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Return Period of Low Water Periods in the River Rhine

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Abstract

The goal of this study is to quantify the return period for the 2018 low flows and determine the effect of climate change on low flow return periods on the Rhine at Lobith. Low flow return periods are important for shipping applications or risk assessments concerning water availability and to prevent salinisation. Discharge data from 1901 to 2020 are used and gained from Rijkswaterstaat, the Dutch water authority. Several durations are taken into account: 1, 7, 30, 90 and 180 days. An average discharge over this duration gives the severity of the low flow. Results of the 95% confidence interval show that a Weibull fit the best fit for all the different durations. Furthermore, the LFFCs show little difference between the 1 and 7 day fit, but generally the larger the duration the higher the discharges. A 1 day discharge of 732 m^3/s, which was the annual minimum of 2018, is likely to occur once every 17.6 years. However, due to climate change in 2085 this can occur once every 6.5 to 22.6 years based on the KNMI'14 scenarios and the GRADE model. A 180 day average discharge of 1017 m^3/s, which was the annual minimum of 2018, is likely to occur once every 29.5 years. However, due to climate change in 2085 this can occur once every 35.3 to 179.5 years based on the KNMI'14 scenarios. The method used can be applied to other rivers to find return periods for low flows, as this is currently not commonly found.

Keywords: Climate change; Droughts; Return periods

1. INTRODUCTION

Water management in the Netherlands has focused on flood protection for a long time. Currently, a different point of view is becoming more and more relevant. Water management is not only about floods anymore, but low flows are increasingly recognized as a problem. Recently, this became most visible in 2018. The year 2018 is in the top 5 of driest years since the beginning of regulated recordings in The Netherlands (Sprokkereef, 2019; KNMI, 2021b). The precipitation deficit of August 2018 even passed record year 1976 for a few days according to the Droogtemonitor (KNMI, 2021a). Furthermore, the water level measured in the river Rhine at Lobith has never been as low as in 2018 (Sprokkereef, 2019).

However, how extreme the 2018 drought event was currently unknown. Low flow return periods in rivers are important for shipping applications, risk assessments concerning water availability or preventing salinisation. The economic impact of the drought in the Netherlands in 2018 has been assessed by Van de Velde et al. (2019) and the total economic effects are estimated at 900 to 1650 million euros. Agriculture is the sector with the biggest losses: 820 to 1400 million euro. After agriculture, shipping is the sector with the biggest effects: 65 to 220 million euro. The low water levels have a large influence on shipping, because ships cannot be loaded to full capacity. This results in the capacity of the transport chain being under pressure.

Climate change is an important factor when looking into droughts, as extremes will become more extreme (De Niel, 2018). The most recent climate scenarios for the Netherlands are the KNMI'14 climate scenarios, which are based on the fifth climate report by the IPCC. In 2023 new scenarios are expected. Following the KNMI'14 scenarios, it is expected that the Netherlands will experience more droughts (KNMI, 2015). However, the scenarios are not unanimous on the increase in droughts. In two of the four scenarios the droughts will increase in number and severity. In the other two, droughts will remain similar to the current situation.

Recent studies into the drought of 2018 are, for example, performed by Kramer et al. (2019). They investigated how extreme the drought of 2018 was with respect to shipping, salinisation and the Ijssel lake buffer. They concluded a return period for the events of 2018 ranging from 35 to 60 years. Sperna Weiland et al. (2015) looked into the implications of the KNMI'14 climate scenarios for the discharge of the Rhine and Meuse. Their results show that the discharge on the Rhine has a general tendency towards increasing discharges in winter and spring and decreasing discharges in (late) summer. For the Rhine and Meuse the mean winter and mean annual maximum discharge are projected to increase whereas the mean summer and mean annual minimum 7-day discharge are projected to decrease. According to most scenarios, mean annual discharge shows a clear increase as well.

Low flow return periods depend on three important aspects: discharge, duration and interdependency between low flows. However, no suitable method was found to accurately take these aspects into account. The goal of this study was to quantify the return period for the 2018 low flows and determine the effect of climate change on low flow return periods in the Rhine at Lobith.

Therefore, the research questions are:

i. What is the return period of the 2018 low water in the river Rhine?
ii. How are the return periods of low water in the Rhine river expected to develop due to climate change?

The outline of this paper is as follows. Section 2 describes the methodology to arrive at low flow frequency curves for different scenarios. Section 3 describes the results of this study for the current climate and the climate scenarios, after which they are compared. Section 4 raises some discussion points and Section 5 gives the conclusion and answer the research questions. Section 6 gives acknowledgements. Section 7 gives the references used in this paper.

2. METHODOLOGY

Observed discharges of the Rhine at Lobith are openly accessible on Waterinfo.nl (Rijkswaterstaat, 2021). The discharge data from Waterinfo have varying intervals but are transformed into daily intervals for the period 1901 to 2020 by taking daily averages. This dataset represents the current climate as 'Waterinfo'. For discharge predictions involving the KNMI'14 scenarios, the GRADE model is used (Hegnauer et al., 2014). GRADE is a hydrological routing model that gives a discharge series with daily discharges for a period of 50,000 years, based on generated precipitation and temperature data. The two most diverging scenarios, GL and WH, are included in this study, for the years 2050 and 2085. The GL scenario assumes a moderate increase in the worldwide temperature, 1°C in 2050 and 1.5°C in 2085, and small influence of air current patterns. The WH scenario assumes a bigger increase in the worldwide temperature, 2°C in 2050 and 3.5°C in 2085, and more influence of air current patterns. The WH scenario is the drier scenario, and the GL scenario is a wetter scenario. These scenarios will be compared to a discharges series generated with the GRADE model, representing the current climate as 'reference data'.

The block method (Booij, 2015) is used to select low flow events (for more details see Van Brenk (2021)). The method assumes annually independent low flows for the period April-March, which is a 6-months shifted hydrological year. The hydrological year is shifted, as low waters often appear in November (De Wit, 2004). As low flow duration is an important factor in low flows, an average discharge is calculated for durations of 1, 7, 30, 90 and 180 days. The lowest average for each duration is selected. The selected minima will be given a non-exceedance probability using the Weibull plotting position, shown in Equation 1 (Maidment, 1996). Next the selected minima are fitted to the Generalized Extreme Value distribution (GEV), shown in Equation 2 (Coles, 2001). This forms the low flow frequency curve.

$$P(X \leq x) = \frac{i}{n+1} \qquad [1]$$

$$G(z) = \exp\left(-\left(1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right)^{\frac{-1}{\xi}}\right) \qquad [2]$$

In which: $P(X \leq x)$ is the non-exceedance probability, i is the i-th smallest observation, which is the opposite ranking compared to high flow statistics, and n is the sample size. In which: $G(z) \approx Pr(X \leq x)$ is the non-exceedance frequency, z is the discharge value, ξ is the shape parameter, μ is the location parameter and σ is the scale parameter.

3. RESULTS

3.1 Current climate

Figure 1 shows the selected minima for the five low flow durations. Little difference is seen between the discharge values with a duration of 1 and 7 days. The durations of 90 and 180 days clearly show higher discharge values than the duration of 30 days. A remarkable observation is that the 180 day discharge of 1922 is lower than that of the other durations. In this year this is due to the fact that the long duration allows to include the low discharges of November 1921.

The lowest 1 day discharge of 575 m^3/s occurred in February 1929. Three of the five 1-day minima occurred in November, but the other two occurred during the winter in February 1929 and January 1963. Low flows are expected to occur in November, but the two other low flows in winter show another cause for low flows: ice (De Wit, 2004). He found the same low discharge values for 1929 and 1963 and stated that ice was present on the Rhine, resulting in lower discharges.

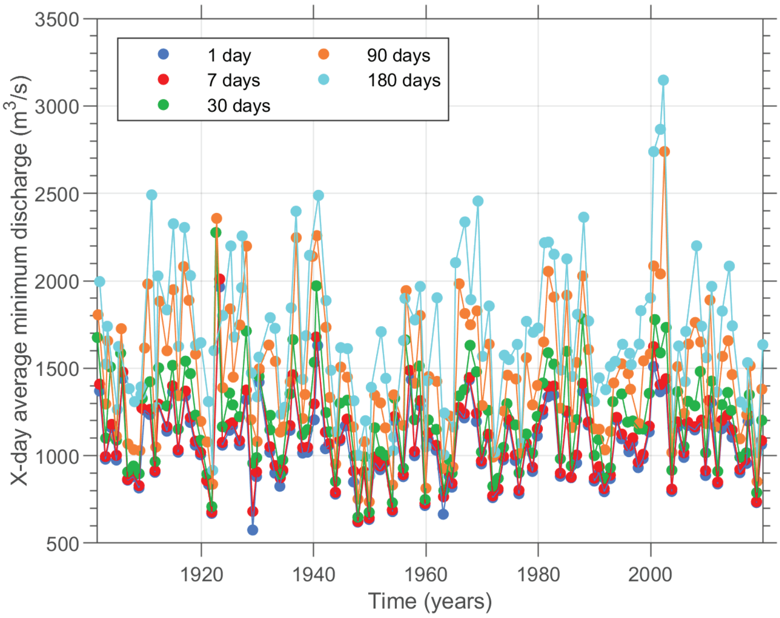


Figure 1. Annual minimum average discharge for different duration for the Waterinfo data.

The GEV distribution consists of three estimated parameters: ξ, σ and μ. The shape parameter, ξ, does not change much for the different durations. For all durations the 95% confidence interval of the ξ value is completely or mostly below 0 and generally has a value of about -0.1 as best fit. This means it is highly likely all the data best fits on the Weibull distribution. The scale parameter, σ, resembles the standard deviation of the data. The value of σ increases with increasing duration. This is not strange, since the discharge values for higher durations also increase, which can also be seen in Figure 1. The location parameter, μ, resembles the mean of the dataset. The value of μ increases with increasing duration. However, the value of σ/μ remains fairly constant with a range of 0.21 to 0.26.

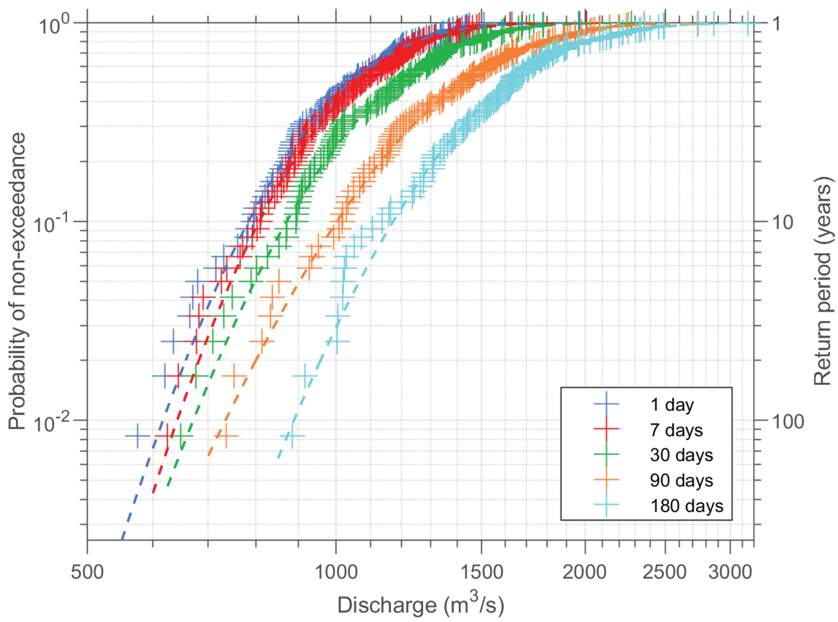


Figure 2. Observed annual minimum discharges (Waterinfo) for different durations and their estimated fit.

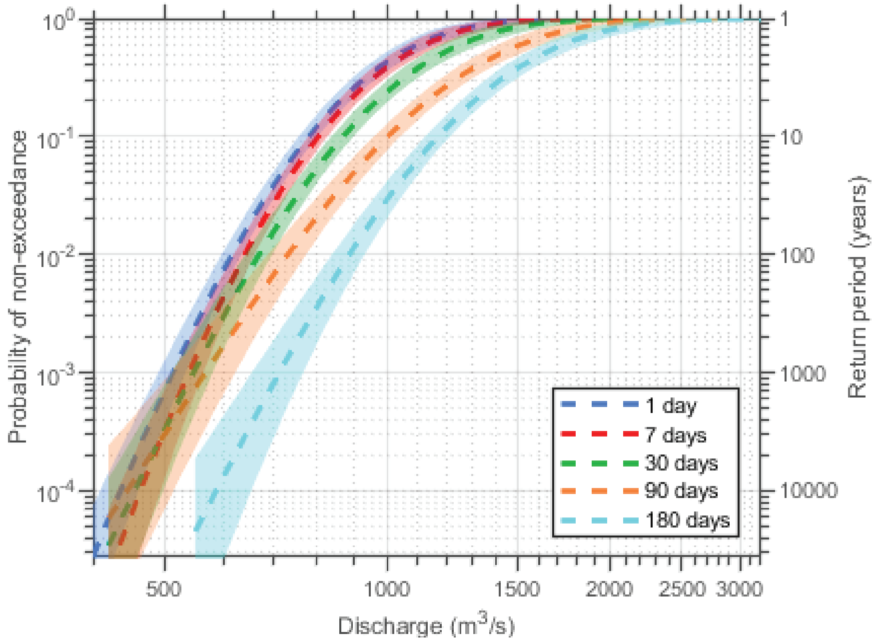


Figure 3. Extrapolation of minimum annual Waterinfo discharges for different durations with the 95% confidence intervals.

The GEV distribution is used to fit the selected discharge data with different durations, seen in Figure 2. All fits seem reasonably well, only the most extreme cases are not represented well by the fit. However, this can be explained by the fact that this is an extreme value analysis. The most extreme event has the most uncertain return period, as there are few cases to determine the occurrence. These fits are extrapolated to higher return periods, which is shown in Figure 3.

The most remarkable observation from Figure 3, is the fact that the fitted distributions of the 7-, 30- and 90-day duration are intersecting each other at a return period of about 7000 years. This underlines the uncertainty in extreme value analysis. Extrapolation beyond a return period of 1000 years, which extrapolates the observations with a factor of about 10, is therefore not recommended.

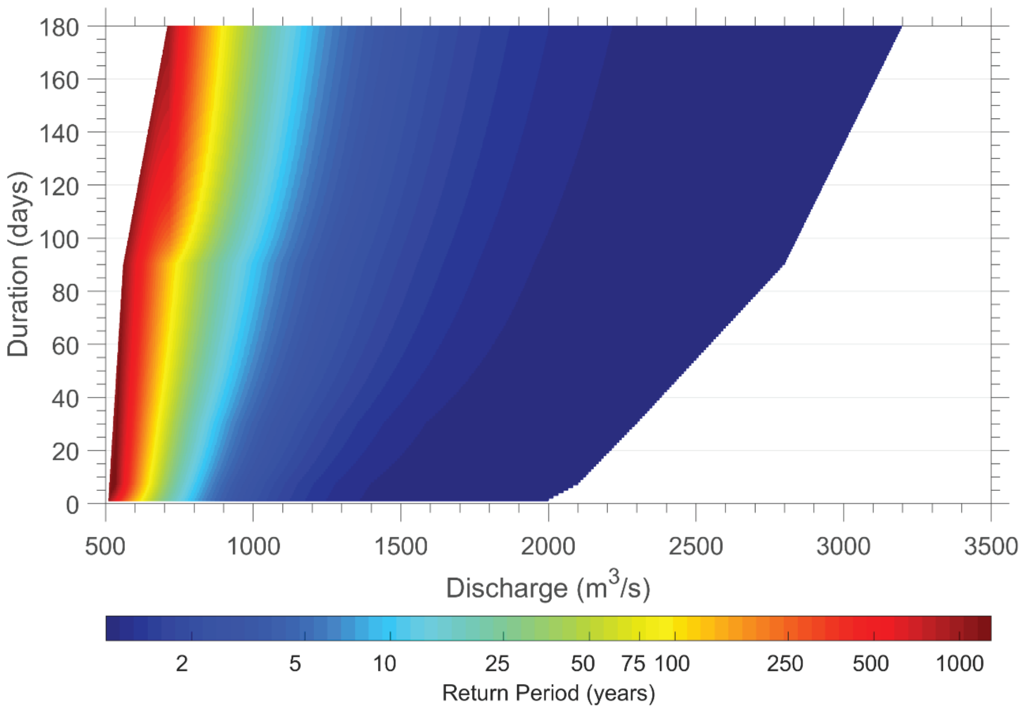
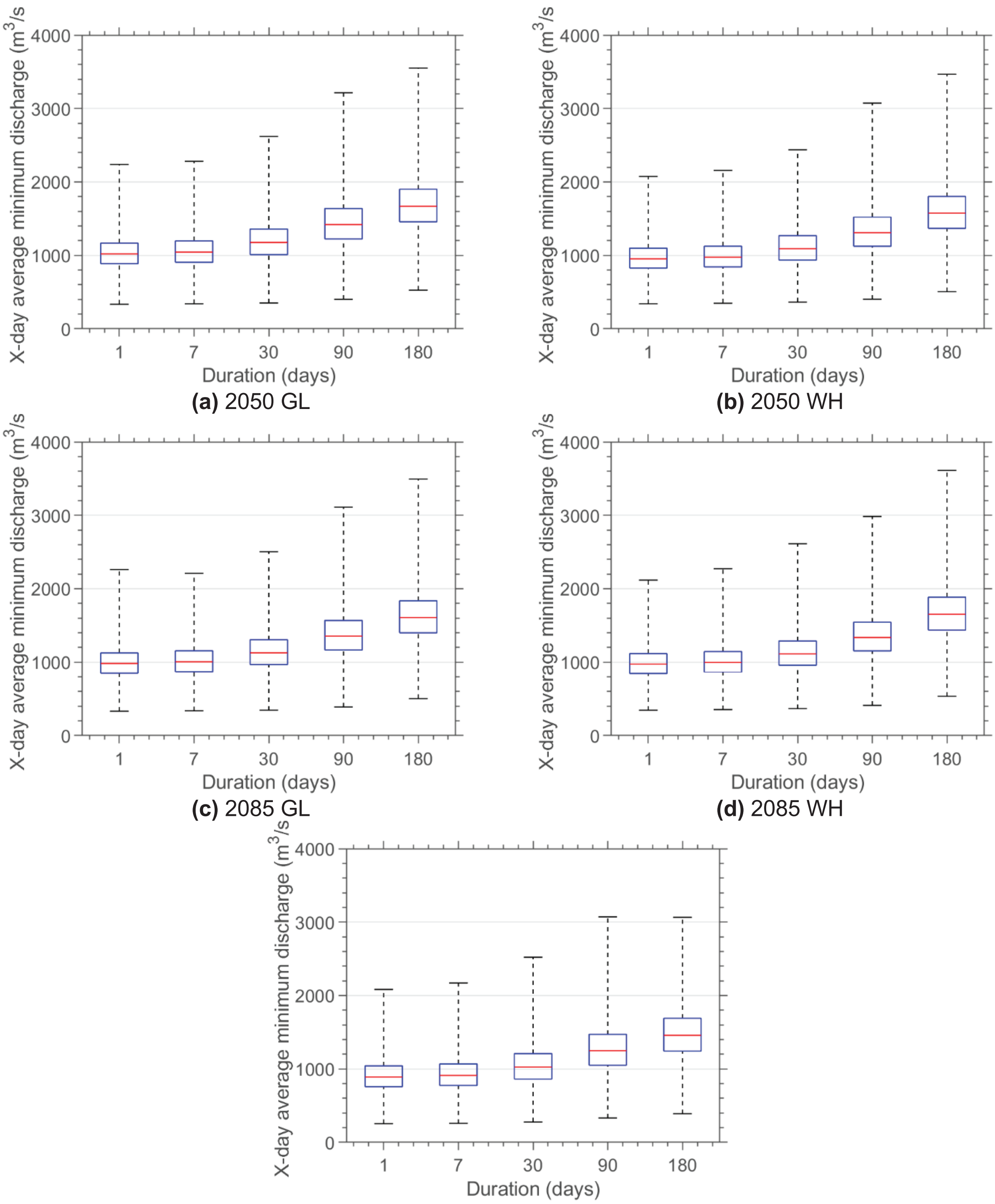


Figure 4. Return period based on discharge and duration, interpolated based on Figure 2 and Figure 3.

Interpolating these fits gives estimated return periods for all combinations of discharges and durations from 1 to 180 days (Figure 4). This different form of plotting makes it more applicable for potential users. A combination between the discharge and duration can be made to see what the corresponding return period of this event is. For example, a problematic discharge for shipping is 1000 m^3/s (Bosschieter, 2005). Figure 4 shows that this occurs almost every year. However, this is only for a short period of time. This average discharge has a probability of occurring once every 5 years for a period of 30 days and once every 10 years for a period of 60 days.

3.2 Climate scenarios



(e) Reference

Figure 5. Boxplots of selected minima for the GRADE reference scenario and climate scenarios 2050 & 2085 GL and WH for different durations.

The selected minima in the four climate scenarios and the GRADE model are shown in Figure 5. The same general observations can be made as for the Waterinfo data: the median increases slightly with increasing duration and half of the discharges are very close to the median and the other half has a wider range. The GEV fit to these scenarios and a GRADE reference scenario are given in Figure 6.

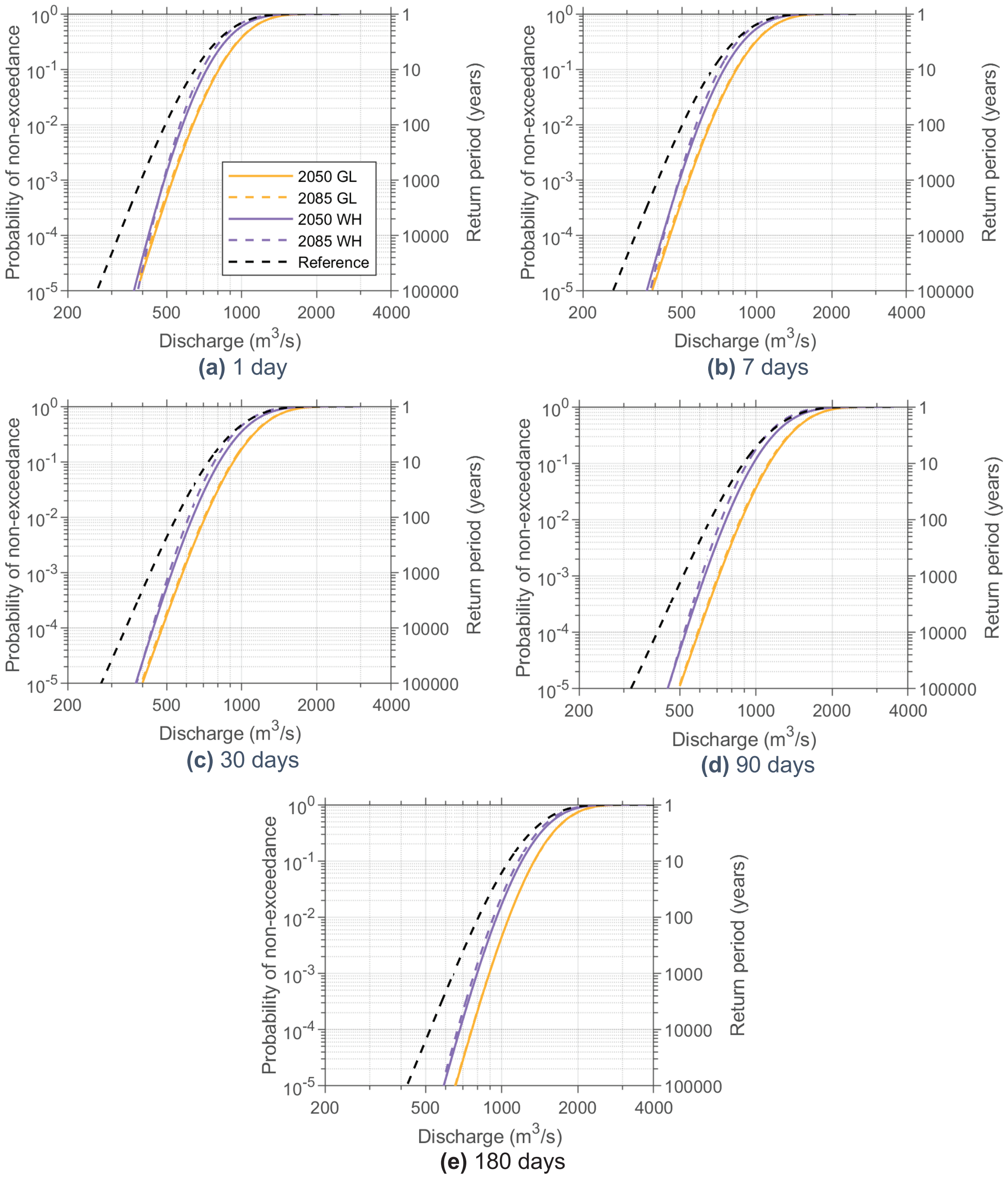
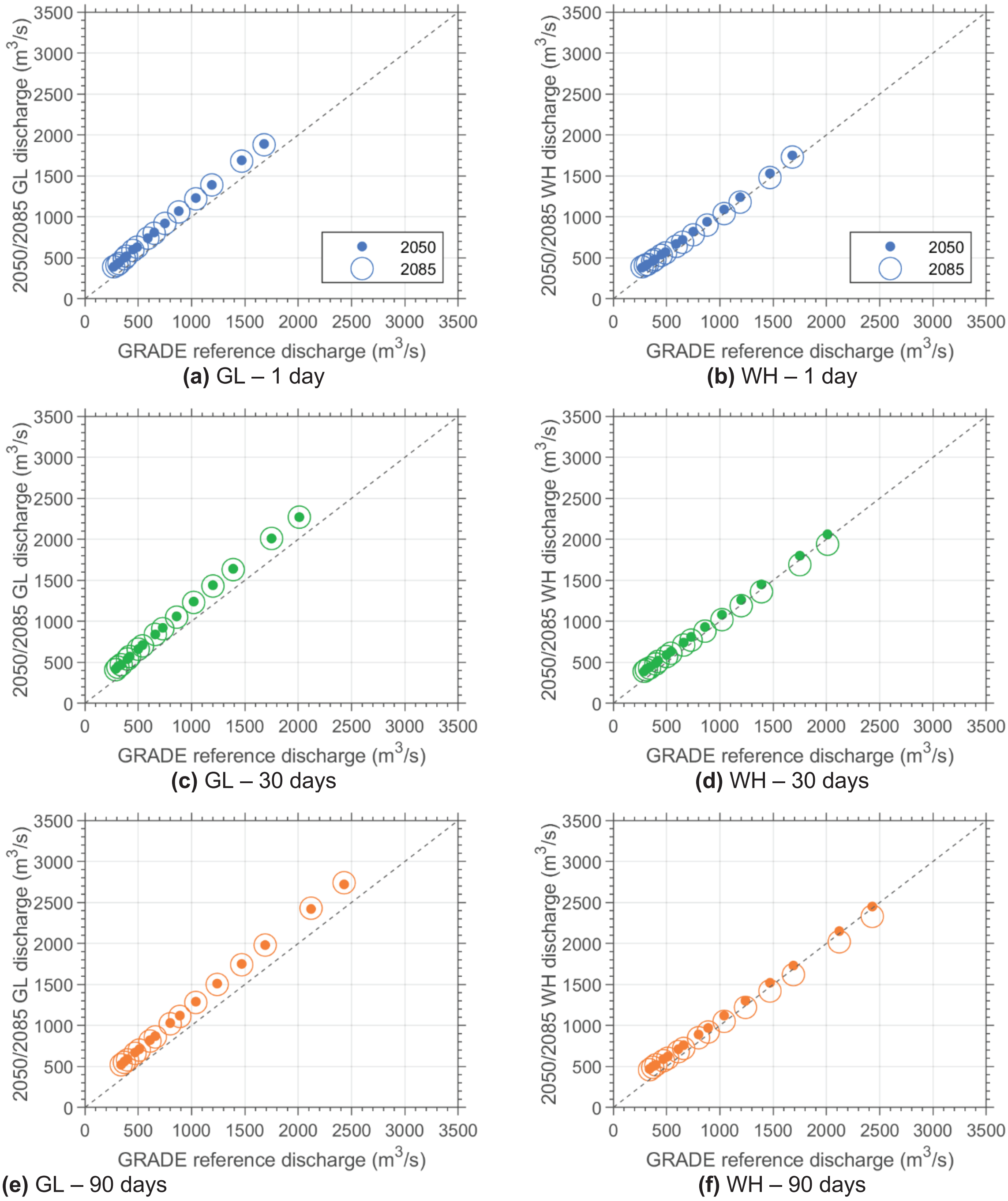


Figure 6. Estimated fit on annual minimum discharges for different climate scenarios based on the GRADE model for different durations.

Figure 6 shows that the 2085WH scenario has slightly lower discharges than the 2050WH scenario. The figure also shows that the 2050GL and 2085GL scenario do not differ much. All 4 climate scenarios have lower discharges compared to the reference scenario. This means that extremely low discharges will become less extreme in the future according to the GRADE predictions.

3.3 Comparison

Figure 7 shows selected quantile-quantile plots (Q-Q plots) for the 4 climate scenarios, 2050GL, 2085GL, 2050WH and 2085WH, compared to the GRADE reference scenario. The selected quantiles vary between a return period of 1 to 50 000 years. The Q-Q plots of the GL scenarios show that the GRADE reference fit always gives lower discharges for the corresponding quantiles than the GL scenarios. There also is little difference between the 2050GL and 2085GL scenarios. This is both in line with the observations from Figure 6.



(a) GL – 1 day
(b) WH – 1 day
(c) GL – 30 days
(d) WH – 30 days
(e) GL – 90 days
(f) WH – 90 days

Figure 7. Q-Q plots of 2050 and 2085 GL and WH scenarios compared to the reference scenario of GRADE for different durations.

The Q-Q plots of the WH scenarios show that the GRADE reference fit always gives lower discharges for the corresponding quantiles than the 2050WH scenario. For higher return periods, the 2050WH and 2085WH scenarios seem to have similar discharges, but for higher return periods, the 2085WH scenario will give lower discharges compared to the 2050WH scenario. Furthermore, the GRADE reference fit gives lower discharges for the corresponding quantiles than the 2085WH scenario for the 1, 7 and 180 day duration. However, for the 30 and 90 day duration, the GRADE reference fit does not always show lower discharges for the corresponding quantiles. For high quantiles, so small return periods, the 2085WH scenario gives lower discharges than the GRADE reference fit.

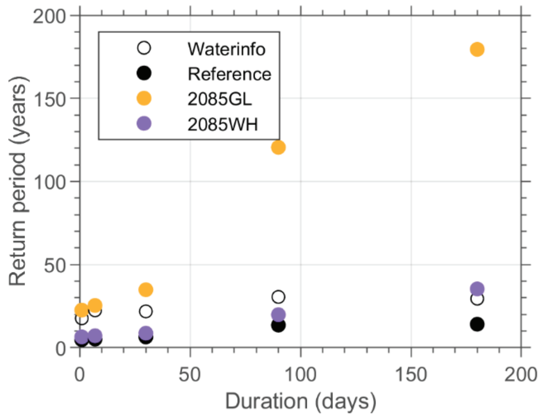


Figure 8. Return periods of 2018-like events for different durations and climate scenarios at Lobith.

Figure 8 shows the low flow return periods for events similar to the ones that occurred in 2018. For the current climate, based on the Waterinfo data, the return periods are 17.6, 22.4, 21.8, 30.5 and 29.5 years for a duration of 1, 7, 30, 90 and 180 days respectively. According to the GRADE reference model, these low flows will occur more often. The 2085 GL and WH scenario show larger return periods compared to the reference scenario. Only the GL scenario shows larger return periods than return periods based on observed data.

In more detail, a 1-day discharge of 732 m^3/s, which was the minimum of 2018, is likely to occur once every 17.6 years. However, due to climate change this can occur once every 6.5 to 22.6 years in 2085 based on the KNMI'14 scenarios and the GRADE model. In 2085, a 1-day event that will occur once every 17.6 years will have a discharge between 655 and 753 m^3/s. This shows that whether a 1-day event similar to 2018 is likely to become more or less common, depends on which climate scenario evolves to be more realistic.

A 30-day discharge of 789 m^3/s, which was the minimum of 2018, is likely to occur once every 21.8 years. However, due to climate change this can occur once every 8.7 to 34.8 years in 2085 based on the KNMI'14 scenarios and the GRADE model. In 2085, a 30-day event that will occur once every 21.8 years will have a discharge between 708 and 832 m^3/s. This again shows that whether a 30-day event similar to 2018 is likely to become more or less common, depends on which climate scenario evolves to be more realistic.

4. DISCUSSION

An important assumption that influences the block method is the fact that the selected annual minima are independent from adjacent selected minima. Currently, there are no guidelines on when low flow events can be considered independent from another low flow event. It is expected that the time between two low flow events needs to be longer than for to high flow events, as groundwater plays a large role in the value of the low discharge and reacts slower than direct runoff from a precipitation event.

The timing of the lowest discharges during the year ranges from November to February. The lowest discharges at Lobith are expected in October and November (Kramer et al., 2019; de Wit, 2004). The Rhine is a mixed river, which means that the discharge is fed by rain and meltwater. Furthermore, the Rhine has a large catchment with origin in the Alps, where Lake Constance is located. Lake Constance works as a water buffer and has a damping function on the discharge in the Rhine. These three factors result in a discharge regime at Lobith of a dampened rain river: higher discharges in the winter and lower discharges in the summer that do not differ much from the average discharge (Lokin, 2020, Klijn et al., 2015). The reason for the low flows during the months October and November, is that they lie between the discharge peaks from melting water and precipitation. Another reason for extremely low flows was found to be ice, when the low flows occurred in January or February.

Results gained from this study are put into context by comparing them to recent similar studies, mentioned in the Introduction. Kramer et al. (2019) estimated that a 135 day period of discharges below 1100 m^3/s will take place once every 60 years in the current climate. It will take place more often, once every 20 years, when considering the 2050WH climate scenario. This was done using the Dutch 'National Water Model'. These results cannot be compared one on one to the results of this study, as there is a difference between a period below a threshold and an average minimum discharge. This means the return period determined by Kramer et al. (2019) should be larger than the return period found in this study for an average discharge of 1100 m^3/s. Figure 4 gives a return period of about 10 years for a 135 day event with an average discharge of 1100 m^3/s. Furthermore, Kramer et al. (2019) showed that return periods will decrease considering the 2050WH scenario. This does not agree with the results of this study. However, it is expected that this is due to the limitations of the GRADE model. The reason for the low GRADE reference values compared to the climate scenarios is unknown at the moment, but it probably has to do with the fact that the GRADE model is calibrated for high flow applications.

5. CONCLUSION

Concluding from this study, the return period of the low flows in 2018 can be quantified. Furthermore, a framework is given to make low flow frequency curves that include the key aspects of low flows: discharge, duration and interdependency between low flow events. With this method and climate scenario discharge data, the influence of climate change on the return period of low flows can be determined. However, the GRADE model that is used in part of this study is not simulating low flows well enough to reasonably determine low flow return periods.

Return periods for the 2018 low flows are 17.6, 22.4, 21.8, 30.5 and 29.5 years for a duration of 1, 7, 30, 90 and 180 days respectively. This shows that the drought of 2018 was severe due to the length of the event, as the return periods generally increase. According to the GRADE reference model, these low flows will occur more often.

Comparing the reference scenario to the 2085 GL and WH scenario, low flows are expected to occur less often in the future. However, when the two climate scenarios are compared to the observed data, the Waterinfo data, it shows that low flow will occur more often in the future according to the WH scenario and less often according to the GL scenario. Whether low flow return periods will increase or decrease in the future, depends on which climate scenario is closer to future reality.

6. ACKNOWLEDGEMENTS

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