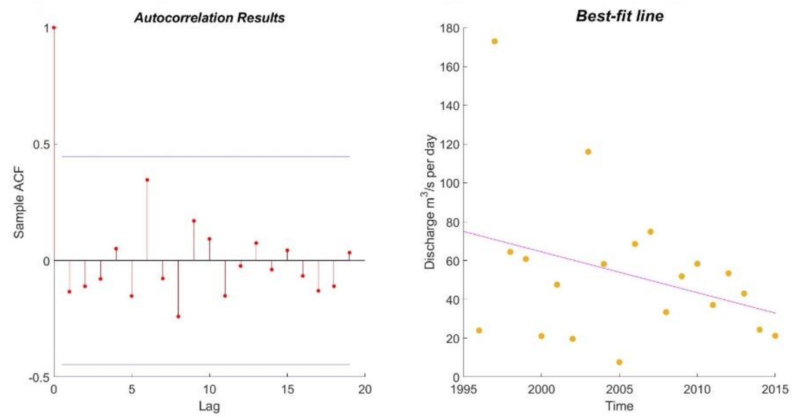


Figure 67: Graphs for the highest maximum annual discharges with the dry initial states (Lesse at Gendron).

Table 36: Statistical results of the highest maximum annual discharges with the dry initial states at Lesse at Gendron.

Results for the first highest dry maximum discharge values at Lesse					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,15465	No Trend	No Trend	No Trend	descending trend
Spearman’s rank correlation test	0,37831	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,22997	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,97051	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,55163	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,67843	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,26612	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

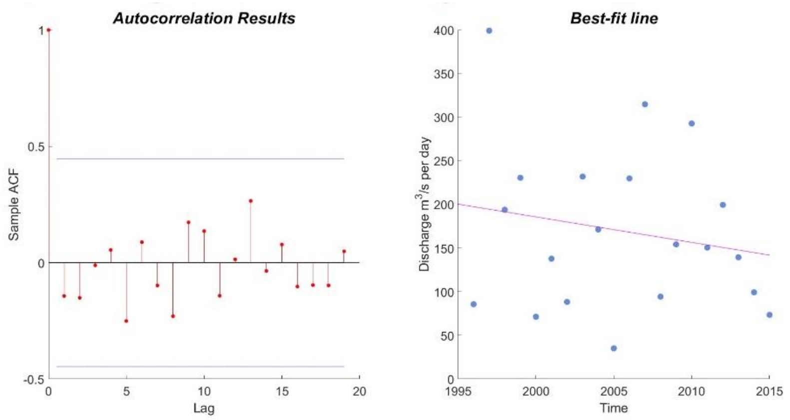


Figure 68: Graphs for the highest maximum annual discharges with the wet initial states (Lesse at Gendron).

Table 37: Statistical results of the highest maximum annual discharges with the wet initial states at Lesse at Gendron.

Results for the first highest wet maximum discharge values at Lesse					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,43440	No Trend	No Trend	No Trend	No Trend
Spearman’s rank correlation test	0,69066	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,58125	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,63053	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,88198	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,96993	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,44453	No Trend	No Trend	No Trend	No Trend

Chiers at Carignan

Comparison of historical vs forecasted extreme discharge values

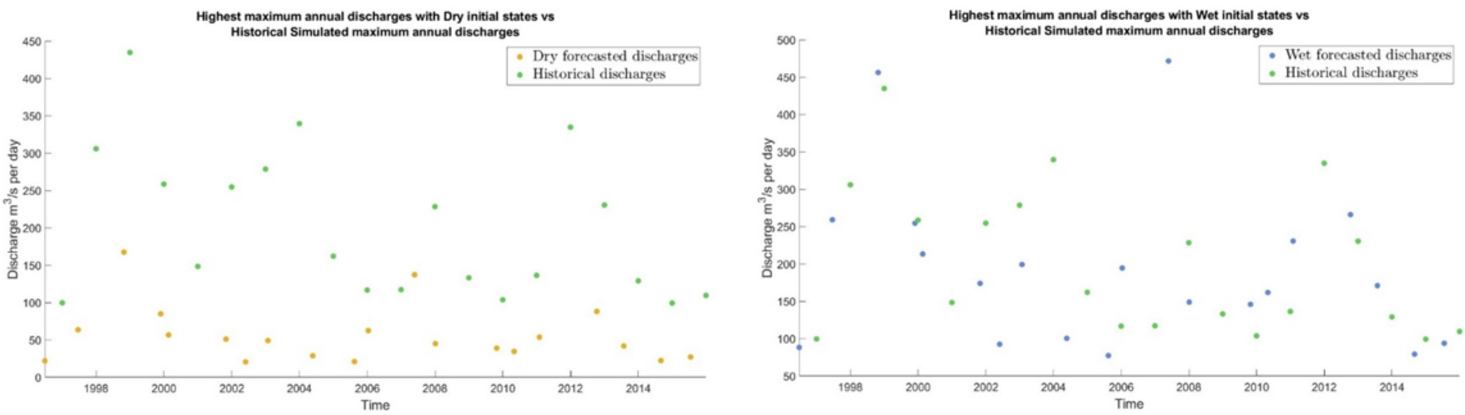


Figure 69: Comparison of historical vs forecasted extreme discharges at Chiers at Carignan.

Statistical analysis for historical simulated maximum annual discharges

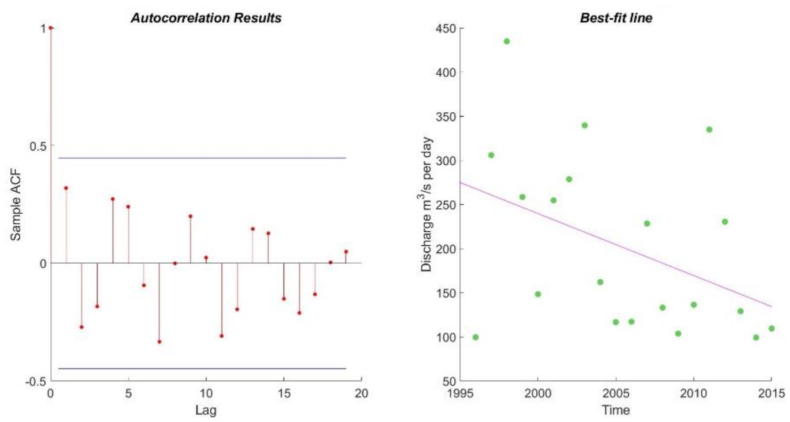


Figure 70: Graphs for the historical simulated maximum annual discharges (Chiers at Carignan).

Table 38: Statistical results of the historical simulated maximum annual discharges at Chiers at Carignan.

Results for the historical discharge values at Chiers					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,06625	No Trend	No Trend	descending trend	descending trend
Spearman's rank correlation test	0,06897	No Trend	No Trend	descending trend	descending trend
Mann-Kendall test	0,05559	No Trend	No Trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,07526	No Trend	No Trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,02505	No Trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,02524	No Trend	descending trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,44453	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

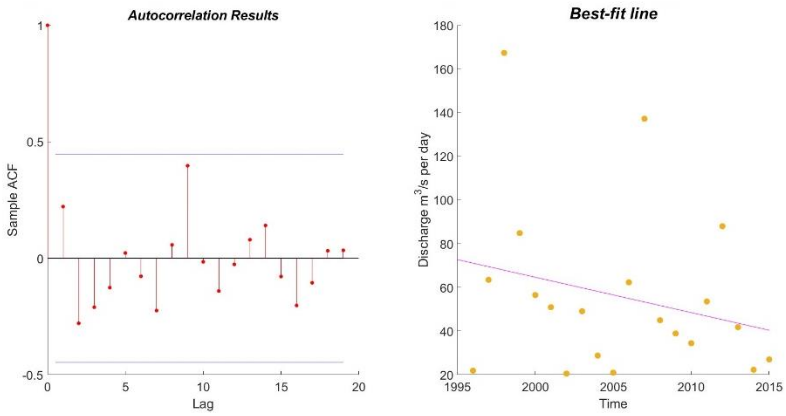


Figure 71: Graphs for the highest maximum annual discharges with the dry initial states (Chiers at Carignan).

Table 39: Statistical results of the highest maximum annual discharges with the dry initial states at Chiers at Carignan.

Results for the first highest dry maximum discharge values at Chiers					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,29328	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,37480	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,25614	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,85343	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,71030	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,47267	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,80005	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

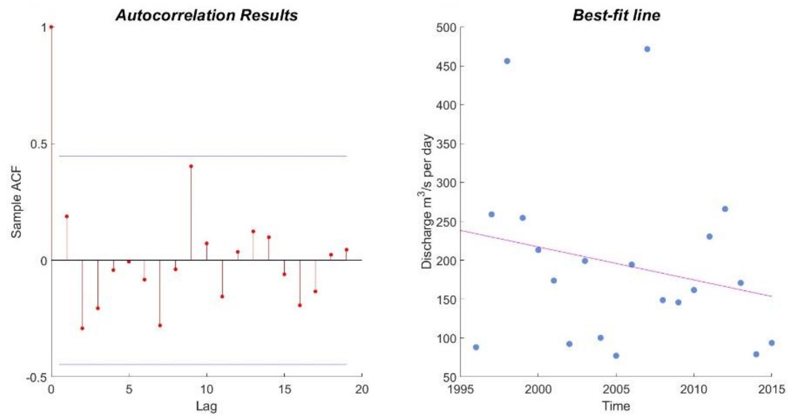


Figure 72: Graphs for the highest maximum annual discharges with the wet initial states (Chiers at Carignan).

Table 40: Statistical results of the highest maximum annual discharges with the wet initial states at Chiers at Carignan.

Results for the first highest wet maximum discharge values at Chiers					
Type of Statistical Test	**P Values**	**Significance Levels**			
		α = 0.01	**α = 0.05**	**α = 0.10**	**α = 0.25**
Pearson t-test	0,33725	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,36437	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,31452	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,97051	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,55163	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,34315	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,86597	No Trend	No Trend	No Trend	No Trend

Bar at Cheveuges

Comparison of historical vs forecasted extreme discharge values

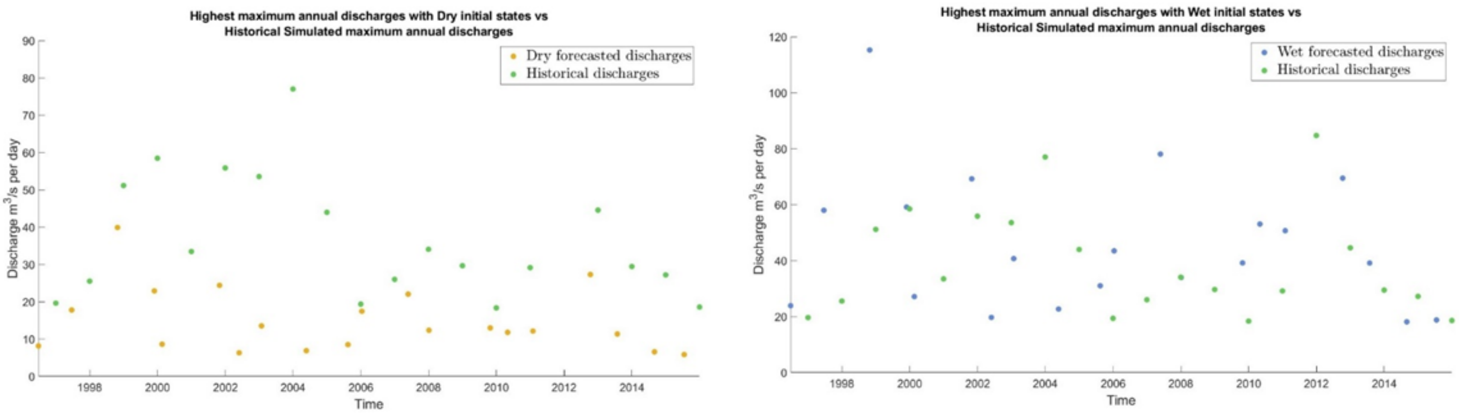


Figure 73: Comparison of historical vs forecasted extreme discharges at Bar at Cheveuges.

Statistical analysis for historical simulated maximum annual discharges

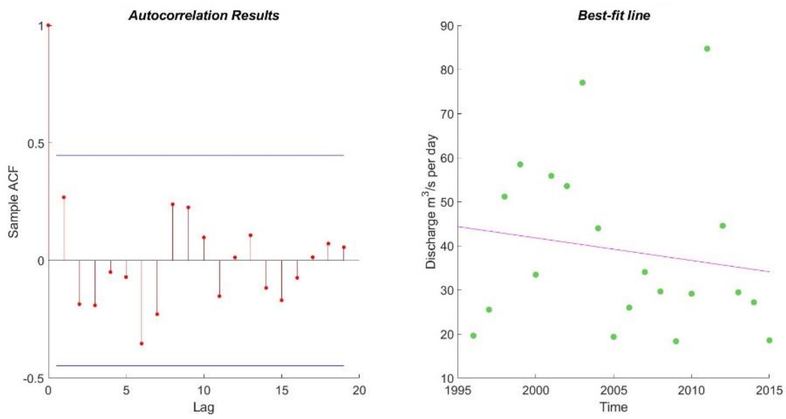


Figure 74: Graphs for the historical simulated maximum annual discharges (Bar at Cheveuges).

Table 41: Statistical results of the historical simulated maximum annual discharges at Bar at Cheveuges.

Results for the historical discharge values at Bar					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,50753	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,37480	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,34676	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,24745	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,08040	No Trend	No Trend	descending trend	descending trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,11527	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	1,00000	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the DRY initial states

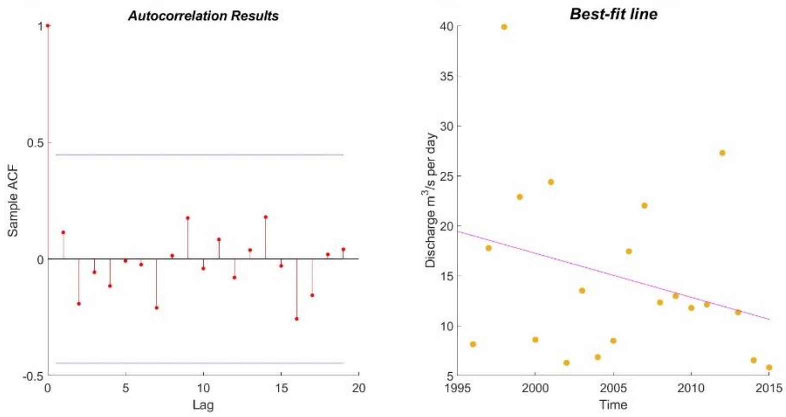


Figure 75: Graphs for the highest maximum annual discharges with the dry initial states (Bar at Cheuveuges).

Table 42: Statistical results of the highest maximum annual discharges with the dry initial states at Bar at Cheveuges.

Results for the first highest dry maximum discharge values at Bar					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,20291	No Trend	No Trend	No Trend	descending trend
Spearman's rank correlation test	0,22379	No Trend	No Trend	No Trend	descending trend
Mann-Kendall test	0,18345	No Trend	No Trend	No Trend	descending trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,91180	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,65563	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,34315	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,34856	No Trend	No Trend	No Trend	No Trend

Statistical Analysis for the highest maximum annual discharges obtained with the WET initial states

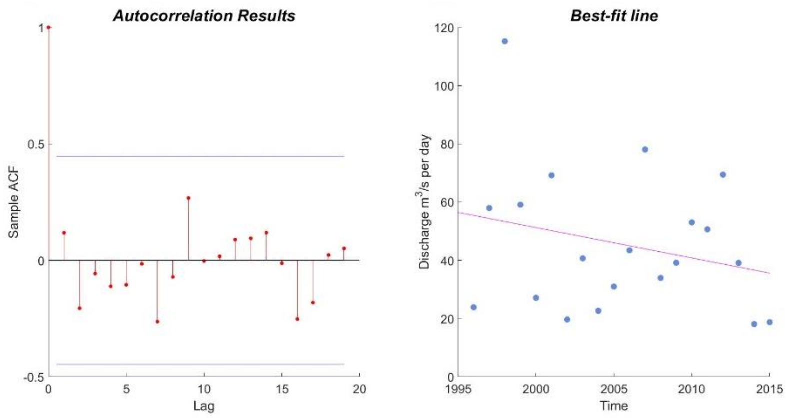


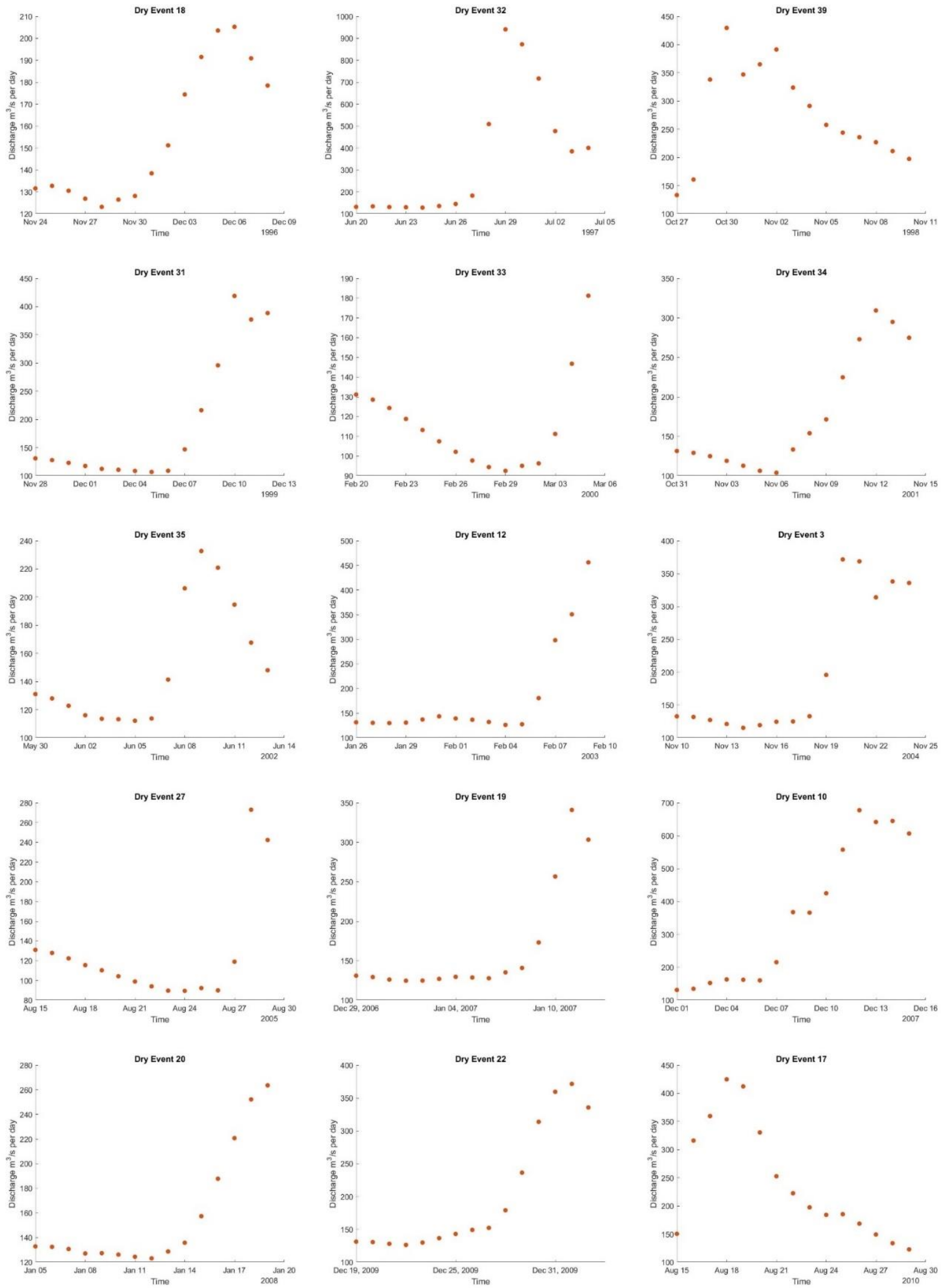
Figure 76: Graphs for the highest maximum annual discharges with the wet initial states (Bar at Cheuveuges).

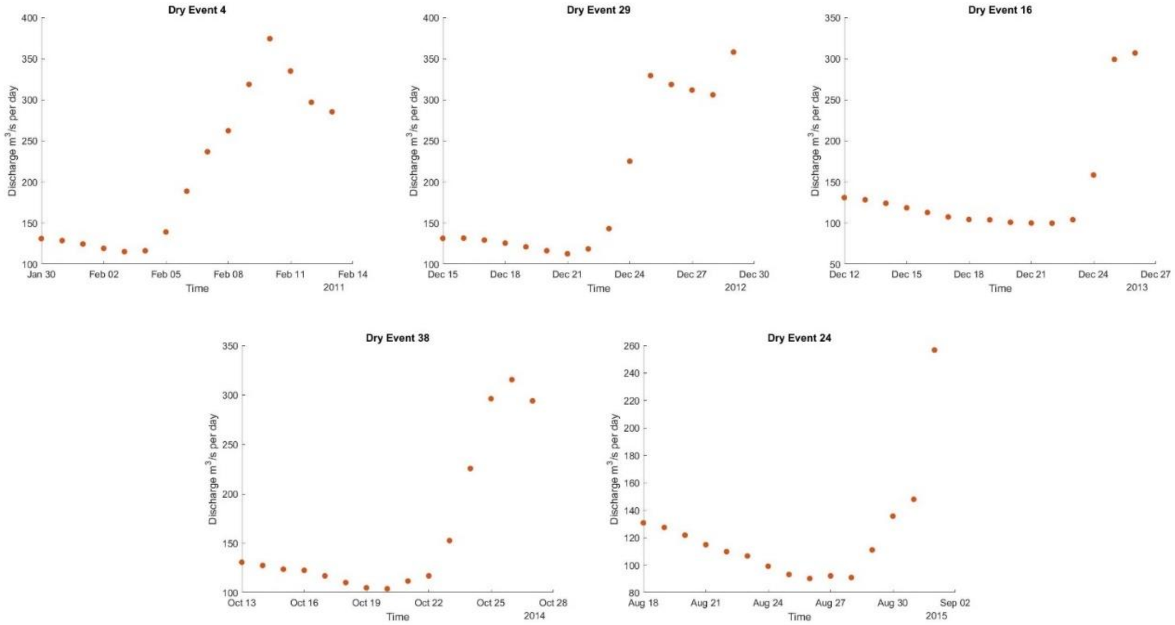
Table 43: Statistical results of the highest maximum annual discharges with the wet initial states at Bar at Cheveuges.

Results for the first highest wet maximum discharge values at Bar					
Type of Statistical Test	P Values	Significance Levels			
		α = 0.01	α = 0.05	α = 0.10	α = 0.25
Pearson t-test	0,28378	No Trend	No Trend	No Trend	No Trend
Spearman's rank correlation test	0,33741	No Trend	No Trend	No Trend	No Trend
Mann-Kendall test	0,49566	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10	0,97051	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11	0,88198	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12	0,52081	No Trend	No Trend	No Trend	No Trend
Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5	0,44453	No Trend	No Trend	No Trend	No Trend

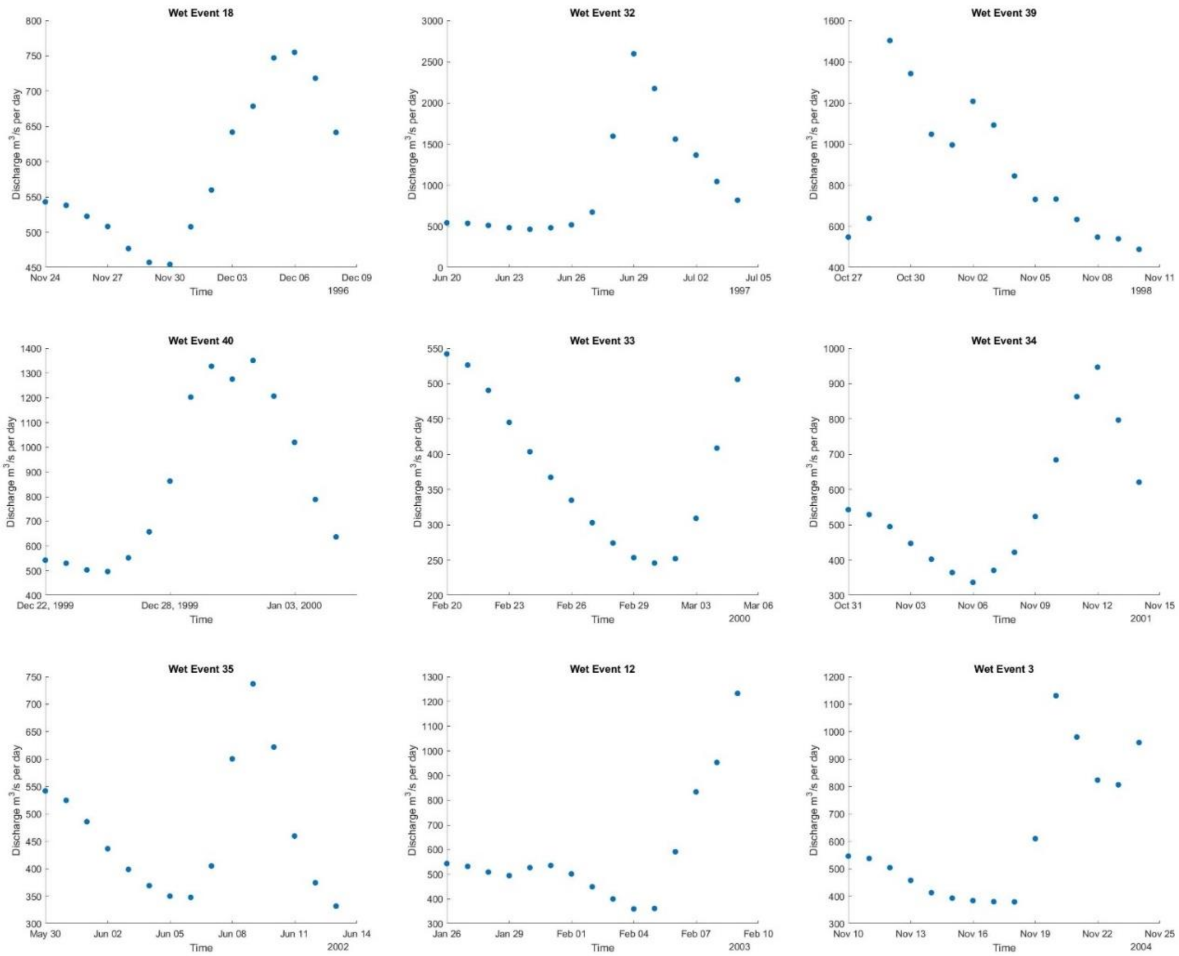
Appendix D: Hydrographs of the forecasted Dry and Wet Events for Borgharen,

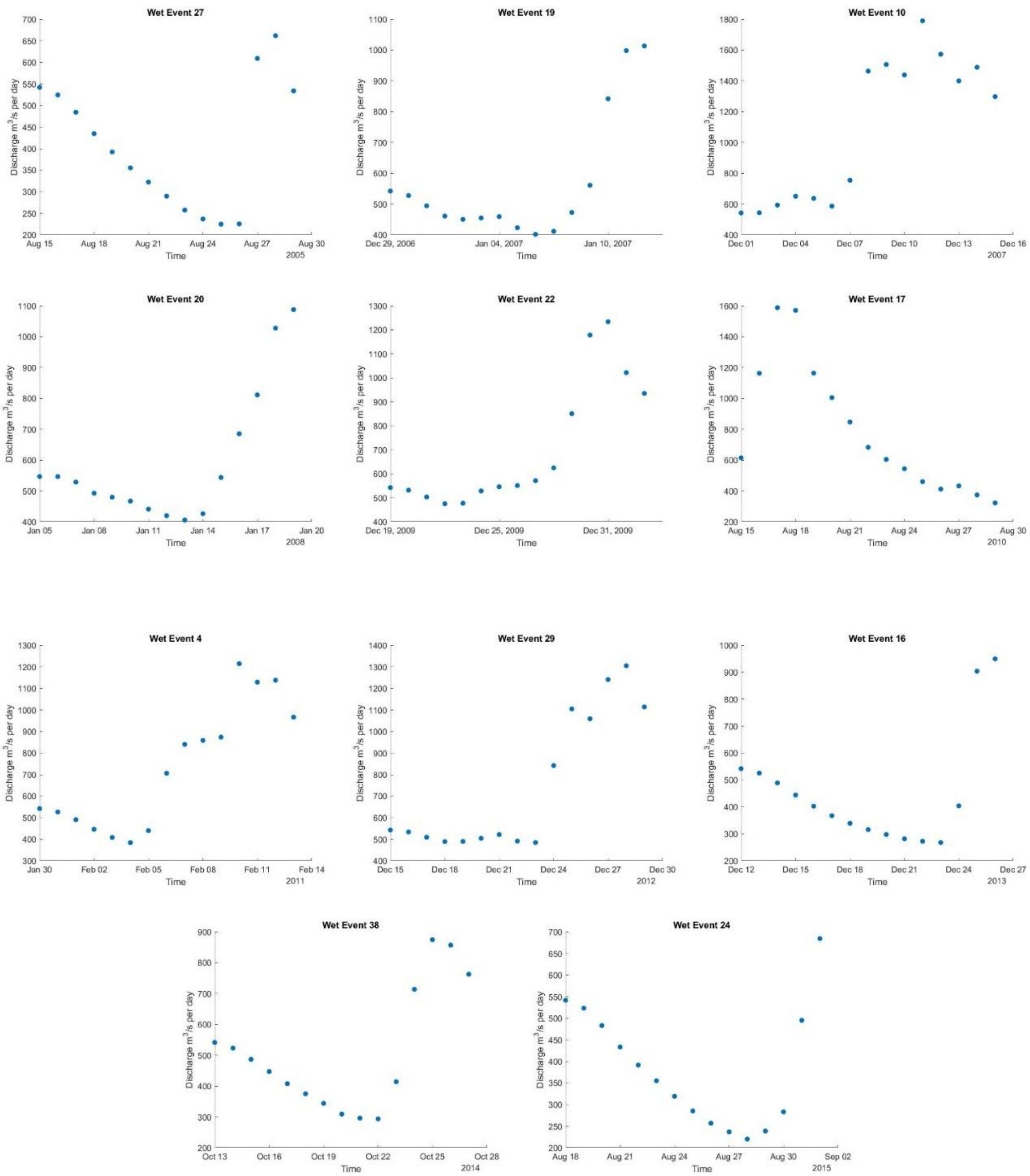
Hydrographs for the 20 most extreme dry events per year





Hydrographs for the 20 most extreme wet events per year





Wet Event 27
Discharge m3/s per day
Time
2005
Wet Event 19
Discharge m3/s per day
Time
Wet Event 10
Discharge m3/s per day
Time
2007
Wet Event 20
Discharge m3/s per day
Time
2008
Wet Event 22
Discharge m3/s per day
Time
Wet Event 17
Discharge m3/s per day
Time
2010
Wet Event 4
Discharge m3/s per day
Time
2011
Wet Event 29
Discharge m3/s per day
Time
2012
Wet Event 16
Discharge m3/s per day
Time
2013
Wet Event 38
Discharge m3/s per day
Time
2014
Wet Event 24
Discharge m3/s per day
Time
2015

Appendix E: Matlab scripts

E1: Main Code

This code was created to perform the autocorrelation test, the best-fit line, comparison of historical with forecasted discharges and statistical analysis of the three data sets of extreme discharges

```
clear all; clc
```

COMMON VARIABLES

```
N= 20;  % number of years
df=2;
indices= [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20];
years= [1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
2015];
```

READING THE FILE THAT CONTAINS THE HISTORICAL DISCHARGES

```
maximum_historical_data= readtable('E:\Carpetas de usuario - Disco E\Escritorio\Jupiter
Scripts\1_results_Borgharen\data_MAXIMUM_HISTORICAL_20_YEARS.xlsx');
maximum_historical_discharges= table2array(maximum_historical_data(:,2));
maximum_historical_discharges= maximum_historical_discharges';

maximum_historical_time= table2array(maximum_historical_data(:,1));
maximum_historical_time= datetime(maximum_historical_time, 'InputFormat','dd-MM-
yyyy''HH:mm:ss','Format','yyyy');
```

READING ALL THE FILES THAT CONTAIN THE FORECASTED DISCHARGE RESULTS

```
% Load all the excell files for each gauge station
[file_list, path_n ] = uigetfile('.xlsx' ,'Grab the files','MultiSelect','on');

% to check if there is any file in another format like a text file and change it to a cell array
if iscell(file_list) == 0
    file_list = {files_list};
end

% Initialize structure
data_structure = [];

% Loop through imported files and add data to structure
for a = 1: length(file_list)
    filename = file_list{a};
    data_in = readtable([path_n filename]);

    % Get subject id
    sub_id = filename(1:end-5);

    % Parse data
    time = table2array(data_in(:,2));
    time = datetime(time, 'InputFormat','yyyy-MM-dd''T''HH:mm:ss', 'Format','dd-MMM-yyyy HH');
    discharge = table2array(data_in(:,3));

    % Add data to structure
```

```
    data_structure.(sub_id).time = time;
    data_structure.(sub_id).discharge = discharge;
end

% AUTOMATE: find structure fields and loop through
fnames = fieldnames(data_structure);  % list of all the event names: dry and wet together
for b = 1 : length(fnames)
    data_structure.(fnames{b}).discharge;
end
```

EXTRACTING THE MAXIMUM DISCHARGE VALUE FOR EACH OF THE 15 VALUES OF EACH DRY EVENT (40 EVENTS)

```
% Every single DRY event has a total of 15 discharge values for each of the 15 days that compose the
event Therefore, the MAXIMUM discharge value of all these 15 values is extracted with its respective
year
maximum_DRY_time = [];
maximum_DRY_discharge = [];
for c = 1 : 40
    time_y = datetime(data_structure.(fnames{c}).time, 'Format','yyyy');
    maximum_DRY_time =[ maximum_DRY_time , time_y(1)];
    maximum_DRY_discharge = [maximum_DRY_discharge , max(data_structure.(fnames{c}).discharge)];
end
[maximum_DRY_time, order] = sort(maximum_DRY_time);    % order the events: 1996, 1996, 1997, 1997,
1998, 1998
maximum_DRY_discharge = maximum_DRY_discharge(order);  % assign to each year its respective discharge
values

% create a table for all the 40 events
varNames1 = ["Time","Discharges"];
table1= table(maximum_DRY_time', maximum_DRY_discharge','VariableNames',varNames1);
table1 = table(table1,'VariableNames',{'40 MAXIMUM DRY FORECASTED EVENTS'})
```

Highest Maximum Annual Discharges Obtained with the Dry Initial States

```
% Selecting just the first highest MAXIMUM discharge values for the DRY EVENTS
for d=1:20
    first_maximum_DRY(d)= max([maximum_DRY_discharge(d*2-1) maximum_DRY_discharge(d*2)]);
end
DRY_years= maximum_DRY_time(1:2:end);

% create a table for the first highest Dry discharges
table2= table(DRY_years', first_maximum_DRY','VariableNames',varNames1);
table2 = table(table2,'VariableNames',{'First Highest DRY MAXIMUM Discharge Values'})
```

EXTRACTING THE MAXIMUM DISCHARGE VALUE FOR EACH OF THE 15 VALUES OF EACH WET EVENT (40 EVENTS)

```
% Every single WET event has a total of 15 discharge values for each of the 15 days that compose the
event. Therefore, the MAXIMUM discharge value of all these 15 values is extracted with its respective
year
maximum_WET_time = [];
maximum_WET_discharge = [];
for e = 41 : 80
    time_y = datetime(data_structure.(fnames{e}).time, 'Format','yyyy');
```

```
    maximum_WET_time =[ maximum_WET_time , time_y(1)];
    maximum_WET_discharge = [maximum_WET_discharge , max(data_structure.(fnames{e}).discharge)];
end
[maximum_WET_time, order] = sort(maximum_WET_time);   % order the events: 1996, 1996, 1997, 1997,
1998, 1998
maximum_WET_discharge = maximum_WET_discharge(order); % assign to each year its respective discharge
values

% create a table for all the 40 events
table3= table(maximum_WET_time', maximum_WET_discharge','VariableNames',varNames1);
table3 = table(table3,'VariableNames',{'40 MAXIMUM WET FORECASTED EVENTS'})
```

Highest Maximum Annual Discharges Obtained with the Wet Initial States

```
% Selecting just the first highest MAXIMUM discharge values for the WET EVENTS
for f=1:20
    first_maximum_WET(f)= max([maximum_WET_discharge(f*2-1) maximum_WET_discharge(f*2)]);
end
WET_years= maximum_WET_time(1:2:end);

% create a table for the first highest Wet discharges
table4= table(WET_years', first_maximum_WET','VariableNames',varNames1);
table4= table(table4,'VariableNames',{'First Highest WET MAXIMUM Discharge Values'})
```

HYDROGRAPHS FOR THE 40 DRY & 40 WET EVENTS

```
% Create the 40 individual plots of the Dry Events
path='C:\Users\moretaur\OneDrive - Stichting Deltares\Desktop\FOR THE
REPORT\1_for_Borgharen\discharge_hydrographs';

for iFig=1:40
    figure(iFig), hold on
    plottime = eval(['data_structure.Dry' num2str(iFig) '.time']);
    plotdischarge = eval(['data_structure.Dry' num2str(iFig) '.discharge']);
    plot(plottime, plotdischarge,'.','MarkerSize',20,'MarkerEdgeColor',[0.8500 0.3250 0.0980])
    title(['Dry Event ' num2str(iFig)])
    xlabel('Time')
    ylabel('Discharge m^3/s per day')
    saveas(figure(iFig),fullfile(path,['Dry' num2str(iFig) '.jpeg']));
    hold off
end

% Create the 40 individual plots of the Wet Events
path='C:\Users\moretaur\OneDrive - Stichting Deltares\Desktop\FOR THE
REPORT\1_for_Borgharen\discharge_hydrographs';
for idx=1:40
    figure(idx), hold on
    plottime = eval(['data_structure.Wet' num2str(idx) '.time']);
    plotdischarge = eval(['data_structure.Wet' num2str(idx) '.discharge']);
    plot(plottime, plotdischarge,'.','MarkerSize',20,'MarkerEdgeColor',[0 0.4470 0.7410])
    title(['Wet Event ' num2str(idx)])
    xlabel('Time')
    ylabel('Discharge m^3/s per day')
    saveas(figure(idx),fullfile(path,['Wet' num2str(idx) '.jpeg']));
    hold off
end
```

PLOTS FOR COMPARISON OF HISTORICAL VS FIRST MAXIMUMS FORECASTED DISCHARGES

```
figure (2), clf(2), hold on
Graph_dry2= plot(DRY_years, first_maximum_DRY,'.','MarkerSize',26,'MarkerEdgeColor',[0.9290 0.6940 0.1250]);
Graph_historical2= plot(maximum_historical_time, maximum_historical_discharges,'.','MarkerSize',26,'MarkerEdgeColor',[0.40 0.80 0.35]);
title({'Highest maximum annual discharges with Dry initial states vs';'Historical Simulated maximum annual discharges'},'FontSize',22)
set(gca, 'FontSize', 15)
xlabel('Time','FontSize',18)
ylabel('Discharge m^3/s per day','FontSize',18)
legend([Graph_dry2 Graph_historical2],{'Dry forecasted discharges','Historical discharges'},'Location','northeast','Interpreter','latex','FontSize',20)
hold off

figure (3), clf(3), hold on
Graph_wet3= plot(WET_years, first_maximum_WET,'.','MarkerSize',26,'MarkerEdgeColor',[0.40 0.55 0.85]);
Graph_historical3= plot(maximum_historical_time, maximum_historical_discharges,'.','MarkerSize',26,'MarkerEdgeColor',[0.40 0.80 0.35]);
title({'Highest maximum annual discharges with Wet initial states vs';'Historical Simulated maximum annual discharges'},'FontSize',22)
set(gca, 'FontSize', 15)
xlabel('Time','FontSize',18)
ylabel('Discharge m^3/s per day','FontSize',18)
legend([Graph_wet3 Graph_historical3],{'Wet forecasted discharges','Historical discharges'},'Location','northeast','Interpreter','latex','FontSize',20)
hold off
```

AUTOCORRELATION TEST FOR THE HISTORICAL AND FORECASTED LISTS

```
varNames2 = ["Lags"," autocorrelation function (ACF)"];

% For Historical discharges
[ACFTb1,bounds1] = autocorr(maximum_historical_discharges);
table5= table(bounds1', ACFTb1','VariableNames',varNames2);
table5 = table(table5,'VariableNames',{'autocorrelation results for Historical Discharges'})

% For Dry Maximum Discharges
[ACFTb2,bounds2] = autocorr(first_maximum_DRY);
table6= table(bounds2', ACFTb2','VariableNames',varNames2);
table6 = table(table6,'VariableNames',{'autocorrelation results for Dry Forecasted Discharges'})

% For Wet Maximum Discharges
[ACFTb3,bounds3] = autocorr(first_maximum_WET);
table7= table(bounds3', ACFTb3','VariableNames',varNames2);
table7 = table(table7,'VariableNames',{'autocorrelation results for Wet Forecasted Discharges'})
```

GRAPHS FOR THE AUTOCORRELATION TEST, BEST-FIT LINE & ABRUPT CHANGE IN THE DATA

```
% Graphs for the HISTORICAL SIMULATED MAXIMUM ANNUAL DISCHARGES
figure (4), clf(4),
sgtitle('Graphs for the Historical Simulated maximum annual discharges','FontSize',24,'FontWeight','bold','Color',[0.6350 0.0780 0.1840])
subplot(1,2,1); hold on
autocorr(maximum_historical_discharges)
```

```
title('Autocorrelation Results','FontSize',20,'FontAngle','italic')
set(gca, 'FontSize', 15)
xlabel('Lag','FontSize',16)
ylabel('Sample ACF','FontSize',16)
hold off
subplot(1,2,2); hold on
plot(year(maximum_historical_time), maximum_historical_discharges,'.','Color',[0.40 0.80
0.35],'MarkerSize',26)
curvefit = fit(year(maximum_historical_time),maximum_historical_discharges','poly1')
plot(curvefit,'m')
legend('Historical Discharges','Fitted curve','Location','best','Interpreter','latex','FontSize',12)
title('Best-fit line','FontSize',20,'FontAngle','italic')
set(gca, 'FontSize', 15)
xlabel('Time','FontSize',16)
ylabel('Discharge m^3/s per day','FontSize',16)
hold off

% Graphs for the HGHEST MAXIMUM ANNUAL DISCHARGES OBTAINED WITH THE DRY INITIAL STATES
figure (6), clf(6),
sgtitle('Graphs for the Highest maximum annual discharges obtained with the dry initial
states','FontSize',24,'FontWeight','bold','Color',[0.6350 0.0780 0.1840])
subplot(1,2,1); hold on
autocorr(first_maximum_DRY)
title('Autocorrelation Results','FontSize',20,'FontAngle','italic')
set(gca, 'FontSize', 15)
xlabel('Lag','FontSize',16)
ylabel('Sample ACF','FontSize',16)
hold off
subplot(1,2,2); hold on
plot(year(DRY_years'), first_maximum_DRY,'.','Color',[0.9290 0.6940 0.1250],'MarkerSize',26)
curvefit = fit(year(DRY_years'),first_maximum_DRY','poly1')
plot(curvefit,'m')
legend('Maximum Dry Discharges','Fitted curve','Interpreter','latex','FontSize',12)
set(gca, 'FontSize', 15)
title('Best-fit line','FontSize',20,'FontAngle','italic')
xlabel('Time','FontSize',16)
ylabel('Discharge m^3/s per day','FontSize',16)
hold off

% Graphs for the HIGHEST MAXIMUM ANNUAL DISCHARGES OBTAINED WITH THE WET INITIAL STATES
figure (8), clf(8),
sgtitle('Graphs for the Highest maximum annual discharges obtained with the wet initial
states','FontSize',24,'FontWeight','bold','Color',[0.6350 0.0780 0.1840])
subplot(1,2,1); hold on
autocorr(first_maximum_WET)
set(gca, 'FontSize', 15)
title('Autocorrelation Results','FontSize',20,'FontAngle','italic')
xlabel('Lag','FontSize',16)
ylabel('Sample ACF','FontSize',16)
hold off
subplot(1,2,2); hold on
plot(year(WET_years'), first_maximum_WET,'.','Color',[0.40 0.55 0.85],'MarkerSize',26);
curvefit = fit(year(WET_years'),first_maximum_WET','poly1')
plot(curvefit,'m')
legend('Maximum Wet Discharges','Fitted curve','Interpreter','latex','FontSize',12)
set(gca, 'FontSize', 15)
title('Best-fit line','FontSize',20,'FontAngle','italic')
xlabel('Time','FontSize',16)
ylabel('Discharge m^3/s per day','FontSize',16)
```

```
hold off
```

STATISTICAL ANALYSIS: HISTORICAL SIMULATED MAXIMUM ANNUAL DISCHARGES

```
% Pearson t-test (linear trend test)
[RHO1,p_value1] = corr(maximum_historical_discharges',years','Type','Pearson')

% Spearman%s rank correlation test
% highest gets a value of 1 and lowest gets a value of 20
[RHO2,p_value2] = corr(maximum_historical_discharges',years','Type','Spearman');

% Mann-Kendall test
%%%% Note: ties are not considered in this test, results may be affected in the presence of ties
[H3,p_value3]=Mann_Kendall_ORIGINAL(maximum_historical_discharges,0.05);

% Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10 values
GroupA1= maximum_historical_discharges(1:10);
GroupB1= maximum_historical_discharges(11:end);
[p_value4,h4,stats4] = ranksum(GroupA1,GroupB1,'alpha',0.05,'tail','both','method','exact');

% Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11 values
GroupC1= maximum_historical_discharges(1:9);
GroupD1= maximum_historical_discharges(10:end);
[p_value5,h5,stats5] = ranksum(GroupC1,GroupD1,'alpha',0.05,'tail','both','method','exact');

% Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12 values
GroupE1= maximum_historical_discharges(1:8);
GroupH1= maximum_historical_discharges(9:end);
[p_value6,h6,stats6] = ranksum(GroupE1,GroupH1,'alpha',0.05,'tail','both','method','exact');

% Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5 values
GroupI1= maximum_historical_discharges(1:15);
GroupK1= maximum_historical_discharges(16:end);
[p_value7,h7,stats7] = ranksum(GroupI1,GroupK1,'alpha',0.05,'tail','both','method','exact');

% table with the results for the HISTORICAL SIMULATED MAXIMUM ANNUAL DISCHARGES
Pval_results1 = [p_value1 p_value2 p_value3 p_value4 p_value5 p_value6 p_value7];
table8 = table(Pval_results1','VariableNames',{'P Values'},'RowNames',{'Pearson t-test','Spearman
test','Mann-Kendall test',...
    'Wilcoxon-Mann-Whitney test: nA= 10 values and nB= 10 values','Wilcoxon-Mann-Whitney test: nC= 9
values and nD= 11 values',...
    'Wilcoxon-Mann-Whitney test: nE= 8 values and nH= 12 values', 'Wilcoxon-Mann-Whitney test: nI= 15
values and nK= 5 values'})
```

STATISTICAL ANALYSIS: HIGHEST MAXIMUM ANNUAL DISCHARGES OBTAINED WITH THE DRY INITIAL STATES

```
% Pearson t-test (linear trend test)
[RHO8,p_value8] = corr(first_maximum_DRY',years','Type','Pearson');

% Spearman%s rank correlation test
% highest gets a value of 1 and lowest gets a value of 20
[RHO9,p_value9] = corr(first_maximum_DRY',years','Type','Spearman');

% Mann-Kendall test
[H10,p_value10]=Mann_Kendall_ORIGINAL(first_maximum_DRY,0.05);
```

```
% Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10 values
GroupA2= first_maximum_DRY(1:10);
GroupB2= first_maximum_DRY(11:end);
[p_value11,h11,stats11] = ranksum(GroupA2,GroupB2,'alpha',0.05,'tail','both','method','exact');

% Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11 values
GroupC2= first_maximum_DRY(1:9);
GroupD2= first_maximum_DRY(10:end);
[p_value12,h12,stats12] = ranksum(GroupC2,GroupD2,'alpha',0.05,'tail','both','method','exact');

% Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12 values
GroupE2= first_maximum_DRY(1:8);
GroupH2= first_maximum_DRY(9:end);
[p_value13,h13,stats13] = ranksum(GroupE2,GroupH2,'alpha',0.05,'tail','both','method','exact');

% Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5 values
GroupI2= first_maximum_DRY(1:15);
GroupK2= first_maximum_DRY(16:end);
[p_value14,h14,stats14] = ranksum(GroupI2,GroupK2,'alpha',0.05,'tail','both','method','exact');

% table with the results for the HIGHEST MAXIMUM ANNUAL DISCHARGES OBTAINED WITH THE DRY INITIAL
STATES
Pval_results2 = [p_value8 p_value9 p_value10 p_value11 p_value12 p_value13 p_value14];
table9 = table(Pval_results2','VariableNames',{'P Values'},'RowNames',{'Pearson t-test','Spearman
test','Mann-Kendall test',...
    'Wilcoxon-Mann-Whitney test: nA= 10 values and nB= 10 values','Wilcoxon-Mann-Whitney test: nC= 9
values and nD= 11 values',...
    'Wilcoxon-Mann-Whitney test: nE= 8 values and nH= 12 values', 'Wilcoxon-Mann-Whitney test: nI= 15
values and nK= 5 values'})
```

STATISTICAL ANALYSIS: HIGHEST MAXIMUM ANNUAL DISCHARGES OBTAINED WITH THE WET INITIAL STATES

```
% Pearson t-test (linear trend test)
[RHO15,p_value15] = corr(first_maximum_WET',years','Type','Pearson');

% Spearman%s rank correlation test
% highest gets a value of 1 and lowest gets a value of 20
[RHO16,p_value16] = corr(first_maximum_WET',years','Type','Spearman');

% Mann-Kendall test
[H17,p_value17]=Mann_Kendall_ORIGINAL(first_maximum_WET,0.05);

% Wilcoxon-Mann-Whitney test nA= 10 values and nB= 10 values
GroupA3= first_maximum_WET(1:10);
GroupB3= first_maximum_WET(11:end);
[p_value18,h18,stats18] = ranksum(GroupA3,GroupB3,'alpha',0.05,'tail','both','method','exact');

% Wilcoxon-Mann-Whitney test nC= 9 values and nD= 11 values
GroupC3= first_maximum_WET(1:9);
GroupD3= first_maximum_WET(10:end);
[p_value19,h19,stats19] = ranksum(GroupC3,GroupD3,'alpha',0.05,'tail','both','method','exact');

% Wilcoxon-Mann-Whitney test nE= 8 values and nH= 12 values
GroupE3= first_maximum_WET(1:8);
GroupH3= first_maximum_WET(9:end);
[p_value20,h20,stats20] = ranksum(GroupE3,GroupH3,'alpha',0.05,'tail','both','method','exact');
```

```
% Wilcoxon-Mann-Whitney test nI= 15 values and nK= 5 values
GroupI3= first_maximum_WET(1:15);
GroupK3= first_maximum_WET(16:end);
[p_value21,h121,stats21] = ranksum(GroupI3,GroupK3,'alpha',0.05,'tail','both','method','exact');

% table with the results for the HIGHEST MAXIMUM ANNUAL DISCHARGES OBTAINED WITH THE WET INITIAL
STATES
Pval_results3 = [p_value15 p_value16 p_value17 p_value18 p_value19 p_value20 p_value21];
table10 = table(Pval_results3','VariableNames',{'P Values'},'RowNames',{'Pearson t-test','Spearman
test','Mann-Kendall test',...
    'Wilcoxon-Mann-Whitney test: nA= 10 values and nB= 10 values','Wilcoxon-Mann-Whitney test: nC= 9
values and nD= 11 values',...
    'Wilcoxon-Mann-Whitney test: nE= 8 values and nH= 12 values', 'Wilcoxon-Mann-Whitney test: nI= 15
values and nK= 5 values'})
```

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E2: Extra function code use for the Mann-Kendal statistical test

```
function[H,p_value]=Mann_Kendall_ORIGINAL(V,alpha)
```

```
% Performs original Mann-Kendall test of the null hypothesis of trend absence in the vector V,
% against the alternative of trend.
% The result of the test is returned in H
% H = 1 indicates a rejection of the null hypothesis at the alpha significance level.
% H = 0 indicates a failure to reject the null hypothesis at the alpha significance level.
Insufficient evidence to reject the null hypothesis
V=reshape(V,length(V),1);
alpha = alpha/2;
n=length(V);
i=0; j=0; S=0;
for i=1:n-1
   for j= i+1:n
      S= S + sign(V(j)-V(i));
   end
end
VarS=(n*(n-1)*(2*n+5))/18;
StdS=sqrt(VarS);
%%%% Note: ties are not considered
if S >= 0
   Z=((S-1)/StdS)*(S~=0);
else
   Z=(S+1)/StdS;
end
p_value=2*(1-normcdf(abs(Z),0,1)); %% Two-tailed test
pz=norminv(1-alpha,0,1);
H=abs(Z)>pz; %%
return
end
```

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