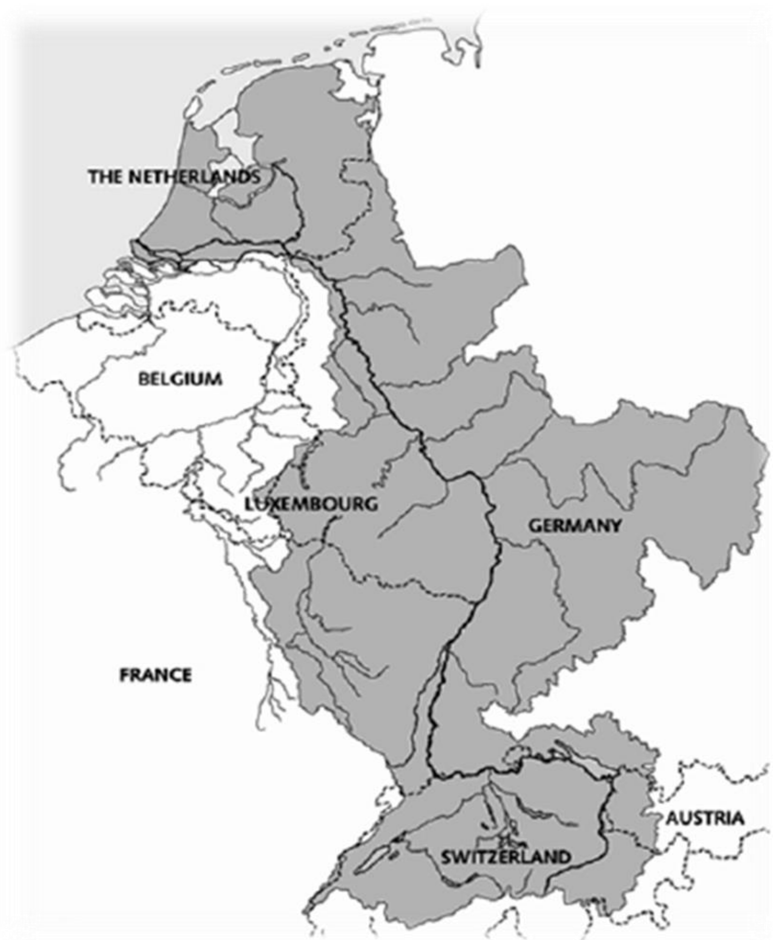
Statistical trend analysis of River Rhine discharge using a twentieth century weather re-analysis



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28 June 2017

Front page picture: River Rhine basin, retrieved from Frijters & Leentvaar (2003).

Statistical trend analysis of River Rhine discharge using a twentieth century weather re-analysis

Bachelor Thesis

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Summary

It is expected that river systems are nowadays changing due to an ascending surface temperature and the subsequent ascending number of extreme situation such as heavy precipitation and droughts. The River Rhine is probably also affected by these climate induced changes, which can cause higher river discharges according to experts. This in combination with the fact that the Netherlands is very vulnerable to floods, because of its low-lying land and the large number of densely populated areas, will cause a rise of the flood risk. To remain safe, it is important that flood protections, such as levees, are implemented close to all submersible areas. This process is time consuming and expensive and thence good policy must be developed. Therefore, it is important for Dutch water managers and policy makers to gain more certainty about the effects of climate change on river systems, such as the River Rhine. However, the outcomes of current river discharge trend analyses are not very certain. This is due to the insufficient quality and amount of data and especially in the River Rhine coincidence of the weather cannot be excluded as the cause for a visible or invisible trend. It is therefore important to try to take into account the uncertainties in the observed discharge time series in trend analyses. It has been tried to lower the uncertainties by using ten other possible discharge time series of the past in the trend analyses. These series are constructed by using a numerical weather product called ERA-CLIM in combination with a hydrological model to transform precipitation and temperature into a discharge at Lobith. ERA-CLIM concerns the re-analysed global weather in the period 1901 until 2010 only based on the average daily sea-surface temperature, sea-ice fraction and radiation scheme. These initial conditions of ERA-CLIM's re-analysis are ten times slightly perturbed to obtain ten equally likely but different weather ensemble members. Variations in the ensemble members approach the uncertainties in the available observational sources on which the ERA-CLIM product is based and therefore they can represent the uncertainties in the observed discharge. Therefore, the objective of this study is as follows:

The objective of this study is to find confirmation for average, seasonal and extreme trends in the River Rhine discharge at Lobith making use of discharge time series created with a hydrological model in combination with a numerical weather product.

First, five types of annual discharge time series were created from the daily observed and ERA-CLIM discharge time series corresponding to five discharge characteristics; a mean discharge characteristic, two seasonal discharge characteristics and two extreme discharge characteristics. The annual discharge time series were also created for a daily time series created with a hydrological model in combination with observed input data, HYRAS discharge time series, to determine the influence of the hydrological model. After comparing both series was concluded that the influence of the hydrological model is negligible and that therefore the ERA-CLIM trends can directly be compared with the trends from the observed series.

Thereafter, the reasonability of the ERA-CLIM discharge time series with respect to the observed series was investigated through a comparison. It turned out that the ERA-CLIM can represent the same kind of weather as observed when looking at the daily series. However, taking a closer look to the annual discharge time series it turned out that the ERA-CLIM series cannot represent the observed weather as same as good for all discharge characteristics. The ERA-CLIM ensembles can for example represent mean and high-flow season discharges quite good in contrast to for example the low-flow season discharges. However, it was concluded that ERA-CLIM can represent the observed series, when keeping in mind the differences between the series. Subsequently the independency of all ERA-CLIM series is tested. It turned out that the ERA-CLIM series are not dependent on each other and also not dependent on the observed series.

Therefore, it is confirmed that the ERA-CLIM series can be treated as ten possible, independent discharge series.

Subsequently, the trends of all discharge time series were calculated for the periods 1901 until 1951, 1951 until 2006 and 1901 until 2010. It turned out that the significances and direction of the trends found in the observed and HYRAS series are almost equal. Moreover, it was concluded that the trends and directions between the several ERA-CLIM series differ. The period for which the trends were calculated had also a major influence on the significance and direction of a trend. Finally, the calculated ERA-CLIM trends were compared with the trends found in the observed series. It turned out that most of the significances and directions of the trends found in the observed and ERA-CLIM series are very different. It could however be concluded that some trends in the observed series could be confirmed by the ERA-CLIM series. Although no trends in the extreme and mean series were confirmed making use of the ERA-CLIM series, the seasonal trends found in the observed series were confirmed making use of the ERA-CLIM series and therefore this study will provide circumstantial evidence for these seasonal trends in the observed series.

Preface

This thesis is the final part of my bachelor Civil Engineering which I have studied at the University of Twente with great enjoyment. During this research at Deltares in Delft, I learned a lot about handling large data sets, programming and trend analysis statistics.

I am grateful to all the people from both the University of Twente and Deltares that were involved in this thesis. In particular, I would like to thank Jaap Kwadijk for giving me the opportunity to perform my bachelor thesis at Deltares and for creating the research topic. I also thank Ferdinand Diermanse and Martijn Booij for always being willing to help me when I was confronted with problems during my thesis and for giving sharp feedback. Further, I would also like to thank Frederiek Sperna Weiland for giving me the data sets I needed for this thesis. Finally, I would like to thank my family and friends for being helpful and supportive during my time studying Civil Engineering at the University of Twente.

I hope you will enjoy reading this thesis.

Danny Booij
Delft, June 2017

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Appendices

1. Introduction

In this chapter, the motivation, state of the art, research gap, research goal, research questions and reading guide of this study will be described.

1.1. Climate change and flood risk

It is widely known that the earth is slowly getting warmer because of climate change. The number of extreme weather conditions, such as droughts and floods, will therefore probably increase (IPCC, 2013). Due to the current emission of greenhouse gasses and the resulting change in the atmospheric composition, it is expected that extreme situations will even become more frequent. Complete systems as oceans, watersheds and glaciers can furthermore change due to the larger number of extreme conditions (IPCC, 2013). It is expected that the sea level will further rise through melting of the ice caps and that climate change will affect the hydrological circle (Quente & Colijn, 2016). The effects of climate change on river discharges are however very uncertain, especially because they differ from region to region (Kwadijk & Rotmans, 1995). River discharges could become higher due to the rise of precipitation and melting of glaciers and river discharges could drop because of droughts in watersheds and the rise of the amount of evapotranspiration (EEA, 2012).

According to Ligtvoet et al. (2013) flooding is an extreme event of which the chance will increase in northern European countries, such as the Netherlands. The Netherlands is in addition very vulnerable to floods, due to its low-lying land and the fact that it is the delta of many big rivers, namely the Rhine, Meuse and Scheldt. Flooding is also one of the most damaging natural hazard phenomena, something we regrettably noticed in the year 1953, see Figure 1 (Klerk, et al., 2015). Therefore, it is important that secure flood protections, such as dikes and reservoirs, are implemented close to all submersible areas. This process is time consuming and expensive and therefore good policy must be developed. For water managers and policy makers in the Netherlands, it is important to know how river systems have changed over the years to validate the expected changes in the river systems determined by models. Furthermore, it is for water managers also important to know where these changes are happening, e.g. in high or low flows. The expected changes namely have direct influence on the design of flood defences. If future changes are underestimated, the safety standards will not be satisfied, and if the changes are overestimated, too many unnecessary costs will be made. Besides, it is also important for policy makers to have grounded scientific evidence for e.g. a positive trend in river discharge to justify the investments for creating more safety.

Figure 1: North Sea flood of 1953 (Rijkswaterstaat, 2017)

This research will further focus on the River Rhine with its corresponding catchment area and the discharge that flows into the Netherlands, measured at Lobith. Investigations in large-scale precipitation characteristics prove that, especially within the last 30 years, the development of annual precipitation totals in Central and Western Europe, the catchment area of the Rhine, have an ascending trend towards more winter precipitation (IPCC, 2013). Furthermore, a trend towards more intense precipitation extremes is notable (IPCC, 2013; EEA, 2012). The changes towards more intense precipitation are due to the growing capacity of the atmosphere to hold water when the temperature in the air increases (Frei, et al., 2000). This in combination with an ascending surface temperature in Central Europe triggers the formation of floods (IKSR, 2009). A rise of the frequency of extreme river discharges and a heightening of the flood chance of the Rhine is therefore expected (Menzel, et al., 2004). However, no strong statistical trend towards an ascending discharge could be found when the analysis is extended over a period of the last hundred years, despite a weak visible rise of the discharge (IPCC, 2013; EAA, 2012; Diermanse et al., 2010). This study is about attaining more certainty about possible trends in river discharges in the past, which in the end will give more certainty about future changes.

1.2. State of the art

Trend analyses have been performed for many rivers around the world to obtain information about changes in river behaviour and about possible changes in the future. The Fifth Assessment Report of the IPCC concluded that "… there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale" (IPCC, 2013). Studies for Europe show evidence for upward, downward and no trend in the height and frequency of floods and droughts, so that there currently is no clear and widespread evidence for observed changes in flooding. In common, hydrologists use continuous historical observations from long term stream measurements for trend analyses.

Compared to the extensive literature on future projections of River Rhine discharge, there are relatively few studies on changes in discharge during the past instrumental record. However, a couple of trend studies for Rhine discharge have been performed. According to the International Commission for the Hydrology of the Rhine Basin, the Rhine at Lobith does not show a significant trend in annual mean discharges. They however concluded that an ascending trend is present in the average winter (high) discharges (Belz, et al., 2007; Pinter, et al., 2006) Higher winter flows are according to experts due to higher winter temperatures, as winter precipitation increasingly falls as rain rather than snow (EEA, 2012). Often used discharge time series for trend analysis are the mean annual or periodic discharge, annual maximum daily discharge and the annual minimum 7- or 10-day discharge (Belz, et al., 2007). Mallakpour and Villarini (2015) for example use a different approach; they used a peak-over-threshold method, to develop a flood record to carry out the trend analysis. The resulting time series registers all events in which discharge exceeded a selected high value. This method thus only focuses on flows that could actually be considered as floods. This method is different, because not only one annual discharge value will be used in the trend analysis, yet all the values higher than the threshold will be used. Commonly used methods for statistical trend analyses are the Mann-Kendall test, Pearson t-test, Spearman's rank correlation test and the Wilcoxon-Mann-Whitney test (Diermanse et al., 2010).

As stated above, statistics show that the evidence available is not sufficient enough to conclude that there is a trend in for example the annual maximum discharges of the Rhine looking at about the past 100 years. According to literature, this is an unexpected finding, since many scientists in the past stated that the effects of climate change on rivers and their belonging catchment areas are high (IPCC, 2013; Diermanse, et al., n.d.). Several factors that could contribute to this fact are the quality of data, amount of data and other exogenous variables (Khaleghi, et al. 2014). Also, coincidence is a factor which cannot be excluded as the cause for a visible or invisible trend, since only about 100 years of observational data is available (Diermanse et al., n.d.). "One or two extremes can … strongly influence the slope of the trend line"

(Diermanse et al., 2010). Natural variation can therefore easily influence whether a trend can be found or not and this gives a major uncertainty.

1.3. Research gap

So far, no research has been performed which tries to take into account the uncertainties of the measured discharge time series in trend analyses, by means of using a numerical weather product, to finally seek for more confirmation about trends in current discharges.

The numerical weather product concerns data of re-analysed weather of the whole twentieth century till now. Essentially, it concerns 110 years of simulated weather based on only the average daily sea-surface temperature and sea-ice fraction (Hersbach, et al., 2013). Changes in the initial conditions of this re-analysis will result in ten ensemble members, all equally likely as past weathers, lying around the deterministic, unknown, best fit reanalysis of the weather. Variations in the various ensemble members approach the uncertainties in the available observational sources on which the ERA-CLIM product is based (Hersbach, et al., 2013). Therefore, due to these variations, the ten ensemble members of this numerical weather product can be used in this study to represent the uncertainties in the observed discharge time series by serving as ten possible, past weathers, considering the fact that river discharges strongly depend on the weather through the water cycle.

1.4. Objective and research questions

As stated, it is important for Dutch water managers and policy makers to gain more certainty about the effects of climate change on river systems, such as the River Rhine. However, the outcomes of trend analyses of observed discharges time series are not very certain. It is therefore important to consider the uncertainties in the trend analysis. Therefore, the Bachelor thesis will have the following objective:

The objective of this study is to find confirmation for average, seasonal and extreme trends in the River Rhine discharge at Lobith making use of discharge time series created with a hydrological model in combination with a numerical weather product.

To achieve the defined research objective, several research questions (RQs) must be answered. First, it must be determined whether the simulated discharge series created with ERA-CLIM can be used as possible, independent discharge time series of the past and what the differences between the ERA-CLIM discharge time series and the observed discharge time series are. Hence, the first research question is the following:

To which extent can the discharge time series constructed with a hydrological model in combination with a numerical weather product serve as possible, independent discharge time series of the past? ***(1)***

Second, it must be determined if a trend can be found in the observed discharges of the Rhine as benchmark for the remainder of the study. Hence, the second research question is the following:

Are there trends noticeable in observed average, seasonal and extreme discharge time series of the Rhine at Lobith? ***(2)***

Since a hydrological model is used to translate the simulated weather (precipitation and temperature) into Rhine discharge at Lobith, the possible effects of the hydrological model on the resulting trends must be determined to be able to draw a valid conclusion. This will later be performed by comparing the trends of the observed series with the trends of the series created with the hydrological model in combination with observed weather. Hence, the third research question is the following:

Are there trends noticeable in simulated average, seasonal and extreme discharge time series of the Rhine at Lobith created with a hydrological model in combination with observed input weather? ***(3)***

When it is known what the influence of the hydrological model and the observed weather is on the discharge series of the Rhine at Lobith, the trends can be calculated for the series constructed with a hydrological model in combination with a numerical weather product. Hence, the fourth research question is the following:

Are there trends noticeable in simulated average, seasonal and extreme discharge time series of the Rhine at Lobith created with a hydrological model in combination with a numerical weather product? ***(4)***

To be able to validly confirm or not confirm the trends in the observed discharge time series, the differences between the trends found in the trend analyses will be analysed. Hence, the last research question is the following:

What are the differences between the trends found in the different series and what do these differences mean? ***(5)***

1.5. Reading guide

The structure of this research is as follows. In chapter 2 an overview will be given of the study area; the Rhine basin and all used data sets will be discussed. Chapter 3 starts with a quick overview of the method, after which each part of the method will be extensively discussed. Firstly, it will be discussed which discharge characteristics are used for calculating trends and how the corresponding discharge time series are constructed. Secondly, the procedure for comparing all discharge time series will be explained, after which the method for performing the trend analysis will be explained. Finally, the procedure for comparing the trends will be explained. Chapter 4 will present the results of the performed method. This is followed by a discussion in chapter 5 and conclusions and recommendations in chapter 6.

2. Study area and data

This chapter describes the study area and the used data sets. Furthermore, the models which were being used to construct the data sets will be briefly described.

2.1. Study area: The Rhine Basin

The River Rhine originates in the Alps in Switzerland and continues its way through Germany before it enters the Netherlands at Lobith and finally flows into the North Sea. With a total length of about 1250 km and an average discharge of about 2230 m^3s^{-1} at Lobith, the Rhine ranks ninth among all Eurasian rivers. The maximum observed discharge was 12600 m^3s^{-1} in 1926 (Te Linde, et al., 2011). The Rhine basin has a climate which gradually changes from the sea to the east and southeast from maritime to more continental. Precipitation occurs at any time of the year and varies with altitude and local topography, just as the temperature (Uehlinger, et al., 2009).

In this study, the catchment area upstream of Lobith is considered, so the whole River Rhine catchment area except the part in the Netherlands. The discharge patterns of the Rhine show the influence of the Alps and the low mountain ranges, hills and plains of the catchment area. The discharge from the most southern basins (Alpine regions) consists largely of melt water and the discharge from the other basins consists largely of rainfall. Rain-fed basins peak mostly during winter while melt water dominated basins peak in summers. The summer discharge at Lobith consists of over fifty per cent of melt water (Uehlinger, et al., 2009).

Furthermore, the River Rhine is one of the most important river basins in Western Europe. It is of economic importance to agriculture, navigation and industry. The basin area is 18500 km^2 and in particular the flood-prone areas in the basin are densely populated. Hence, flood management has predominantly focused on major dike reinforcements along the Rhine over the last 20 to 30 years (Te Linde, et al., 2011).

2.2. Hydrological model

The HBV-96 model (Hydrologiska Byrans Vattenbalansavdelning) has been used by Deltares as hydrological model to transform precipitation and potential evapotranspiration series into discharges for the River Rhine. It was decided to use the HBV-model after an evaluation of rainfall-runoff models by Passchier (1996) and furthermore because this model is commonly used for the Rhine basin. HBV is a conceptual model, which means that the model components represent real-world layout of the basin in such a way that the runoff generating processes are described realistically (Hegnauer, et al., 2014).

The HBV model consists of four routines. In the “snow routine” accumulation of snow and snow melt are determined according to the temperature. The "soil routine" controls which part of the rainfall and melt water forms excess water and how much is evaporated or stored in the soil. The “runoff generation routine” consists of an upper, nonlinear reservoir representing fast runoff components and a lower, linear reservoir representing base flow. Runoff is routed along the river with a simplified Muskingum approach (Hegnauer, et al., 2014).

The discharge time series used in this study are created with a HBV version of 148 sub-basins, covering the complete Rhine basin upstream of Lobith. The HBV model runs with a daily time step and the model input consists of daily average precipitation and temperature for each sub-basin. Daily potential evapotranspiration is calculated using a daily temperature based correction of long term monthly mean potential evaporation. The model has been re-calibrated by Hegnauer et al. (2014) for high discharges using the GLUE (Generalized Likelihood Uncertainty Estimation) method. This method tries to find multiple parameter sets that lead to satisfactory results. In this method, the performance criteria that were used are related to the overall performance (Nash-Sutcliffe efficiency), a volume measure (Relative Volume Error) and the reproduction of extreme peaks (Generalized Extreme Value Error) (Hegnauer, et al., 2014). The HYRAS data set (which will be discussed in section 2.4) was used as weather input for this calibration.

2.3. Time series of River Rhine discharge: Observations

The discharge time series of observed discharges at Lobith is obtained from the 'Waterbase' from Rijkswaterstaat. The set consists of two parts of measurements. The first part from the years 1901 up to 1988 consists of one single daily measurement at 8 a.m. and the second part from the years 1989 up to 2010 consists of measurements of the daily mean discharge.

2.4. Time series of River Rhine discharge: Observed weather

The simulated discharge time series created with observed weather have been constructed by means of the HBV-model by Deltares. The discharge time series used in this study are created with the HYRAS data set for precipitation and the E-Obs data set for temperature. Both series contain daily data which cover a period from 1951 up to 2006.

The HYRAS dataset was made available by the German Weather Service (DWD) via the Federal Institute of Hydrology (BfG). It is a data set which covers the river basins in Germany and neighbouring countries. The HYRAS dataset has a high spatial resolution of 5 x 5 km and a daily temporal resolution that is based on up to 6200 precipitation stations (Rauthe, et al., 2013). For the period of coverage, the daily precipitation fields were calculated from the station data using the REGNIE method. This is a combination between multiple linear regression and inverse distance weighting.

The E-Obs temperature (v14.0) dataset has been made available within the project ECA&D of the European Climate Support Network of EUMETNET. The objective of the ECA&D project is to combine daily series of observations at meteorological stations, quality control, analysis of extremes and dissemination of both the daily data and the analysis results (ECA&D, 2013). The dataset has a resolution of 25 x 25 km and data are available on a daily basis.

2.5. Time series of River Rhine discharge: ERA-CLIM weather

The simulated discharge time series created with ERA-CLIM weather have also been constructed by means of the HBV-model by Deltares. The precipitation and temperature data are obtained from the European Reanalysis of Global Climate observations (ERA-CLIM) project provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The exact name of the dataset which was used for creating the discharge series is called ERA-20CM. This product is a numerical weather product which concerns the re-analysed day-to-day weather of the whole twentieth century. A specific goal of ERA-CLIM is to improve the quality and consistency of climate observations from 1901 to 2010 through global reanalyses (ECMWF, n.d.). According to ECMWF, the reanalysis is a well-established method to reconcile historical data sets.

The model environment in which the ERA-20CM data set is created is called the Integrated Forecasting System (IFS) of ECMWF. The IFS runs in a deterministic forecasting mode and the model formulation is based on a set of basic equations, of which some describe the static relationship between pressure, density, temperature and height, and some describe the time evolution of the horizontal wind components, surface pressure, temperature and the water vapour contents of an air parcel (ECMWF, 2015). Furthermore, the IFS consists of several components: an atmospheric general circulation model, an ocean wave model, a land surface model and an ocean general circulation model (ECMWF, 2015).

ERA-20CM consists of ten ensemble members covering the period 1901 to 2010 with a 3-hourly time-step and a spatial resolution of about 125 km. Due to the large amount of output (weather data), the century long run is split into yearly chunks for the construction of the time series (Hersbach, et al., 2013). The ERA-20CM construction is forced by three daily observationally-based prescribed conditions: the average sea ice concentration (SIC), the sea surface temperature (SST) and the radiation scheme.

The first two forcing terms are obtained from the observational product HadISST2 which is also part of the ERA-CLIM project. HadISST2 comprises an ensemble of ten realizations of SST and one realization of SIC on about a 25 x 25 km scale. For each of the ten HadISST2 realizations, daily averages were calculated and time series were produced. The SIC and SST series are both created by connecting in-situ measurements, those made at the surface as opposed to those made remotely by satellites or aircraft, by means of using statistical techniques such as interpolation or pattern filling to fill the gaps in the regions without SIC and SST observations (Kennedy, 2014). Different ensembles of SST were created by using different stochastic techniques. The SST differences of each HadISST2 member are the result of a random drawing from a large SST ensemble which are all equally likely (Hersbach, et al., 2013). The ten different ensemble members of ERA-CLIM's ERA-20CM are created by using a different SST member. According to Kennedy (2014), variations in the ensembles reflect uncertainties in the available observational sources and bias adjustments. It is known that each HadISST2 realisation has a realistic and homogeneous spatial variability that is consistent with the known structure of the SST, the available observations and their uncertainties (Kennedy, 2014).

The last forcing term in the model is the radiation scheme. It follows from the CMIP5 recommendations from the World Climate Research Programme. CMIP5 comprises of a data set which contains the solar irradiance data from 1850 up to 2008 constructed by using interpolating measurements (Lean, 2009). The data set includes solar forcing, greenhouse gases, ozone and aerosols (Hersbach, et al., 2013).

Both the ocean-surface and radiative forcing incorporate a proper long-term evolution of climate trends in the twentieth century, and the occurrence of major events, such as the El Nino-Southern Oscillations and volcanic eruptions (Hersbach, et al., 2013). In addition, it is known that the SST contains a linear climate induced warming of the earth of around 0.37 ^{o}C over the period of 1901 until 2010 (Kennedy, 2014).

Since no atmospheric observations were used to produce the ERA-CLIM data, it is not able to reproduce the actual weather. The ensembles, however, provide a statistical estimate of the climate. The temperature rise over land is in fair agreement with observations and the warming over land exceeds the warming over sea, which is also right according to observations (Hersbach, et al., 2013). In summary, all observational information is incorporated in the model boundary conditions and forcing. These account for the evolution of the SST, sea ice concentration and the solar forcing, ozone, aerosols, and greenhouse gases (Hersbach, et al., 2013).

3. Method

This chapter describes step by step which method will be followed to answer the research questions. First a short overview of the method will be given in section 3.1. Thereafter, each of the steps from the method outline will be described in the following sections.

3.1. Method outline

In section 3.2, it will be discussed which discharge characteristics are dealt with in this study and how the corresponding annual discharge time series are constructed. Secondly, the procedure for comparing all discharge time series will be discussed in section 3.3, after which the method for performing the trend analysis will be extensively discussed in section 3.4. Finally, in section 3.5, the procedure for comparing the trends will be explained. A short overview of the method is given in Figure 2.

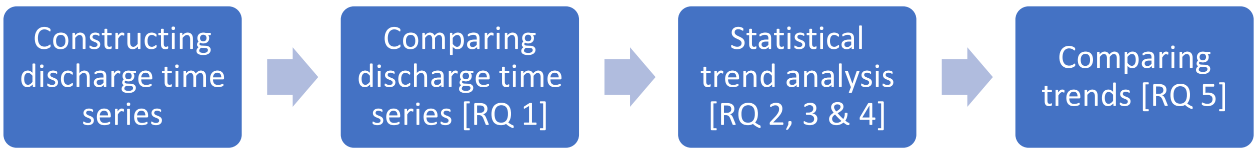


Figure 2: Method outline

3.2. Constructing discharge time series

The first step in this study is the construction of annual discharge time series from the daily discharge time series which will serve as input for the trend analyses. This step is performed for all available data: one discharge time series created of observations (called "*observed (discharge time) series*"), one discharge time series created with the HBV-model in combination with observed weather from the datasets HYRAS and E-Obs (called "*HYRAS (discharge time) series*") and ten discharge time series created with the HBV-model in combination with simulated weather of ERA-CLIM (called "*ERA-CLIM (discharge time) series*"). The annual time series will be constructed for each of the following discharge characteristics:

- Annual mean discharge;
- Annual maximum daily discharge;
- Annual minimum 7-day discharge;
- Annual mean low-flow season discharge;
- Annual mean high-flow season discharge.

This implies that twelve times five annual discharge time series will be created.

Annual mean discharge

This river discharge characteristic is an indicator for mean flows in rivers. This discharge characteristic is relevant because of the insight water managers can gain into the changing behaviour of the river.

Annual maximum daily discharge

This river discharge characteristic is an indicator for extreme high flows in the River Rhine. It is the value for discharges associated with the highest daily stream flow measured or computed in a year (Diermanse et al., 2010). A possible ascending trend in this series is of major importance for water managers. Water managers use the annual maximum discharges to determine design discharges which influence the designs of flood defences and therefore they are good indicator for extreme high discharges (Diermanse et al., 2010).

Annual minimum 7-day discharge

This river discharge characteristic is an indicator for extreme low flows in the River Rhine. It is the annual lowest mean discharge for seven consecutive days with a one-year recurrence interval (CHR, 2010). The annual minimum 7-day discharge is chosen, because a possible trend (ascending or descending) in this series is also of major importance for water managers. Changes in low flow river behaviour affect water allocation, water supply planning, aquatic maintenance (in stream flow) requirements, and waste-load allocation for point and nonpoint source discharges for protecting the water quality (IPCC, 2013).

Annual mean high-flow season discharge

This river discharge characteristic is an indicator for seasonal high flows in the River Rhine. It is the mean of the daily discharges considering the three months with the highest discharge of a year. Water managers can gain insight into the periods where changes occur in the river discharge through analysing the series with respect to this discharge characteristic.

Annual mean low-flow season discharge

This river discharge characteristic is an indicator for the seasonal low flows in the River Rhine. It is the mean of the daily discharges considering the three months with the lowest discharge of a year. Water managers can also gain insight into the periods where changes occur in the river discharge through analysing the series with respect to this discharge characteristic.

Determination hydrological years

The annual discharge time series are created by considering different hydrological years depending on the type of discharge characteristic. A properly chosen period is needed to prevent problems in the discharge series as using two annual maximum discharge values from the same discharge wave. When different hydrological years are not considered, potentially, a distorted view of the discharge series could be created and wrong trends could be determined when applying the trend analysis methods.

In this study, two different hydrological years will be determined, namely the hydrological years for the discharge characteristics: *annual maximum daily discharge* and the *annual minimum 7-day discharge*. No hydrological year will be determined with respect to the discharge characteristic *annual mean discharge*, since this discharge characteristic cover a whole calendar year. Furthermore, also no hydrological year will be determined with respect to the discharge characteristics *annual mean low-flow season discharge* and *annual mean high-flow season discharge*, since the construction of the series of these discharge characteristics do not depend on hydrological years yet on months. For these two discharge characteristics, the three months with the lowest and highest mean discharge considering the observed discharges from 1901 until 2010 are determined.

The determination of the hydrological years contains two steps:

1. Determining the mean daily and monthly discharge of observed discharges from 1901 until 2010;
2. Determining the hydrological year per discharge characteristic and determining the three months with the lowest and highest mean discharge.

The hydrological year which will be used for the discharge characteristic *annual maximum daily discharge* will start on the first day of the month which contains the lowest mean daily discharge and the year will end one day before this date.

The hydrological year which will be used for the discharge characteristic *annual minimum 7-day discharge* will start on the first day of the month which contains the highest mean daily discharge and the year will end one day before this date.

Building time series

After the hydrological years are known, the discharge time series of each specific discharge characteristic can be created. The time series will be constructed by selecting or calculating a discharge value for each discharge characteristic per year, so that annual time series will be constructed. The constructed series are not all from the same length. The observed discharge time series and ERA-CLIM discharge time series will contain 109 or 110 years depending on the discharge characteristic and the HYRAS discharge time series will contain 54 or 55 years depending on the discharge characteristic.

3.3. Comparing discharge time series

The discharge series of all data sets will be used in this comparison. Goal of the comparison is to determine whether the ERA-CLIM series are reasonable when comparing them with the observed discharge time series and whether the ERA-CLIM series can serve as possible, independent discharge time series. This includes the comparison of the observed series with the HYRAS series. This analysis is needed to determine the influence of the hydrological model on the ERA-CLIM discharge time series and the corresponding trends. If the influence is negligible, the observed discharge time series and ERA-CLIM discharge time series could directly be compared, else the series must be compared with the HYRAS series first. Last goal of the analysis is to determine the mutual differences between the ten ERA-CLIM discharge time series.

The comparison will consist of two parts: a general comparison of daily discharge time series and a more in-depth comparison of the annual discharge time series. The general comparison is needed to determine whether the ten ERA-CLIM series contain strange discharge behaviour, such as impossible low river flows, which otherwise will be missed by the analysis of the smoothed annual discharge time series.

Daily discharge time series analysis

To be able to draw valid conclusions about trends in River Rhine discharges using ERA-CLIM series, it is important to know what the differences are between the observed discharge time series, the HYRAS discharge time series and the ERA-CLIM discharge time series. It is needed to investigate whether the ERA-CLIM series are reasonable. The series are reasonable when the series have around the same distribution as the observed time series and when the series are independently from each other. In this daily discharge analysis, the discharge data is used from all three types of series. First the observed discharge will be compared with the HYRAS discharge and second the ERA-CLIM discharge will be compared with the observed discharge and HYRAS discharge. The daily river discharge series will be compared by means of figures and the following statistics:

- Discharge average and standard deviation of all discharge time series. In this step, also the mean and standard deviation of the observed and ERA-CLIM discharge time series over the same period as the HYRAS discharge time series will be calculated. This means that the mean and standard deviation will be calculated over 55 years instead of 110 years.
- Theoretical probability density functions (PDFs) of discharge time series derived from histograms for the period 1901 until 2010 and for the period 1951 until 2006. These functions are very useful to determine the spread and skewness of the time series (Hersel & Hirsch, 2012). PDF's are chosen instead of histograms, because PDFs enable to easily compare discharge time series.

Annual discharge time series analysis

The annual ERA-CLIM discharge time series as described in section 3.2 are all constructed with another ERA-CLIM ensemble. Since it is assumed that the ten ERA-CLIM discharge series are ten possible, independent discharge series of the past, it is important to investigate how independent these series actually are and if this assumption was correct. Moreover, the mutual dependency of the series explains how the series are built up. When the discharge series are independent, the changing part of the forcing terms within the ERA-CLIM production has a major influence. When the discharge series are dependent, the changing part of the forcing terms has a minor influence.

In addition, the dependency between the ten ERA-CLIM discharge series and the observed discharge series will be calculated. This comparison will cause statements about the suitability of the series. It will become clear whether the series can be used as possible, independent discharge time series or not. The series can be used when the ERA-CLIM series are mutually independent and not dependent on the observed series.

An independency analysis will be performed on the discharge series. The Pearson Correlation coefficient r will be used as measure of correlation. This test measures the linear association between two variables, x and y. The Pearson Correlation coefficient will be calculated using equation 1.

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i - x_{avg}}{s_x}\right) * \left(\frac{y_i - y_{avg}}{s_y}\right) \qquad (1)$$

where n is the length of the discharge time series, x is the i^{th} value of x, x_{avg} is the mean of the whole series of x and s_x is the standard deviation of the series of x, y_i is the i^{th} value of y, y_{avg} is the mean of the series of y and s_y is the standard deviation of the series of y. In this case, x and y both correspond to values of a discharge time series.

If the data lie exactly along a straight line with positive slope, then r = 1. When the slope is negative then r = -1, otherwise the value or r is somewhere between -1 and 1. The significance of a correlation will be tested by determining whether r differs from zero (Hersel & Hirsch, 2012). The test statistic t_r can be computed with equation 2, and it can thereafter be used to calculated the corresponding p-value with the two-sided Student's t distribution with n-2 degrees of freedom. When the test statistic t_r exceeds the p-value, the null hypothesis of no trend will be rejected.

$$t_r = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \qquad (2)$$

where *n* is the length of the discharge time series.

Thereafter, the annual discharge time series with respect to all discharge characteristics will be compared by means of their means and standard deviations and theoretical probability density functions derived from histograms will be constructed to further investigate the differences between the annual series.

3.4. Statistical trend analysis

In this study, statistical tests are used to determine whether the annual discharge time series show a significant downward or upward trend. To be able to exclude the weaknesses from the statistical tests in this study four statistical tests will be used, since the statistical tests have not the same detection power and strengths for each discharge characteristic according to Diermanse et al. (2010).

All used tests are hypothesis tests. These tests check whether hypotheses are supported given the evidence provided by the available data (Hersel & Hirsch, 2012). The tests start from a null hypothesis that the process is stationary. The null hypothesis is what is assumed to be true about the system under study prior to data collection, until indicated otherwise. This is usually stated as the "null" situation -- no difference between groups, no relation between variables (Hersel & Hirsch, 2012). The likelihood of this hypothesis is evaluated based on the value of a test statistic. The alternative hypothesis is the situation anticipated to be true if the evidence shows that the null hypothesis is unlikely (Hersel & Hirsch, 2012). Alternative hypotheses come in two general types: one-sided and two-sided. One-sided tests should be applied when departures in only one direction from the null hypothesis would cause the null hypothesis to be rejected. If it cannot be stated prior to looking at the data that departures from the null hypothesis in only one direction are of interest, a two-sided test should be carried out (Hersel & Hirsch, 2012). In this study is chosen to only perform two-sided tests, since it is a priori unknown what kind of trends the ERA-CLIM discharge time series have.

The α-value, or significance level, is the probability of incorrectly rejecting the null hypothesis. Statistical tradition in water management uses a default of 5 % (0.05) for α. For that reason, this value will also be used in this study. Furthermore, the p-value is the probability of obtaining the computed test statistic when the null hypothesis is true (Hersel & Hirsch, 2012). When the p-value is less than the α-value, the null hypothesis is rejected, which means that you can be 95 % confident that there is a trend. This p-value is derived from the data using a statistical test and it expresses the evidence against the null hypothesis contained in the data.

The statistical tests which will be applied in this study will be explained in the next section. These tests were chosen to be consistent with comparable studies which have used these tests frequently before (Diermanse, et al., 2010; Belz, et al., 2007; Paquette, n.d.).

Pearson t-test

The classical Student's t-test evaluates the significance of the correlation between the series x and y. This test uses the correlation-coefficient of Pearson r. It is also called the linear correlation coefficient since r measures the linear association between two variables (Hersel & Hirsch, 2012).

The parametric test considers the linear regression of the discharge values y on the time x. The regression coefficient r is computed from the data with equation 1. The significance of r can be tested by determining whether r differs from zero. With Pearson's $r,$ the test statistic of equation 2 can be calculated.

The test statistic is compared with the Student's t distribution with degrees of freedom n-2, where n is the sample size. The hypothesis that there is no trend is rejected when the test statistic t_r computed in equation 2 is larger in absolute value than the calculated p-value from the Student's t distribution (Önöz & Bayazit, 2002).

Mann-Kendall statistical test

The Mann-Kendall test is a non-parametric significance test for a monotonic trend in a time series. Non-parametric statistics do not rely on the assumption that the data are drawn from a given probability distribution. The statistical test measures the strength of the relationship between two variables. It is a rank-based procedure and therefore it is resistant to the effect of a small number of unusual values, which is good for statistical trend analysis of discharges (Hersel & Hirsch, 2012).

The Mann-Kendall test can be stated most generally as a test which checks if y values tend to increase or decrease with x. So, in this study will be checked if discharge values y tend to increase or decrease over time x. The Mann-Kendall test is based on the test statistic S. This test statistic is calculated by subtracting the number of pairs where y decreases as x increases, from the number of pairs where y increases as x increases:

$$S = P - M \tag{3}$$

where P is the number of times the y's increase as the x's increase and M is the number of times the y's decrease as the x's increase.

The null hypothesis of no change is rejected when S is significantly different from zero (Hersel & Hirsch, 2012). Then can be concluded that there is a significant trend in the discharge time series. The test statistic Z, which measures the strength of the monotonic association between two variables can be closely approximated by a normal distribution, since the number of discharge values in the series is larger than ten. Z can be calculated with equation 4 (Önöz & Bayazit, 2002).

$$Z = \begin{cases} \frac{S-1}{\sigma_s} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sigma_s} & if\ S < 0 \end{cases} \tag{4}$$

where

$$\sigma_s = \sqrt{\frac{n(n-1)(2n+5)}{18}} \tag{5}$$

n = number of discharge values.

The null hypothesis that there is no trend is rejected when the computed Z value is larger than Z_{crit} in absolute value, where Z_{crit} is the value of the standard normal distribution with a probability of exceedance of $\alpha/2$ (α = 5 %).

Spearman's rank correlation test

The Spearman's rank correlation test in another non-parametric test. The test statistic is Spearman's rank correlation coefficient r_s, which is the correlation between the ranks of the discharges and their years of observation (Diermanse, et al., 2010).

In this test, which assumes that the discharge time series data are independent and identically distributed, the null hypothesis indicates no trend over time and the alternative hypothesis is that a trend exists and that data changes over time. The test statistic can be calculated with equation 6 (Ahmed, et al., 2015).

$$r_s = 1 - \frac{6 * \sum_{i=1}^{n} (D_i - i)^2}{n^3 - n} \tag{6}$$

In this equation, D_i is the rank of i^{th} observation, *I* is the chronological order number and n is the total length of the discharge series. The significance of r_s can be tested by determining whether r_s differs from zero, using equation 2. Just as like the Pearson t-test, the test statistic follows the Student's t distribution with degrees of freedom n-2. The hypothesis that there is no trend is rejected when the t value computed in equation 2 is greater in absolute value than the critical value $t_{\alpha/2}$ (Önöz & Bayazit, 2002).

Wilcoxon-Mann-Whitney test

This test statistic is a non-parametric test for two independent samples. The Wilcoxon-Mann-Whitney test can be used for trend analysis by splitting the time series into a first and second half and testing the null hypothesis that the two sets are taken from the same distribution. When the two sub-sets are statistically taken from the same distribution, it can be concluded that there is no trend (Diermanse et al., 2010).

As stated, the first step in applying the Wilcoxon-Mann-Whitney test is splitting the discharge series into halves, so that there are two groups (A with length n and B with length m) of independent data. Then the joint ranks R of the data in data sets A and B must be calculated. This means that all data points in A and B obtain a rank between R = 1 to (N = n + m). The test statistic $\mathrm{W_{rs}}$ can be determined afterwards applying equation 7. $\mathrm{W_{rs}}$ is the sum of the ranks for the data set having the smallest sample size.

$$W_{rs} = \sum R_a \; or \sum R_b \tag{7}$$

The distribution of the test statistic $\mathrm{W_{rs}}$ closely approximates a normal distribution when the sample size for each group is 10 or more, which is in this study the case. This however does not imply that the data are or must be normally distributed. It is only based on the near normality of the test statistic at large sample sizes. The standardized test statistic Z can therefore be calculated by applying equation 8, 9 and 10 (Hersel & Hirsch, 2012).

$$Z = \begin{cases} \frac{W_{rs} - \frac{1}{2} - \mu_W}{\sigma_W} & if \; W_{rs} > \mu_W \\ 0 & if \; W_{rs} = \mu_W \\ \frac{W_{rs} + \frac{1}{2} - \mu_W}{\sigma_W} & if \; W_{rs} < \mu_W \end{cases} \tag{8}$$

where

$$\mu_W = n * \frac{(N+1)}{2} \tag{9}$$

$$\sigma_W = \sqrt{\frac{n * m * (N+1)}{12}} \tag{10}$$

$$N = (n + m)$$

where μ_W is the mean of $\mathrm{W_{rs}}$ and σ_W is the standard deviation of $\mathrm{W_{rs}}$.

The null hypothesis that there is no trend is rejected when the computed value Z is greater than Z_{crit} in absolute value, where Z_{crit} is the value of the standard normal distribution with a probability of exceedance of $\alpha/2$.

3.5. Comparing trends

To gain insight into the differences between the trends found in observed, HYRAS and ERA-CLIM discharge time series, the p-values and directions of the trend from the statistical tests of the previous sections will be compared. This will be performed by shortening the observed and ERA-CLIM discharge time series until the period, 1951 until 2006, of the HYRAS time series. To give a complete image of the trends in the series, the trends will be calculated for the period 1901 until 1950 as well. This will give understanding about the strength of the trends in the different series. Furthermore, the significance level of 20 % will be used, in addition to the significance level of 5 %, to obtain better insight in the differences between the series.

4. Results

The outline of this chapter is as follows. First in section 4.1, the hydrological years will be presented and discussed. Thereafter in section 4.2 the discharge time series will be compared with each other. Then in section 4.3 the trend analyses of observed discharge time series will be performed. The trend analyses of HYRAS discharge times series and the trend analyses of ERA-CLIM discharge time series will thereafter be performed. These results are respectively shown in section 4.4 and 4.5. In section 4.6, a comparison will be made between trends found during the trend analyses.

4.1. Determination of hydrological year

As mentioned in section 3.2, two different hydrological years must be determined for constructing the annual discharge time series.

First, the mean discharge per day and per month were determined with 110 years of daily discharge data. The mean discharge value of the 29th of February is not considered, because the corresponding mean discharge value is based on a too small number of years to be a good representation of weather in the whole century. However, it has been checked whether this value was the highest/lowest value and this was not the case. It turned out that the highest mean discharge occurred in January and that the lowest mean discharge occurred in October. The results of the determination of the hydrological years is shown in Table 1. The exact values of the maximum and minimum discharge and the distribution of the mean discharge over 110 years are given in Appendix A.

Table 1: Hydrological year results

Discharge characteristic	**Hydrological year**
Annual maximum daily discharge	1 October - 30 September
Annual minimum 7-day discharge	1 January - 31 December

The discharge characteristic *annual mean discharge* will start at the beginning of a calendar year, so also the first of January. The results of the determination of the three months with the highest mean discharge and the three months with the lowest mean discharge are given in Table 2. The exact values of all twelve-monthly means are given in Appendix A.

Table 2: 3 months with highest and lowest discharge

Description	**Months**
3 months with lowest mean discharge	August, September and October
3 months with highest mean discharge	January, February and March

4.2. Comparing discharge time series

In this section, the results of the comparison between the observed, HYRAS and ERA-CLIM discharge time series will be discussed.

Daily time series analysis

As mentioned in section 3.4 the daily discharge time series at Lobith of all three data sets are used in this analysis. The considered time series in these analyses cover the period 1901 up to 2010, except for the HYRAS discharge time series which covers a period from 1951 up to 2006.

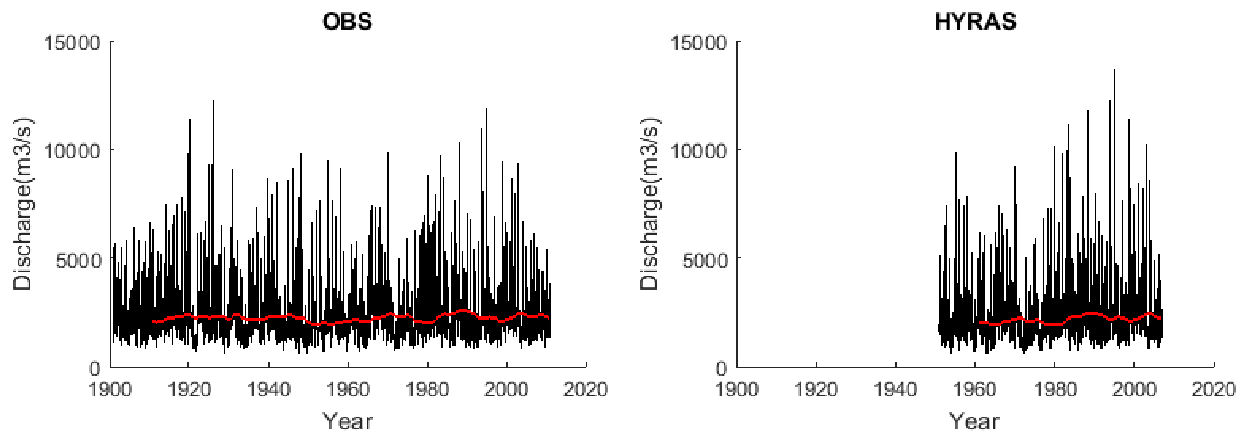


Figure 3: Daily discharge time series with running 10-year average (red line). Only the figures of the observed discharge time series and the HYRAS discharge time series are depicted. Appendix B contains the figures of the ERA-CLIM discharge time series.

According to Figure 3 and especially looking at the red line, the progress of the observed discharge time series and HYRAS time series are quite the same. Moreover, the figures show discharge peaks at around the same time. These peaks however are slightly overestimated by the series HYRAS-series. This finding is considered in this study, however this is not very important, since a small overestimation in a few points will not cause that a trend in the series can or cannot be detected. Figure 4-A confirms the findings of Figure 3. From this figure can be concluded that the series have almost the same distribution of discharge values, except that the HYRAS series has a slightly smaller spread. The standard deviation displayed in Table 3 shows the same behaviour. The standard deviation of the HYRAS discharge time series is lower than the value of the observed discharge time series. The mean of the HYRAS time series is also slightly lower than the mean of the observed time series. However, from these findings it can be concluded that the observed and HYRAS series are equal in this study. So, the (trends in the) ERA-CLIM discharge time series can directly be compared with the observed time series. This conclusion will later in this study be checked by comparing the trends found in both (observed and HYRAS) discharge time series.

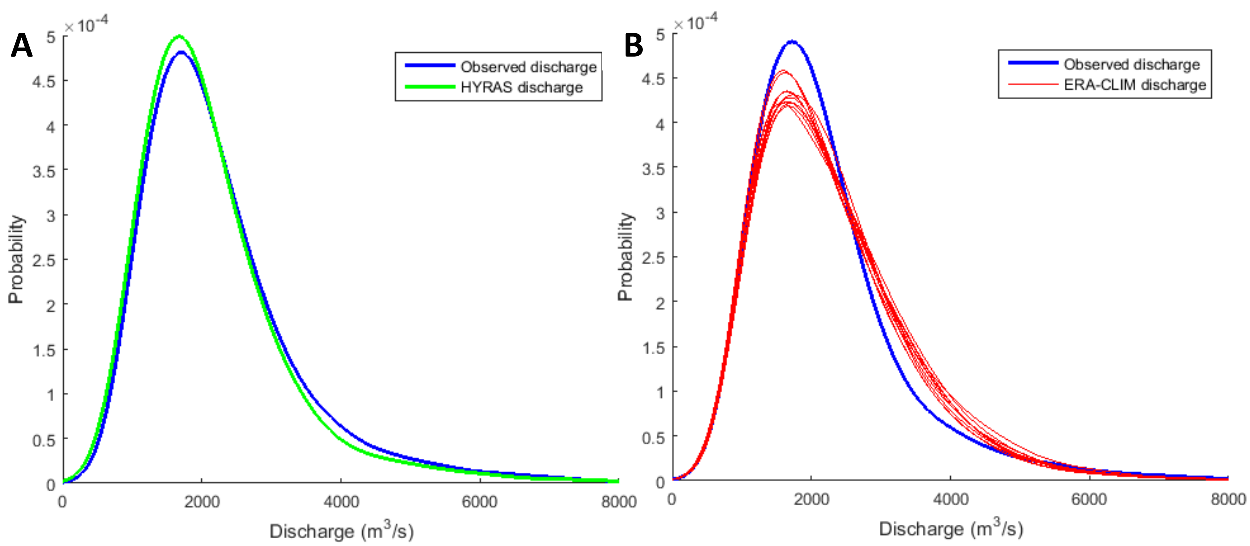


Figure 4: Theoretical probability density function of (A) observed and HYRAS daily discharge series for the period 1951 up to 2006 and (B) observed and ERA-CLIM daily discharge series for the period 1901 up to 2010.

Looking at the remainder of Figure 3 in Appendix B, it can be stated that there are major differences between the ten ERA-CLIM discharge time series and the observed discharge series, especially the number and distribution of the peaks over time. Some series contain more medium peaks (peaks in between 5000 and 10.000 m^3s^{-1}) than the other simulations and some series contain more high peaks (peaks upward of 10.000 m^3s^{-1}) and a low number of medium peaks. These findings are the first indicator for the required independency of the ERA-CLIM series for this study. On average, the ERA-CLIM time series have a lower number of high peaks and more medium peaks than the observed time series. Furthermore, the other directly visible differences are not very large with respect to the observed discharge time series.

Figure 4-B shows the daily discharges of the River Rhine at Lobith for the observed discharge time series and for each of the ten ERA-CLIM discharge time series based on ERA-CLIM ensemble members. Looking at the ERA-CLIM discharge time series zero to nine, the differences are large with respect to the observed discharge data, however based on these lines it can be seen that the River Rhine is represented. It turned out that the ERA-CLIM discharge time series contain a lower number of discharge values between 1000 and 3000 m^3s^{-1} and that they contain a higher number of discharge values between 3000 and 5000 m^3s^{-1}.

Similar results follow from Table 3. The standard deviation of the ERA-CLIM discharge time series is on average slightly lower than the standard deviation of the observed time series and the mean of the ERA-CLIM series is slightly higher than the mean of the observed series.

Table 3: Mean and standard deviation [m^3s^{-1}] of total series; Daily discharge time series. OBS-S displays the mean and standard deviation of the observed discharge time series with the same length as the HYRAS discharge time series.

	OBS	**OBS-S**	**HYRAS**	**ERA-CLIM 0**	**ERA-CLIM 1**	**ERA-CLIM 2**	**ERA-CLIM 3**	**ERA-CLIM 4**	**ERA-CLIM 5**	**ERA-CLIM 6**	**ERA-CLIM 7**	**ERA-CLIM 8**	**ERA-CLIM 9**
Mean	2226	2265	2162	2220	2378	2353	2331	2300	2308	2250	2301	2270	2319
Standard deviation	1138	1168	1143	1055	1199	1109	1132	1081	1111	1089	1116	1085	1098

From the above can be concluded that, despite the present differences, the ERA-CLIM discharge time series are applicable in this study when using them as possible discharge time series of the past. This follows from the finding that the ERA-CLIM series are quite similar to observed discharge time series looking at the distribution of the discharge values. The ERA-CLIM discharges values have about the same order of magnitude and the series do not contain impossible low or high extremes. However, the present differences will be considered when calculating and interpreting the trends later in this study.

Annual time series analysis

When analysing the constructed annual discharge time series, a closer look can be taken at the different series. The mean and standard deviation of the twelve annual discharge time series were calculated for the period 1901 until 2010 and for the period 1951 until 2006. The results are displayed in Figure 5 and in Figure 6.

Looking at Figure 5, the mean and standard deviation for all discharge characteristics except for the *annual maximum daily discharge* are about the same. The mean of the ERA-CLIM series for the discharge characteristic *annual mean discharge* are all slightly higher than the mean of the observed series, just as concluded earlier, and the mean of the ERA-CLIM series of the discharge characteristic *annual mean low-flow season discharge* are all slightly lower than the mean of the observed series. These differences are however negligible.

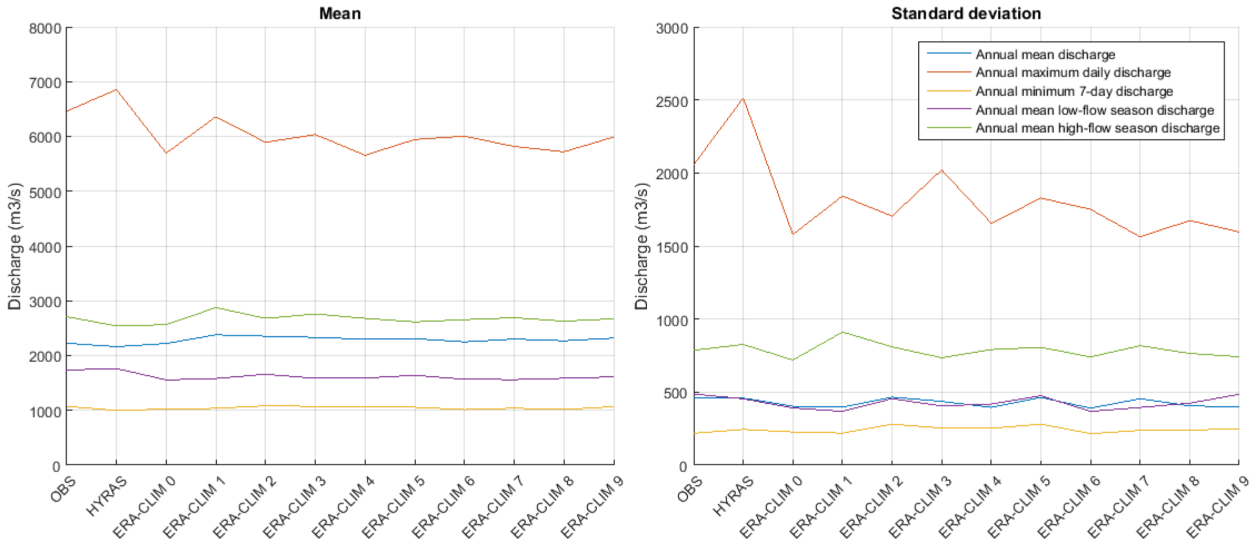


Figure 5: Mean and standard deviation of annual discharge time series for the period 1901 - 2010, except for the mean and standard deviation of the HYRAS series which is calculated for the period 1951 - 2006.

The only large differences can be found at the discharge characteristic *annual maximum daily discharge*. Both the mean and standard deviation of the ERA-CLIM series are considerable smaller than the mean and standard deviation of the observed series and HYRAS series. The mean and standard deviation of the HYRAS series are however higher than the mean and standard deviation of the observed and ERA-CLIM series. This is expected to be partly due to the difference in period and party due to the HBV-model in combination with HYRAS weather input. This has been checked with Figure 6.

Comparing Figure 5 and Figure 6, it turned out that both figures barely differ. The only noticeable differences can be found by the discharge characteristic *annual maximum daily discharge*. The differences between the observed and HYRAS series have only partly disappeared and therefore it can be concluded that the HBV-model in combination with its observed input weather overestimates high peak flows.

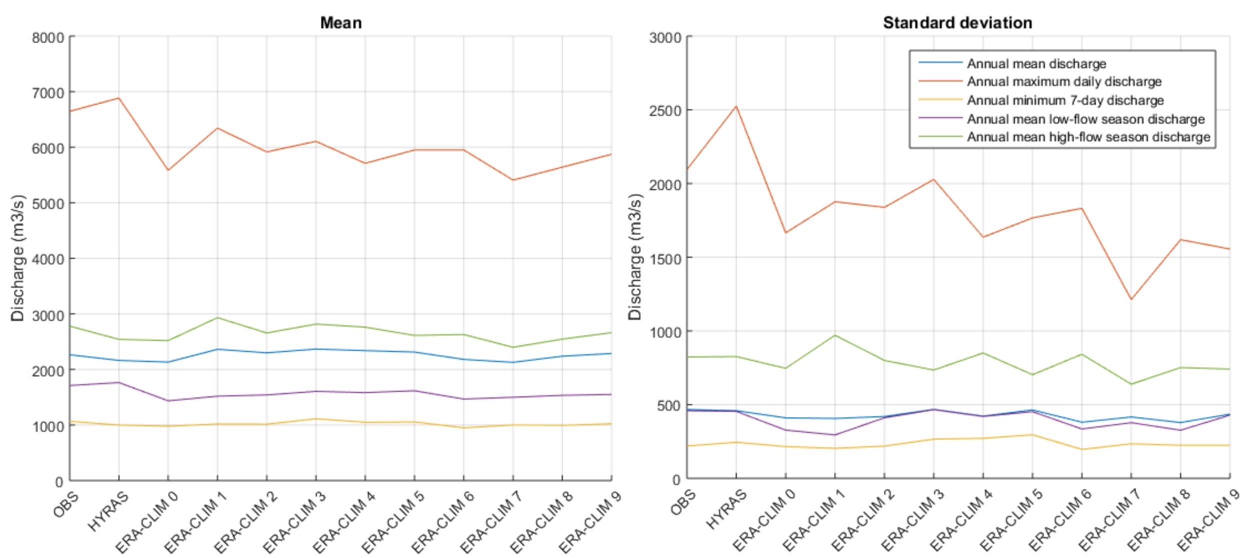


Figure 6: Mean and standard deviation of annual discharge time series for the period 1951 until 2006

Finally, to better interpret the differences between the annual discharge time series, theoretical probability density functions were created from the annual time series for the period 1901 until 2010 and 1951 until 2006. Two remarkable PDFs are shown in Figure 7 and Appendix C contains the remainder of the PDFs.

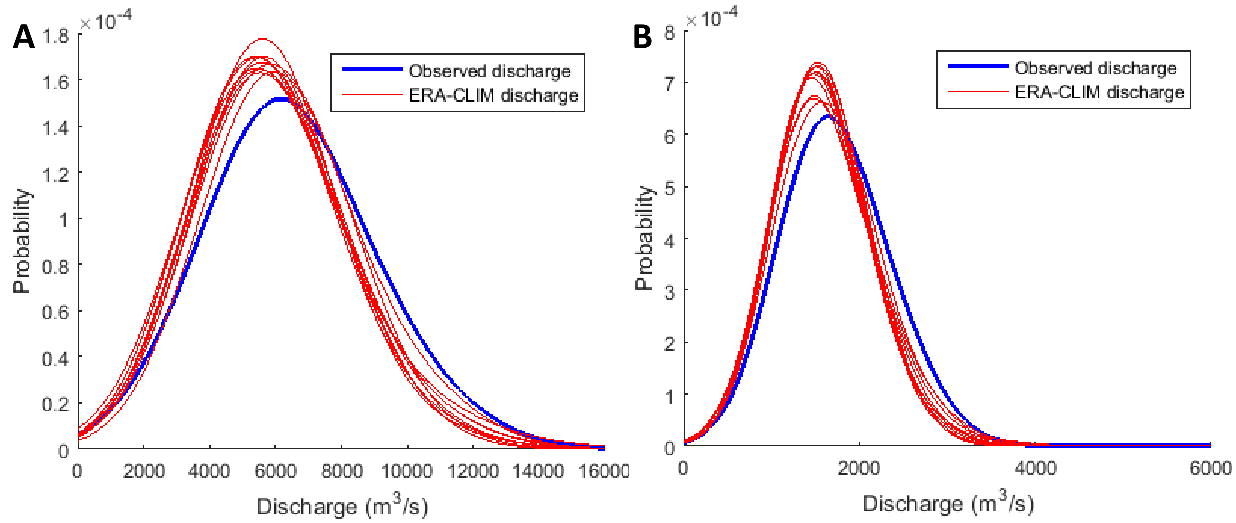


Figure 7: Theoretical PDFs for the discharge characteristics: Annual maximum daily discharge (A) and annual mean low-flow season discharge for the period 1901 - 2010 (B).

Looking at the theoretical PDFs of both periods, the ERA-CLIM series have about the same spread of discharges as the observed time series and HYRAS time series, except for the discharge characteristics *annual mean low-flow season* and *annual maximum daily discharge*. For the *annual mean low-flow season discharge* it turned out that observed and HYRAS discharge time series do have less low annual discharge values than the ERA-CLIM series. For the discharge characteristic *annual maximum daily discharge,* it turned out that the observed and HYRAS series do have higher annual peaks than the ERA-CLIM series. For the other discharge characteristics, all probability density functions are very close to each other. This means that, for these situations, the ERA-CLIM series can represent the observed situation quite good.

Furthermore, it is tested whether the ten ERA-CLIM discharge time series are dependent on each other and whether the ten ERA-CLIM discharge time series are dependent on the observed discharge time series. For each combination of the annual ERA-CLIM series per discharge characteristic the correlation coefficient has been calculated. The results are displayed in Figure 8 in combination with the calculated threshold-value of significance for p = 5 %. As can be seen in this figure, the Pearson Correlation coefficients obtained from the ERA-CLIM discharge time series are low and most of the values are not significant for all discharge characteristics. The difference between the discharges characteristics is not that large too. Only 12 % of the correlation coefficients obtained from all combinations of discharge series with respect to all discharge characteristics is significantly correlated. Therefore, the ERA-CLIM time series can be treated as mutually independent (Sperna Weiland, et al., n.d.).

In addition, this means that the influences of the stochastic SST part of the forcing terms within the ERA-CLIM weather model simulation is important. If the influence of the stochastic SST part of the forcing terms was not major, the mutual correlations should have been much higher. This can only be claimed with keeping in mind that the IFS model environment is deterministic. If the model environment was stochastic the independency of the series could have been arisen by the model itself.

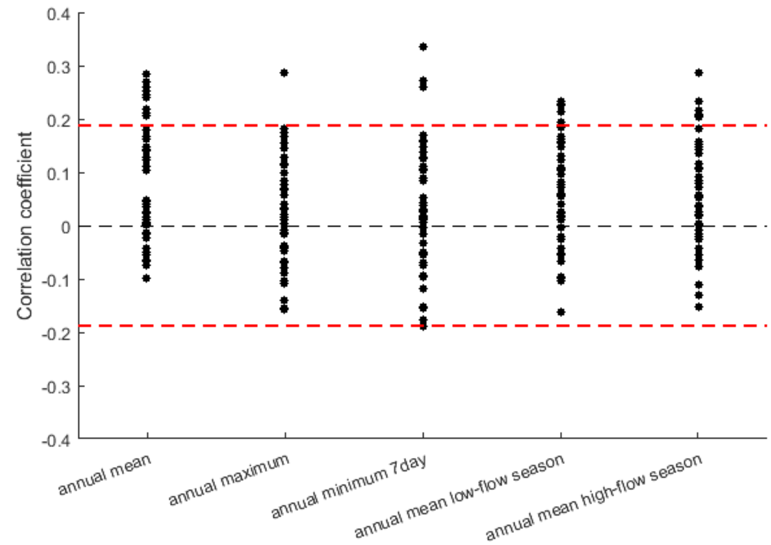


Figure 8: Mutual correlations of ERA-CLIM discharge series. The figure contains the threshold value for significance (dotted red line). For each discharge characteristic, the black dots show the correlation coefficients for all combinations of ERA-CLIM series per discharge characteristic. Per discharge characteristic 45 point are displayed.

Figure 9 shows the results of the dependency analysis between the annual ERA-CLIM discharge time series and annual observed time series per discharge characteristic. The Pearson correlation coefficients obtained from comparing the ERA-CLIM discharge time series with the observed discharge time series are low and the majority of these values is also not significant for all discharge characteristics. Only 8 % of all correlation coefficients indicate a significant correlation between the observed and 10 ERA-CLIM time series. This indicates a large diversity between the observed and ERA-CLIM discharge time series. The variation is partly due to the limited observed information in the ERA-CLIM weather model simulation. This finding shows the variation between the all ERA-CLIM time series and the observed time series which is good for this study since the ERA-CLIM series are used as a range of possible weathers of the last century which include climate variability.

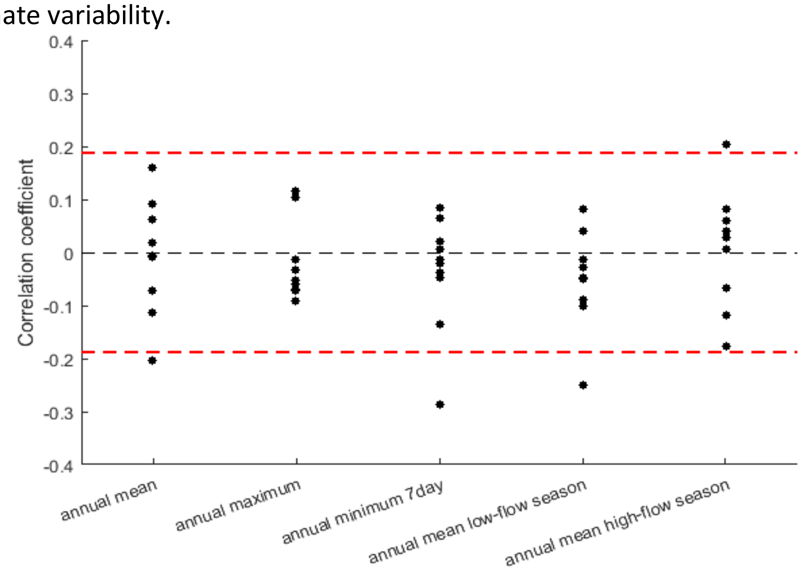


Figure 9: Mutual correlations of ERA-CLIM discharge series and observed discharge series. The figure contains the threshold value for significance (dotted red line). For each discharge characteristic, the black dots show the correlation coefficients for all combinations of ERA-CLIM series per discharge characteristic. Per discharge characteristic 10 point are displayed.

4.3. Trend analysis of observed discharge time series

The four statistical tests were applied to test the presence and significance of a trend in observed discharge time series of the five discharges characteristics of the River Rhine at Lobith for the hydrological years 1901 until 2010. The presence, probability value (p-value) and direction of a possible trend are calculated. The results of the trend analysis are given in Table 4. The p-values obtained against the null hypothesis, of no trend in the discharge time series, have shown that there is no significant trend at 0.05 (5%) significance level for any of the four statistical tests for all discharge characteristics. Therefore, it cannot be stated with more than 95% certainty, based on these statistical tests, that there is a positive of negative trend in the time series.

Table 4: Results statistical tests applied to the observed discharge time series

	Annual mean discharge		**Annual maximum daily discharge**		**Annual minimum 7-day discharge**		**Annual mean low-flow season discharge**		**Annual mean high-flow season discharge**	
Statistical test	P-value	Trend	P-value	Trend	P-value	Trend	P-value	Trend	P-value	Trend
Pearson t-test	42.0 %	No	32.0 %	No	49.3 %	No	40.3 %	No	17.9 %	No
Mann-Kendall statistical test	42.0 %	No	29.6 %	No	40.3 %	No	51.8 %	No	16.6 %	No
Spearman's rank correlation test	46.3 %	No	34.2 %	No	18.1 %	No	45.3 %	No	16.8 %	No
Wilcoxon-Mann-Whitney test	34.5 %	No	77.0 %	No	48.4 %	No	87.2 %	No	22.7 %	No

4.4. Trend analysis of HYRAS discharge time series

The four statistical tests were applied to test the presence and significance of a trend in the HYRAS discharge time series of the five discharges characteristics of the River Rhine at Lobith for the hydrological years 1951 until 2006. The results of the trend analyses are given in Table 5.

Table 5: Results statistical tests applied to the HYRAS discharge time series

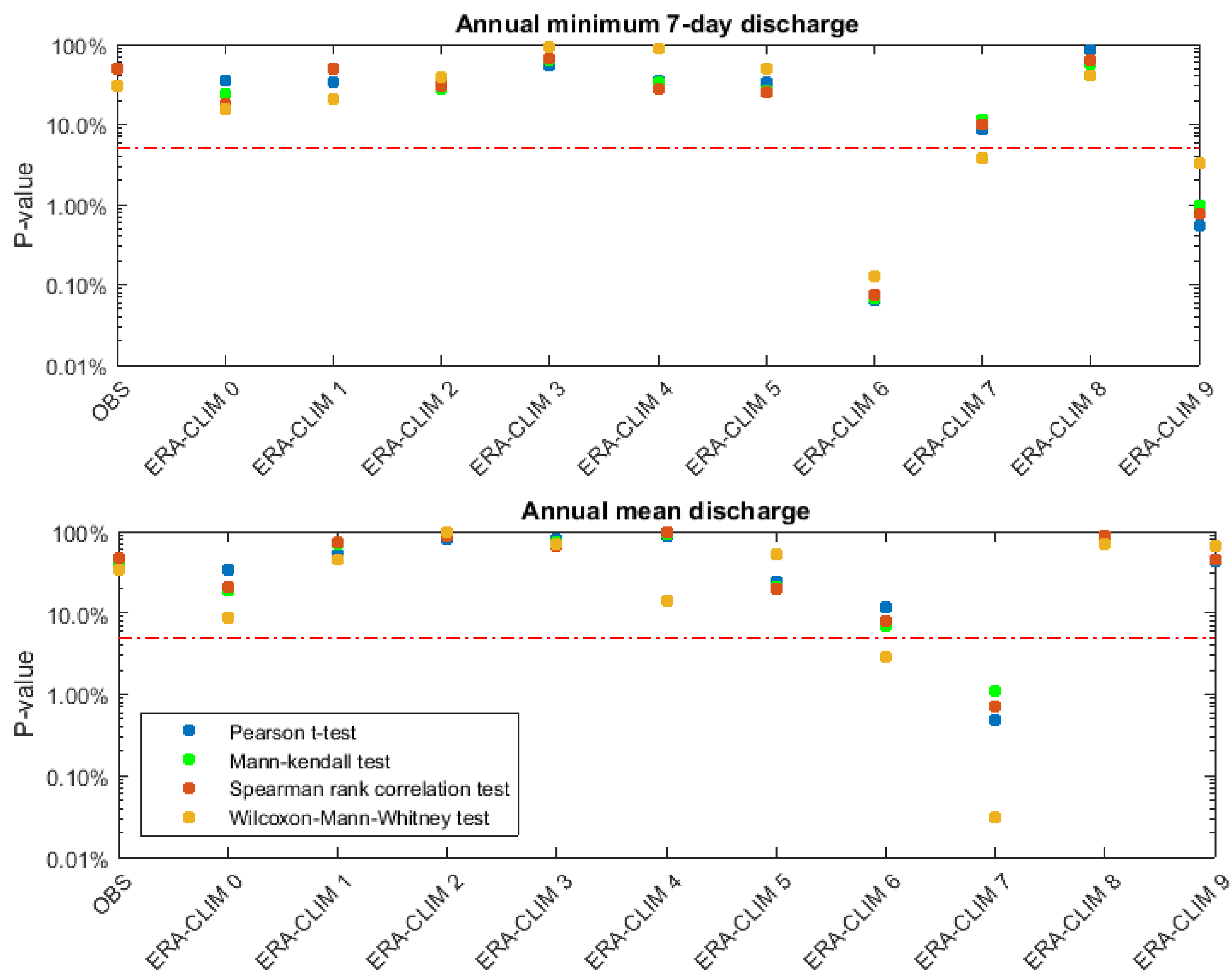
	Annual mean discharge		**Annual maximum daily discharge**		**Annual minimum 7-day discharge**		**Annual mean low-flow season discharge**		**Annual mean high-flow season discharge**	
Statistical test	P-value	Trend	P-value	Trend	P-value	Trend	P-value	Trend	P-value	Trend
Pearson t-test	20.3 %	No	6.35 %	No	0.61 %	Yes, rising	68.1 %	No	5.50 %	No
Mann-Kendall statistical test	19.1 %	No	14.3 %	No	0.87 %	Yes, rising	86.0 %	No	11.5 %	No
Spearman's rank correlation test	23.9 %	No	12.5 %	No	0.81 %	Yes, rising	78.4 %	No	11.2 %	No
Wilcoxon-Mann-Whitney test	5.02 %	No	0.74 %	Yes, rising	0.16 %	Yes, rising	81.2 %	No	2.99 %	Yes, rising

The probability values obtained against the null hypothesis have shown that there is no significant trend at 5 % significance level for two of the five discharge characteristics considering all four statistical tests. The p-values of the discharge characteristic *annual mean low-flow season discharge*, e.g. 68.1% and 86.0%, are far from the significance level of 5 %. However, the p-values from the tests of the discharge characteristic *annual mean discharge*, e.g. 5.02% and 19.1%, are closer to the significance level of 5 %.

The probability values with respect to the discharge characteristic *annual minimum 7-day discharge* show that there is a significant trend at 5% significance level for all four statistical tests. Therefore, it can be stated with more than 95% certainty, based on these statistical tests, that there is a positive trend in the time series. The probability values with respect to the discharge characteristics *annual mean high-flow season discharge* and *annual maximum daily discharge* show that there is a significant trend at 5% significance level for one of the four statistical tests. However, it can also be stated with more than 95% certainty that there is a positive trend in the time series.

4.5. Trend analysis of ERA-CLIM discharge time series

To test the significance of a trend in the ERA-CLIM discharge time series based on ERA-CLIM, the four statistical tests were applied. The discharge time series are calculated for the five discharges characteristics at Lobith and the considered hydrological years are 1901 until 2010. The results of the trend analysis are given in Figure 10. These figures also include the results of section 4.3 to be able to compare the findings.



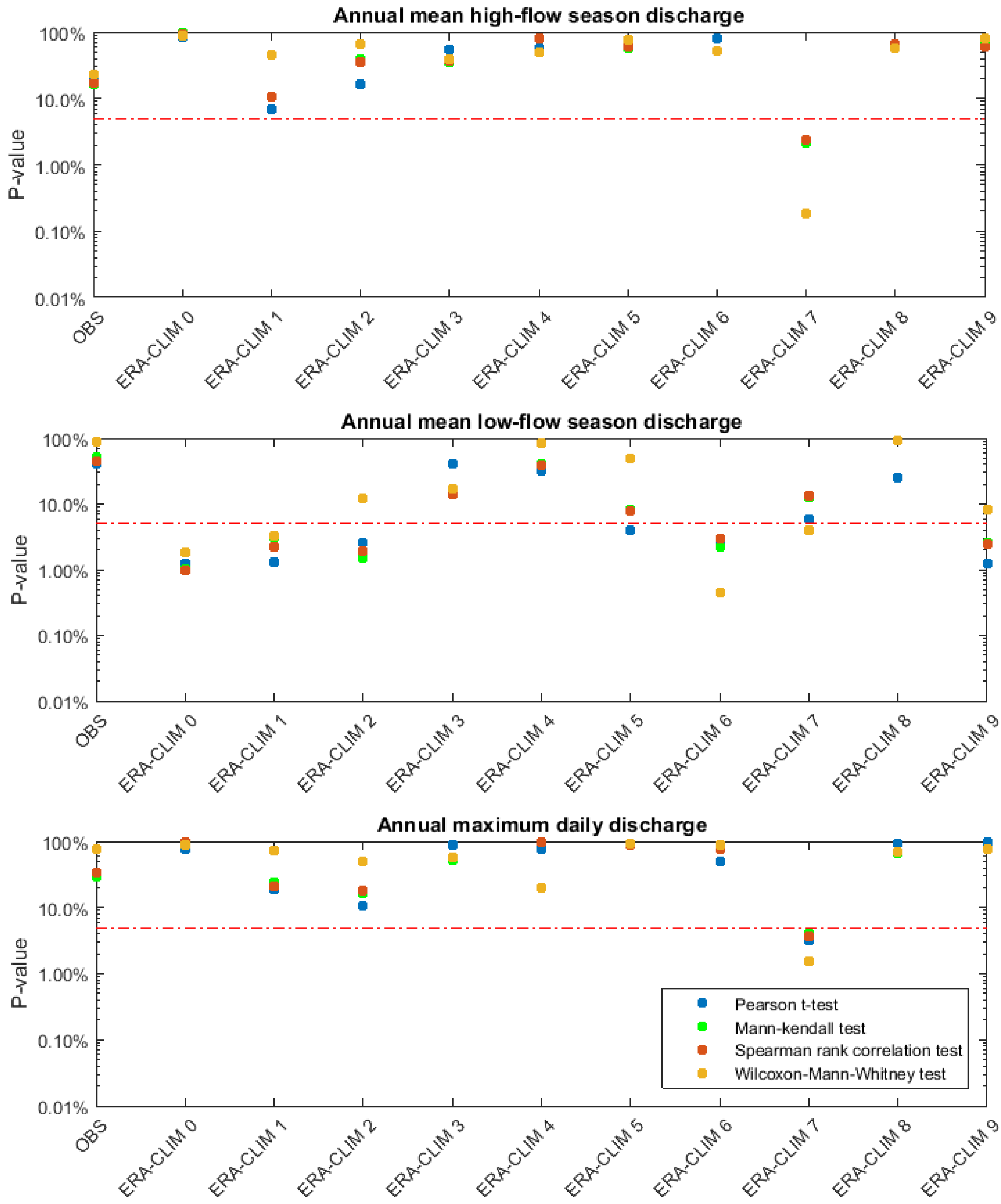


Figure 10: P-values of statistical tests of ERA-CLIM discharge time series and p-values of statistical tests of observed discharge time series (OBS) per discharge characteristic. The dotted line indicates the α-value of 0.05 for significance testing.

In summary, it can be claimed that no statistical evidence can be found in most of the ERA-CLIM discharge series which concludes that there is a significant positive of negative trend. However, ERA-CLIM 6 and ERA-

CLIM 9 show a significant trend for both discharge characteristics which indicate low flow situations: *annual minimum 7-day discharge* and *annual mean low-flow season discharge*. When looking at the differences between the two characteristics, it can be concluded that a stronger trend is visible for the characteristic *annual minimum 7-day discharge* than for the other characteristic. For this characteristic, all four statistical tests show a trend instead of only a couple of tests showing a trend.

ERA-CLIM 7 shows a significant trend for all discharge characteristics which indicate high and mean water situations: *annual mean discharge*, *annual maximum daily discharge* and *annual mean high-flow season discharge*. When looking at the differences between the four statistical methods, the Wilcoxon-Mann-Whitney test results in the smallest p-values. Besides ERA-CLIM 0, 1 and 2 show also significant trends for the discharge characteristic *annual mean low-flow season discharge*.

4.6. Comparison of trends

When comparing the findings of the trend analysis of the previous section, it can be stated that the trends found in the observed series and the trends found in the ERA-CLIM series are not the same at all. Some p-values are very high, e.g. about 99 %, and some are very low, e.g. about 0.10 %.

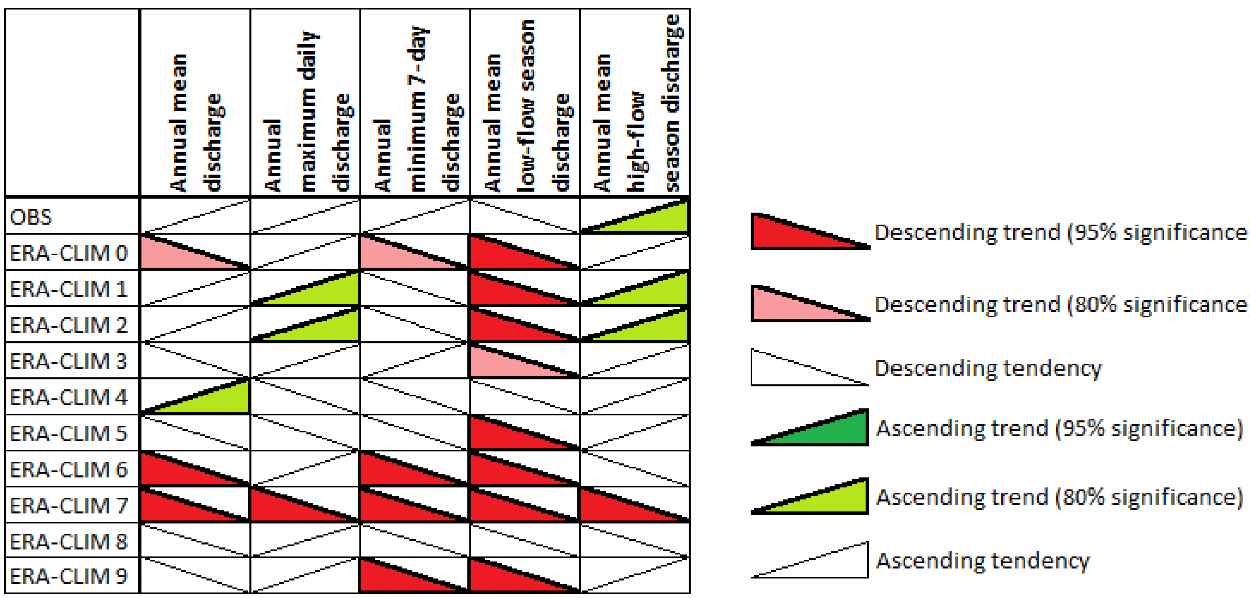


Figure 11:Trends and directions of all combinations of discharge characteristics and discharge time series (1901-2010). The figure is based on figure 6.6 from Belz et al. (2007).

Figure 11 shows the trends and corresponding directions of the observed and ERA-CLIM discharge times series. All trends are determined by using series which cover a period of 110 years and the 80% significance level is added to be able to better compare the several series. It turned out that the ERA-CLIM series show more significant trends than the observed series trend. Another remarkable finding is that the directions of the trends from the ERA-CLIM series are often different from the direction of the tendencies from the observed series, however it must be kept in mind that the trends from the observed series are not significant, and therefore the directions could change quickly. Where the observed series often show ascending tendencies, the ERA-CLIM series generally show descending tendencies. However, the ERA-CLIM series show the same behaviour as the observed series for the discharge characteristic *annual mean low-flow season discharge*. Also, the trends found for the discharge characteristic *annual mean high-flow season discharge* show slightly the same behaviour, however these trends are not significant. The series do not further show any clear similarity with respect to the other discharge characteristics. It can also be seen that the direction of the trends with respect to the low-flow discharge characteristics are in general downwards, while the directions of the trends with respect to the high-flow discharge characteristics are in general upwards for the observed and ERA-CLIM discharge time series.

To be able to fairly compare the results of the different discharge time series, the trends and the corresponding directions of the observed and ERA-CLIM time series for the same period as the HYRAS series were calculated too. The influence of the HBV-model can be determined using these results. The 80 % significance level is also added to be able to compare the different series. Figure 12 displays the results.

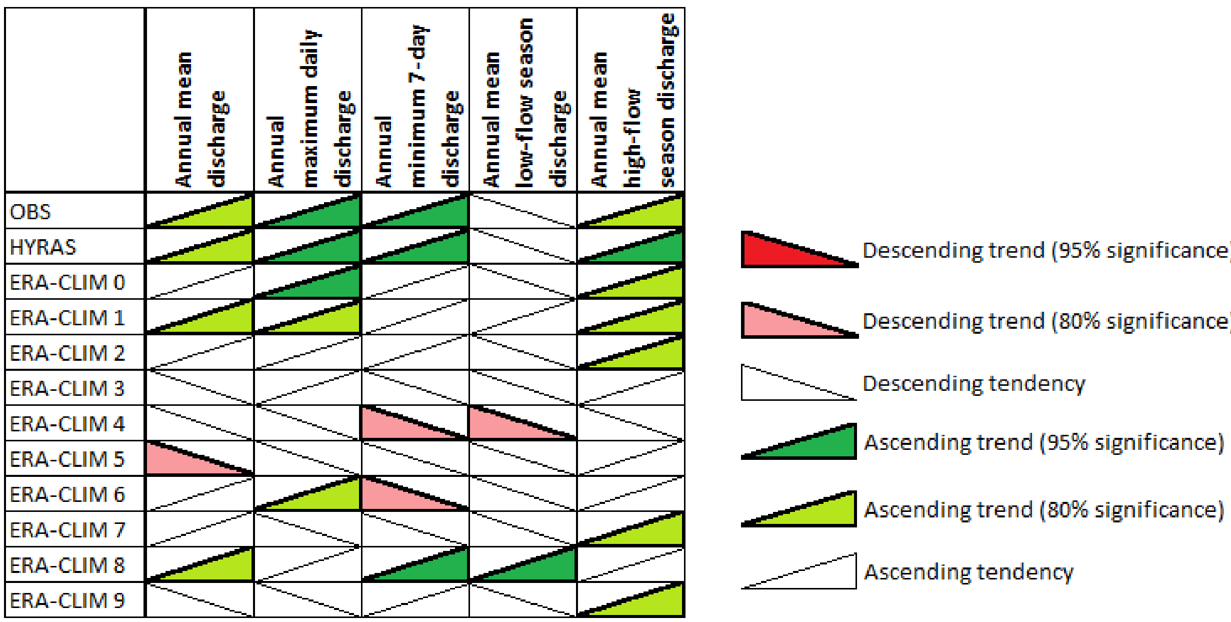


Figure 12:Trends and directions of discharge characteristics and discharge time series (1951-2006)

It turned out that only a small difference is present between the trends found in the observed and HYRAS time series and that therefore the HYRAS series can represent the trends in the observed series quite could. Taking a closer look at the corresponding p-values shows that the significance of the trends of the HYRAS time series is larger for any discharge characteristic, see Table 6. This difference is partly due to the differences in the time series and partly due to the use of the HBV-model in combination with the HYRAS input weather which already has been concluded in section 4.2. This finding must be considered when comparing the trends of the observed and ERA-CLIM series. However, the trends of the observed series can directly be compared with the trends in the ERA-CLIM series.

Looking at the observed series and ERA-CLIM series, the *annual mean high-flow season discharge* trends of the ERA-CLIM series show the same behaviour as the trend of the observed series. The series do not further show any clear, similar trends for the other discharge characteristics.

Table 6: P-values of the significant trends in observed and HYRAS discharge time series for a period of 55 years

	Annual mean discharge	**Annual maximum daily discharge**	**Annual minimum 7-day discharge**	**Annual mean low-flow season discharge**	**Annual mean high-flow season discharge**
OBS	0.15	0.03	0.05	-	0.13
HYRAS	0.05	0.005	0.002	-	0.03

When comparing Figure 11 and Figure 12 with each other, many large differences are visible. It is primarily striking that the direction of several trends of combinations of ERA-CLIM time series and discharge characteristics became the opposite. This shows that strong descending trends are only present when looking at a long series and that especially looking at around the last 50 years the tendencies in the same series are more ascending.

To give an overall picture of the trends in the series and to understand the differences between Figure 11 and Figure 12, the trends are also being calculated for the period from 1901 until 1951 for the observed and ERA-CLIM discharge time series. The results are displayed in Figure 13.

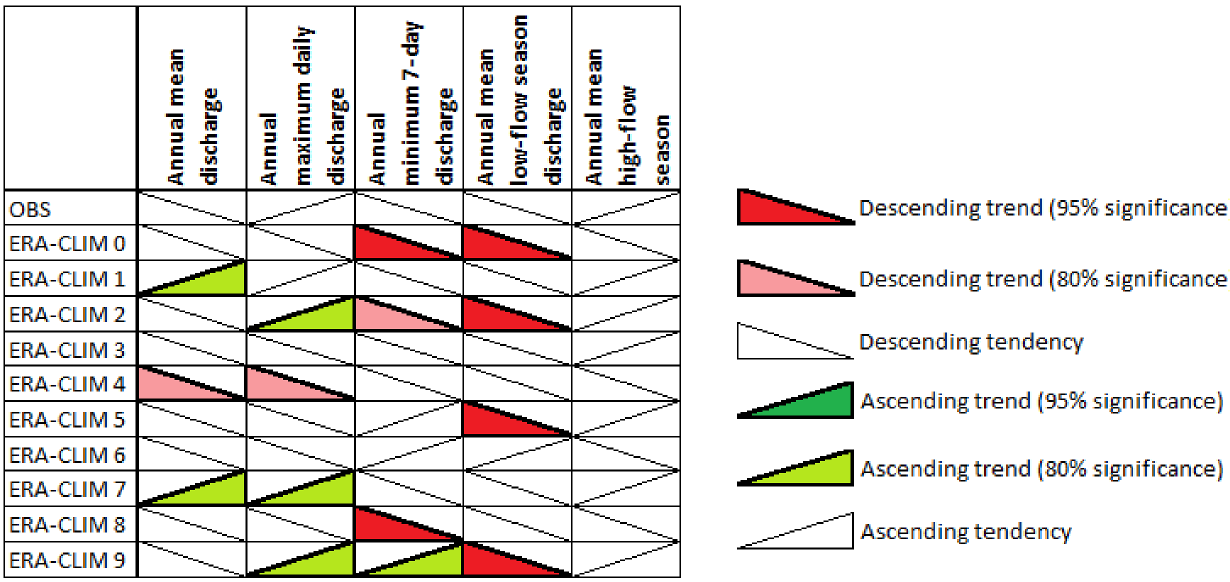


Figure 13:Trends and directions of discharge characteristics and discharge time series (1901-1951)

It is eye-catching that no significant trend is noticeable for the discharge characteristics annual mean high-flow season. The observed and ERA-CLIM time series do not show any clear similar trend with respect to all the discharge characteristics. Some directions of the trends in this table differ from the directions of the two previous tables.

Furthermore, looking at Figure 11, 12 and 13, it seems to be strange that the overall trend is descending in some cases when both trends in the two halves are ascending. Using Figure 14, it turned out that both halves of this series can contain positive trends while the overall trend is negative. Looking at the running 10-year mean, it can be stated that there is a bent in the discharge values which causes this behaviour.

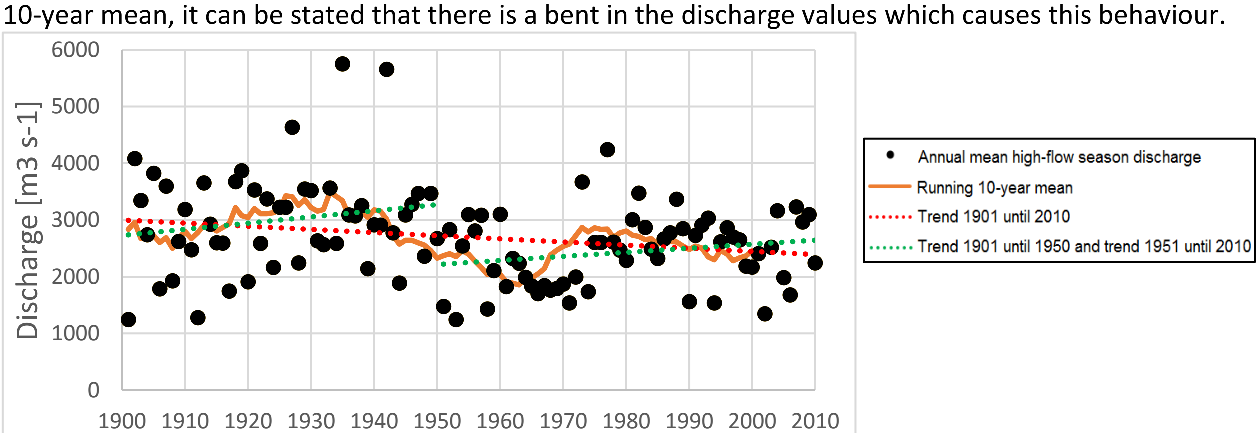


Figure 14: Annual mean high-flow season discharge (series ERA-CLIM 7) with corresponding trends and running 10-year mean

5. Discussion

5.1. Data

The observed daily discharge time series used in this study comprises a period from 1901 up to 2010. The series consists of two parts of measurement. As state in chapter 2.3, the first part from the years 1901 up to 1988 consists of one single daily measurement at 8 a.m. and the second part from the years 1989 up to 2010 consists of measurements of the daily mean discharge. The method for gathering the first part of the series can be doubted a bit since the belonging discharge values will not give a totally good representation of the discharge of the whole day. It is possible that by chance a discharge is measured which is not a good representation of the whole day. Therefore, this series contains, especially up to the year 1988, an uncertainty. Besides, it is known that the quality of the data from especially the first half of the twentieth century can be doubted, and besides the data originally does not comprise each day. To construct one long daily discharge series homogenisations were implemented. It is however unknown which and how many homogenisations were implemented.

The HYRAS discharge series can be doubted too, since this series is constructed with precipitation and temperature data which is gathered by means of up to 6200 stations. It is expected that this number of stations will give a quite good representation, however there still remains a small uncertainty, since the data poor regions are filled by means of linear regression. The small uncertainty with respect to this series is not that large in relation to the uncertainty with respect to the ERA-CLIM series.

The input parameters for ERA-CLIM: the sea surface temperature and the sea ice concentration cause major uncertainties. They are obtained from data sets with very large gaps to cover the total planet. Filling these gaps by means of statistical methods resulted in many uncertainties which can finally result in unrealistic weather. This has however not been tested in this study. It is known that the sea surface temperatures of ERA-CLIM show lower temperatures than observed. During some months, this underestimation goes up to 5 degrees Celsius (Huiskes, 2016). It is however not known why this is happening, however this means that the ERA-CLIM weather assimilation should be researched and improved in this field (Huiskes, 2016).

When taking a closer look at the ERA-CLIM product, the temperature rise over land is according to Hersbach et al. (2013) in fair agreement with observations and therefore the product can provide a good statistical estimate of the past climate. This implies that the temperature rise on earth is around 0.37 ^{o}C over the period of 1901 until 2010 (Kennedy, 2014). However, this behaviour cannot be clearly seen in the ERA-CLIM series and corresponding trends, since there are no strong ascending trends in the discharge time series. This is a remarkable finding.

5.2. Method

A factor which could heighten the uncertainty in the ERA-CLIM series is that the HBV-model is calibrated to the HYRAS series, therefore HBV is probably not able to perfectly transform the ERA-CLIM precipitation and temperature data into discharges. The ability of the HBV-model to translate precipitation and temperature into discharges can also be doubted. In Kramer et al. (2010) it was shown that an overestimation of the serial correlation of the daily discharges, resulting in too smooth hydrographs, was present (Kramer, Winsemius, & De Keizer, 2010).

There is a possibility that more trends, with respect to other discharge characteristics than used in this study, can be found in the River Rhine discharge, when for example looking at the annual mean autumn or spring discharge. Besides, the definition of a discharge characteristic can influence whether a trend can be found or not. For example, the 3-month period of the *annual high- and low-flow season discharge* can influence the presence of a trend. When the 3 months were chosen slightly different, the presence of a trend was probably different.

Using statistical test for trend analysis in this study can be doubted. According to Diermanse et al. (2010), statistical tests have insufficient detection power for a relatively weak trend in an around 100-year discharge series. This however has been neglected in this study, since using statistical tests is the commonly used method for trend analysis nowadays. Another important thing to consider with respect the trend analysis is that finding no trend may only mean that the data was insufficient to find the trend. Therefore, performing trend analysis will always include lots of uncertainties. Only when the trends are identified with very strong p-values, you can be almost complete sure about your conclusion.

The significance level of 20 % used in this study for better understanding the differences between the several series (observed, HYRAS and ERA-CLIM) causes many uncertainties about the trends present with respect to this significance level. Using a lower significance level causes that more trends will be found, however it also causes that more trends will be found which actually are no trends.

5.3. Results

When comparing the trend results with literature, it can be stated that the same results were found with respect to the observed discharge time series. As concluded by Belz et al. (2007) and Diermanse et al. (2010), no trends can be found in the annual mean discharge and annual high or low extreme discharge of the Rhine. However, like Belz et al. (2007) and Pinter et al. (2006) concluded too, a significant trend can be found in the high-flow season discharge of the River Rhine.

It turned out that the visibility and direction of a trend is heavily affected by the period in which the trend is calculated. Different periods resulted in different directions and strong or weak significance levels. It must be kept in mind that long periods in common give a better representation of the present trends than short periods which results can fluctuate very often because of extreme low or high discharge values.

The trend analysis results are heavily influenced and the reliability of the findings of this study can be doubted because of the manner the ERA-CLIM ensembles are constructed. The ten ensemble members of ERA-CLIM are created by randomly drawing different sea surface temperature (SST) ensembles from a large SST ensemble. The identified trends in the ERA-CLIM time series could be very different when ten other SST ensembles were drawn, since it is not known how other SST ensembles look like and which variation the large SST ensemble contains.

6. Conclusions and recommendations

6.1. Conclusions

This research focussed on finding confirmation for average, seasonal and extreme trends in the River Rhine discharge at Lobith making use of discharge time series created with a hydrological model in combination with a numerical weather product to lower the uncertainties in the current trend analyses. The numerical weather product (ERA-CLIM) is a dataset of ten ensembles which concerns the re-analysed day-to-day weather of 1901 until 2010. In this research, the suitability of the discharge time series constructed with ERA-CLIM was first investigated with respect to the HYRAS and observed discharge time series. Subsequently, the trends of all the discharge time series were calculated. Finally, the calculated ERA-CLIM trends were compared with the trends found in the HYRAS and observed time series.

To which extent can the discharge time series constructed with a hydrological model in combination with a numerical weather product serve as possible, independent discharge time series of the past? ***(1)***

The observed and HYRAS series are compared to determine what the influence is of the HBV-model on the resulting discharge time series. It turned out that the differences between both series are negligibly small considering the progression through time and the mean and standard deviation. The only difference is the overestimation of a small number of peak values of the HYRAS series, which is partly due to the HBV-model and partly due to the input data. When comparing the observed and ERA-CLIM series on a daily basis by means of theoretical probability functions, means and standard deviations, the ERA-CLIM series can represent the observed discharge very well, when not considering the difference in the distribution of discharge values over time which could be seen by plotting the series.

Looking at the annual discharge time series, it can be concluded that the ERA-CLIM series cannot represent the observed series quite well for all discharge characteristics. ERA-CLIM can represent the discharge characteristics *annual mean discharge*, *annual high-flow season discharge* and *annual minimum 7-day discharge* very well, since the probability density functions, mean and standard deviation of the observed series and ERA-CLIM series are almost the same. ERA-CLIM is less good in representing the other discharges characteristics, especially the *annual maximum daily discharge*. It can however be concluded that ERA-CLIM can represent the observed series, when keeping in mind the differences.

It also turned out that the ten ERA-CLIM series are not dependent on each other and that the ERA-CLIM series are also not dependent on the observed series. This means that the ten ERA-CLIM series can serve as ten possible, even likely independent discharge time series of the past. Moreover, this means that the series can also properly represent climate variability, since they are not dependent on the observed series. The ability of the ERA-CLIM series to represent climate variability causes that the uncertainties of the measured discharge time series can be considered by using the ERA-CLIM time series in the trend analyses.

Are there trends noticeable in observed average, seasonal and extreme discharge time series of the Rhine at Lobith? ***(2)***

The evidence obtained against the null hypothesis, of no trend in the discharge time series for a period from 1901 until 2010, has shown that there is no significant trend at 5 % significance level for any of the four statistical tests with respect to all discharge characteristics. Therefore, it cannot be stated with more than 95% certainty, based on these statistical tests, that there is a positive of negative trend in the time series. However, a significant, weak ascending trend can be found using a 20 % significance level with respect to the discharge characteristic *annual mean high-flow season discharge*.

For the period from 1951 until 2006 significant ascending trends were found with respect to the discharge characteristics *annual maximum daily discharge* and *annual minimum 7-day discharge* at 5 % significance level and significant ascending trends were found for the discharge characteristics *annual mean discharge* and *annual mean high-flow season discharge* at 20 % significance level. No significant trends were found for the period 1901 until 1950.

It turned out that the period for which the trend is calculated influences the significance and direction of the trend. The directions of the trends in the observed series do not change when changing the period from 1901 until 2010 to 1951 until 2006. Changing to the first half of the century does change the direction of the discharge characteristics *annual mean discharge* and *annual minimum 7-day discharge* to descending, which indicates that the trend in the 20th century changed from descending to ascending.

Are there trends noticeable in simulated average, seasonal and extreme discharge time series of the Rhine at Lobith created with a hydrological model in combination with observed input weather? ***(3)***

The evidence obtained against the null hypothesis, of no trend in the HYRAS discharge time series with a period from 1951 until 2006, has shown that there are significant ascending trends with respect to the discharge characteristics *annual maximum daily discharge*, *annual minimum 7-day discharge* and *annual mean high-flow season discharge* at 5 % significance level and that there is a significant ascending trend at the discharge characteristic *annual mean discharge* at 20 % significance level.

Are there trends noticeable in simulated average, seasonal and extreme discharge time series of the Rhine at Lobith created with a hydrological model in combination with a numerical weather product? ***(4)***

The evidence obtained against the null hypothesis, of no trend in the ERA-CLIM discharge time series with a period from 1901 until 2010, has shown that there are strong descending trends in two of the ten ERA-CLIM series for almost all discharge characteristics and in almost all ERA-CLIM series for the discharge characteristic *annual mean low-flow season discharge* at 5 % significance level. Besides, there are some significant ascending and descending trends found at 20 % significance level. The last notable finding is the major difference in visible trends between the ERA-CLIM series.

When calculating the trends for the period 1951 until 2006 other trends were found. The strong ascending trends with respect to the period 1901 until 2010 were not visible anymore, and some more significant ascending trends at 20 % and 5 % significance level were found, especially for the discharge characteristic *annual mean high-flow season discharge*.

The trends in the series for the period 1901 until 1950 are also calculated. Several series do contain an ascending or descending trend. However, the ERA-CLIM series do not contain a common trend for one of the discharge characteristics. The only notable finding is that the discharge characteristic *annual mean low-flow season discharge* shows a descending significant trend for 5 % significance level at four ERA-CLIM series and that almost all other ERA-CLIM series show descending tendencies.

It is also concluded that the period for which the trend is calculated affects the direction and significance of the trend. Many significant trends in the ERA-CLIM series changed to non-significant and directions of trends shifted, when changing the period from 1901 - 2010 to the first or second half of the century.

What are the differences between the trends found in the different series and what do these differences mean? ***(5)***

The differences between the trends found in the observed and HYRAS series are analysed to find the influence of the HBV-model on the resulting trends. It can be concluded that the trends in both series are almost the same. So, HYRAS in combination with the HBV-model can together quite good represent the observed trends in the second half of the twentieth century. Only a very small difference is present between the trends found in the observed and HYRAS series and this means that the HBV-model does not have a major influence on trends. By taking a closer look to the corresponding p-values, it has been shown that the significance levels of the trends found in the HYRAS series are slightly larger than the significance levels found in the observed series. It cannot be concluded in this study that the HBV-model causes this behaviour alone, since it could also have been caused because of the HYRAS input weather or a combination of both. This must be further investigated. However, it can be concluded that the HBV-model will not strongly influence the direction and visibility of a trend. So, the trends in de ERA-CLIM series can directly be compared with the trend in the observed series.

After comparing the trends found in the observed and ERA-CLIM series, the following conclusions can be drawn. Many directions and significance levels of the trends found in the ERA-CLIM series are different than the directions and significance levels of the trends found in the observed series. There is also a large variation present between the directions and significance levels of the trends in the ten ERA-CLIM series. The ERA-CLIM series only clearly confirm two types of observed trends. Looking at the period from 1901 until 2010 the ERA-CLIM series confirm the observed descending tendency with respect to the discharges characteristic *annual mean low-flow season discharge* and looking at the period from 1951 until 2006 the ERA-CLIM series confirm the ascending trend with respect to the discharge characteristic *annual mean high-flow season discharge*. These conclusions, especially the conclusion regarding the discharge characteristic *annual mean high-flow season*, can be drawn despite the present differences between the observed and ERA-CLIM series, because the trends are very significant.

In summary, no trends in the extreme and mean discharge time series are confirmed making use of the ERA-CLIM series. The seasonal trends found in the observed discharge time series are however confirmed making use of the ERA-CLIM series and therefore this study will provide, taking into account the many uncertainties, circumstantial evidence for these trends in the observed series.

6.2. Recommendations

Based on the discussion and previous conclusions some recommendations can be made to support further research.

Firstly, it can be recommended to perform an analysis of the underlying precipitation and temperature data with which the ERA-CLIM discharge time series were constructed to gain insight into the way the major differences between the ERA-CLIM series are arisen. With this analysis, it can also be examined why the influence of the imposed temperature rise is not directly visible in the ERA-CLIM discharge time series, while this influence is expected to be present by means of more heavy precipitation and melting of glaciers.

Secondly, it can be recommended to investigate what the exact influence is of the HBV-model on the HYRAS discharge time series and the resulting trends, since there is in this study only concluded that both the HBV-model and the HYRAS data set could cause the differences between the observed and HYRAS series.

Another recommendation concerns the significant ascending trends in the observed and HYRAS discharge time series in about the second half of the twentieth century (1951 until 2006). It is interesting to investigate what the origin of these ascending trends is.

From this study, it could not be concluded yet that ERA-CLIM can be used in combination with the HBV-model to construct discharge time series which can be used in data poor regions to form expectations about the trends in the current river discharges. This may become possible, when many more ERA-CLIM ensemble members are available or when the ERA-CLIM series are improved. Furthermore, since ERA-CLIM data are available worldwide other river basins could be assessed too to see if the same conclusion can be drawn about the ERA-CLIM series. From this study, it could however be concluded that it is possible to use the HYRAS data set in combination with the HBV-model to simulate the current trends in the River Rhine discharge.

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Appendix A – Results hydrological year calculation

Table A-1: Highest and lowest mean discharge

Description	Discharge (m^3s^{-1})	Date
Minimum mean discharge	1610	7 October
Maximum mean discharge	2907	5 January

Table A-2 contains the monthly means of the all days within a specific month for the period 1901 until 2010.

Table A-2: Monthly means

Months	Monthly mean (m^3s^{-1})	Months	Monthly mean (m^3s^{-1})
January	2743	***July***	2124
February	2710	***August***	1855
March	2680	***September***	1699
April	2497	***October***	1655
May	2226	***November***	1957
June	2238	***December***	2371

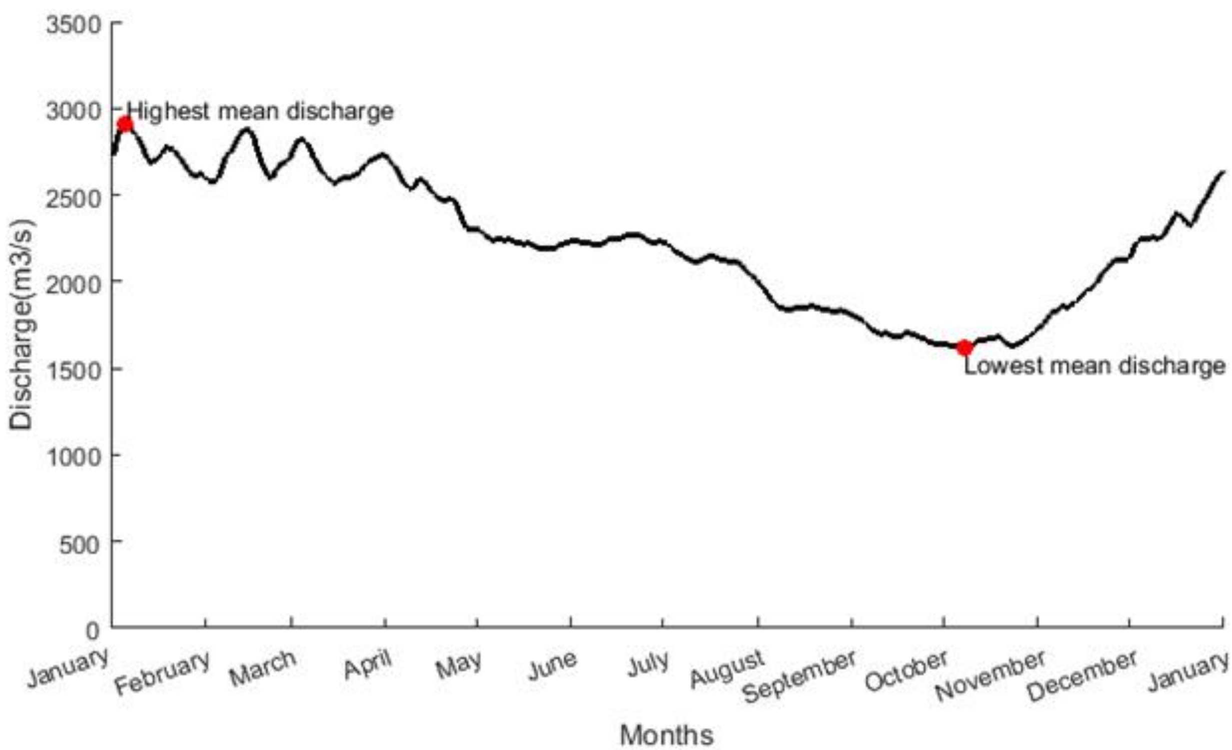
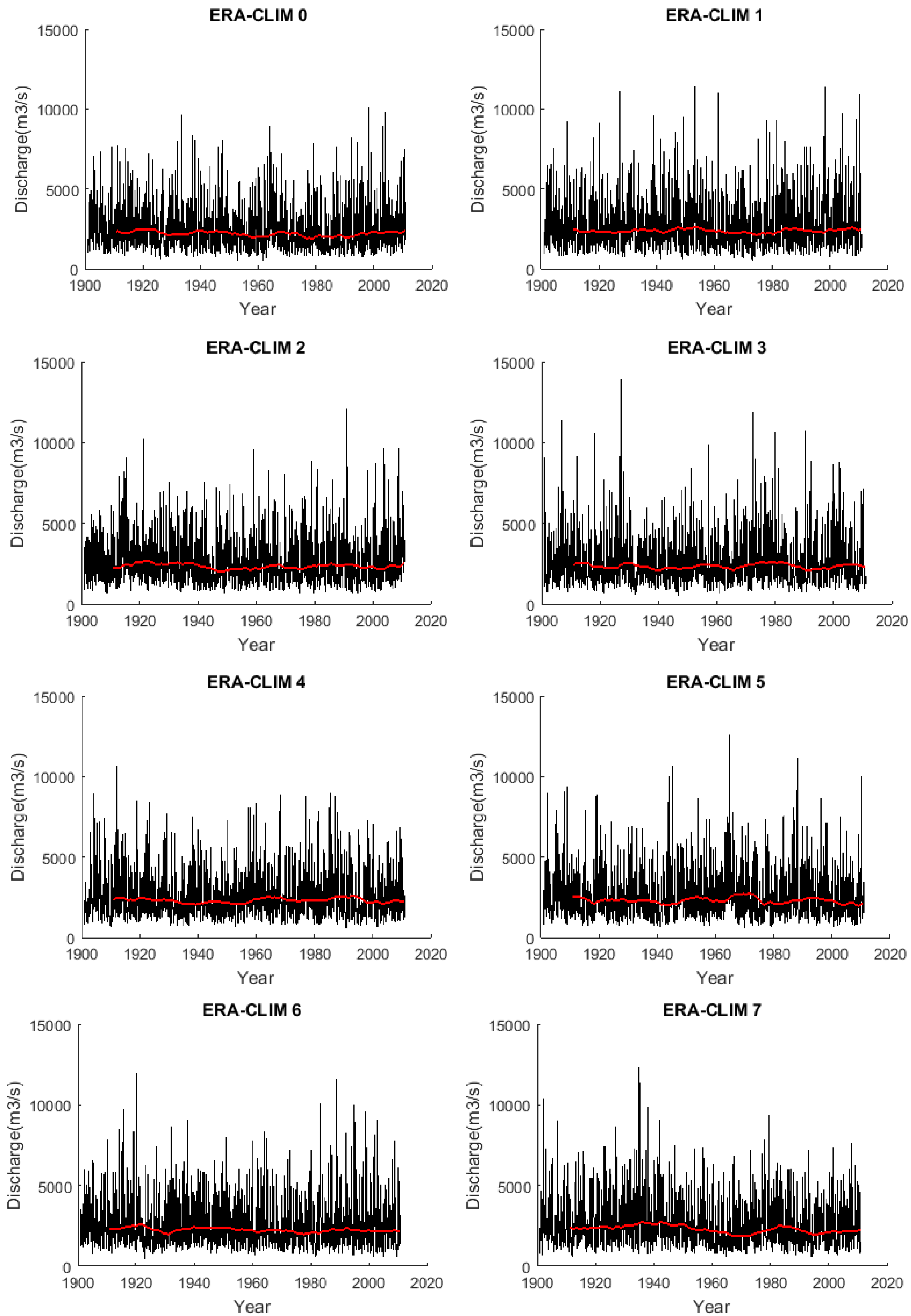


Figure A-1: Mean discharge per day determined over a period of 110 year.

Appendix B – Daily discharge time series of ERA-CLIM



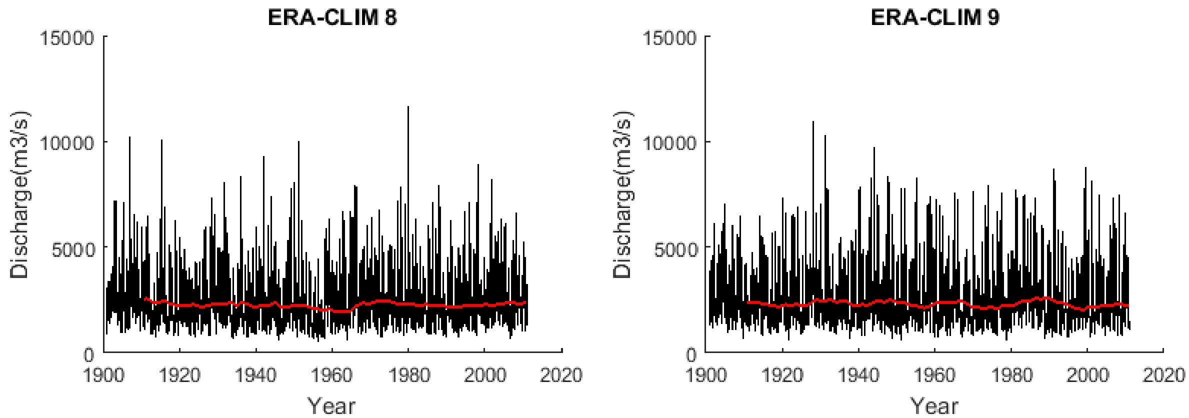


Figure B-1: Daily Discharge Time Series of ERA-CLIM discharge time series.

Appendix C – Theoretical probability density functions

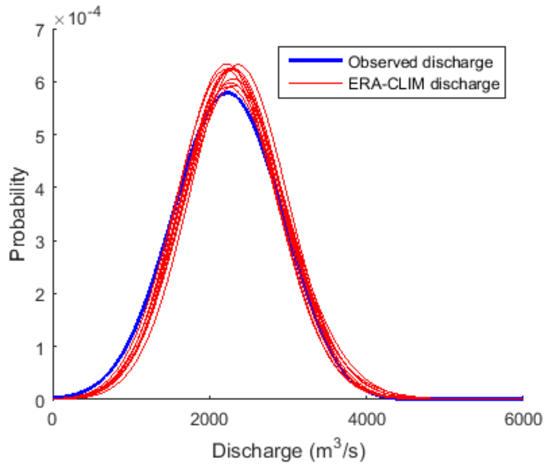


Figure C-1.1: PDF of annual mean discharge (1901-2010)

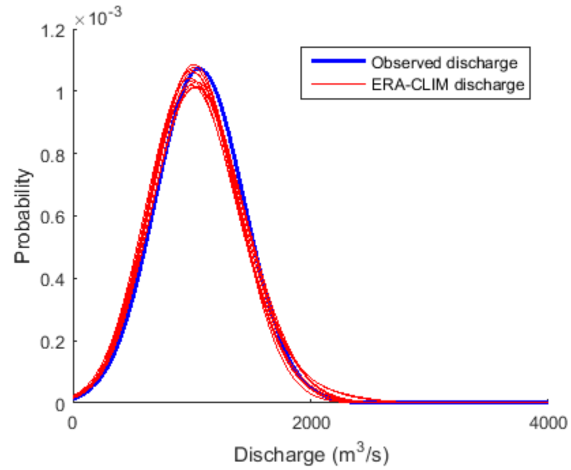


Figure C-1.2: PDF of annual minimum 7-day discharge (1901-2010)

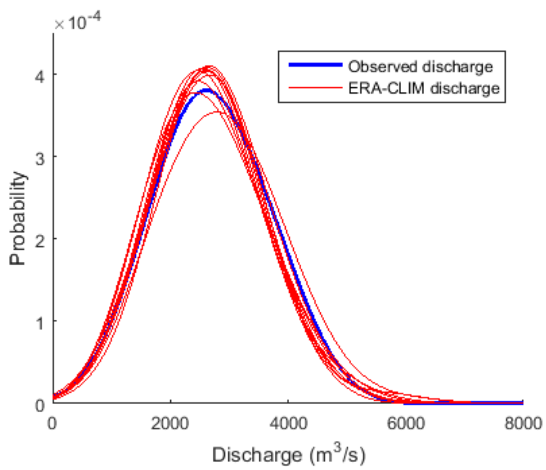


Figure C-1.3: PDF of annual mean high-flow season discharge (1901-2010)

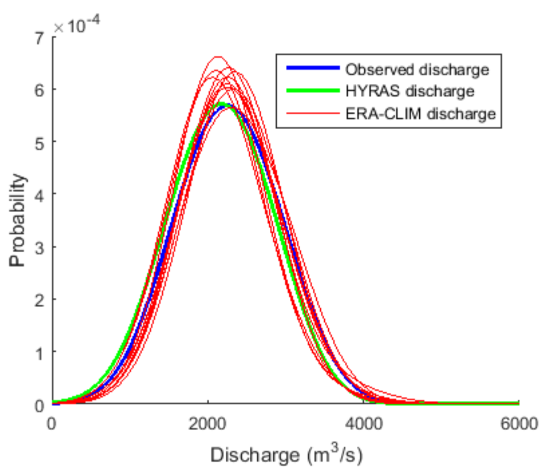


Figure C-2.1: PDF of annual mean discharge (1951-

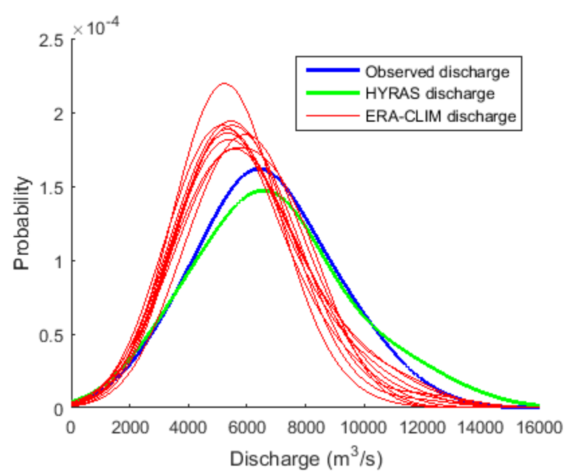


Figure C-2.2: PDF of annual maximum daily discharge (1951-2006)

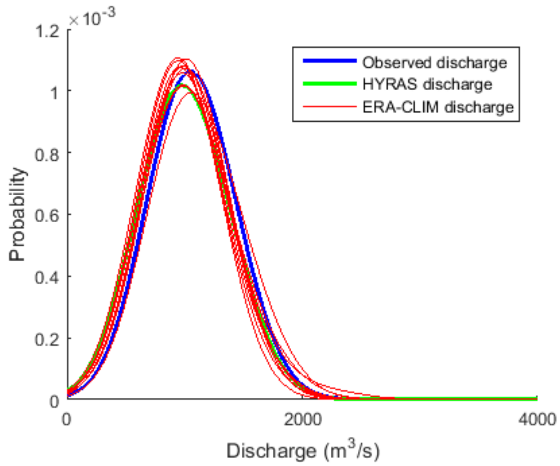


Figure C-2.3: PDF of annual minimum 7-day discharge (1951-2006)

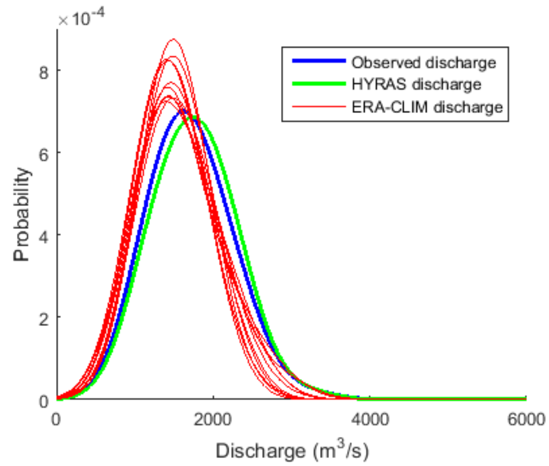


Figure C-2.4: PDF of annual mean low-flow season discharge (1951-2006)

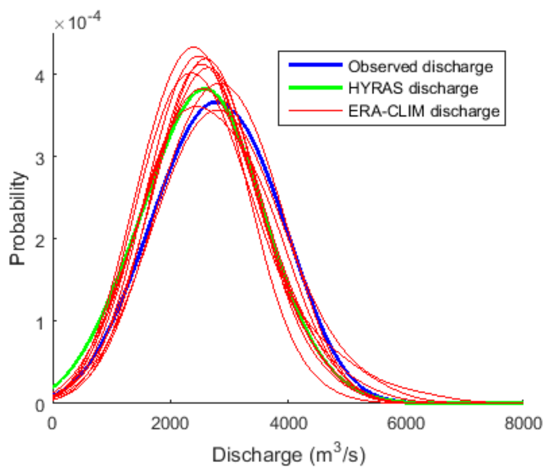


Figure C-2.5: PDF of annual mean high-flow season discharge (1951-2006)