Impacts of the 2018 summer drought on the Dutch part of the Rhine river

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2. Summary

Rivers and river ecosystems provide essential services to the earth's natural processes and to society. Droughts are a threat to these ecosystems that rely heavily on the availability of water. Especially in areas like the Netherlands, where ecosystems are used to a wet climate, droughts can have severe impacts. In the summer 2018, the Netherlands experienced one of its most severe droughts. Measures were taken to protect drinking water quality, and research after the drought also mainly focused on impacts on drinking water. No studies have been done on the impacts to river ecosystems. Therefore, this study aims to answer the following research question: What impact did the drought of 2018 have on the Dutch part of the Rhine river in terms of discharge, temperature, pH, dissolved oxygen content, and ammonium concentration? These parameters will serve as indicators to several drought impacts on river ecosystems, namely: habitat loss, heat stress, oxygen stress and toxicity.

Statistical analysis comparing the summer of 2018 to the summers of the years 2009-2017 found a significant difference on the parameter temperature, but not on any of the other parameters. From this it is concluded that heat stress was an impact of the 2018 drought, while oxygen stress and habitat loss were not. Toxicity as an effect of ammonium was not indicated by the results of the analysis, toxicity due other toxic compounds not included in this study was proven to be an impact of the 2018 drought as well.

3. Introduction

3.1 Background

In the spring and summer of 2018, parts of Europe experienced extended periods of drought. The situation was unique as the drought took place in central and northern Europe, while southern Europe experienced unusually wet conditions (Toreti et al., 2019). The drought was accompanied by a record-breaking heatwave and left a trail of impacts all across the continent. The World Meteorological Organization (WMO) reported that deadly forest fires, increased elderly mortality, severe decline in crop yields, large algae blooms in the Baltic sea that poisoned water for humans and animals alike, shutdowns of nuclear power plants and crashing of electrical grids can all be attributed to the drought and heatwave (WMO, 2018). Because of factors such as population growth and increased agriculture and industry, the demand for water has never been higher, which increases the likelihood of water scarcity (Mishra & Singh, 2010).

Extended periods of drought, like in the summer of 2018, can also gravely impact river ecosystems via interfering with various physical and chemical processes, altering the habitat conditions for flora and fauna inhabiting the rivers (Sabater & Tockner, 2010). Extended droughts can cause massive drops in river water levels, leaving inhabitants of the highly productive zones near the shores stranded (Bond et al., 2008). As droughts often go hand in hand with high temperatures, heat stress to aquatic fauna is also a factor to be considered. This also brings into the question oxygen levels, which often decrease when water temperature rises, causing oxygen stress on top of heat stress, a combination that is dangerous to some fish species (Bond et al., 2008).

Ecosystems, and river ecosystems by extension, like in the Netherlands that usually have a relatively wet climate are not equipped to handle these extreme drought conditions (Sterk & Wamelink, 2019). In the Netherlands for example, the decline in crop yields was not only due to the lack of precipitation, but because of river water levels being so low that an irrigation ban was implemented (Sterk & Wamelink, 2019). Another example is the shutting down of nuclear power plants along the Rhine in Germany because the river water that is used to cool the nuclear reactors had reached critically high temperatures (DPA, 2018). While these measures protected river ecosystems from suffering even more, it did affect the services ecosystems provided to society.

The cause of the 2018 drought has since been attributed to the changing climate. The KNMI (Royal Netherlands Meteorological Institute), in association with the World Weather Attribution, estimated that climate change more than doubled the overall likelihood of a drought and heatwave (World Weather Attribution, 2018). The direct cause was identified to be a weakened jet stream, which the KNMI believed to be a result of a polar amplification of global warming. The changing climate will cause more extreme weather events in the future, including droughts like the one in 2018.

3.2 Problem statement

With extreme weather events like the drought of 2018 becoming more prevalent, it is important to identify their impacts on rivers. Especially in areas where river ecosystems are not adapted to handle droughts, the effects can be detrimental. Changes in water quality and quantity as a result of drought have to be identified, before drawing conclusions about how these changes might impact ecosystems. Parameters such as discharge, water temperature, pH and dissolved oxygen content can be used to identify how drought influences river characteristics. Additionally, they can be used as indicators of stress on ecosystems. It is important to identify the extent of changes to these parameters, so further research can be launched to develop adequate sustainable adaptation measures.

Rivers and river ecosystems play an essential part in the natural processes on earth and provide habitat to an incredible number of species. While freshwater only accounts for 0.01% of all water on earth, it provides habitat to one third of all vertebrate species on earth (Dudgeon et al., 2005; Strayer et al., 2010). Additionally, rivers provide ecosystem services that have benefits outside their riverbanks as well. These services include water purification, C and N sequestration, food production and flood control (Palmer et al., 2009). This multitude of services is enough to state that it is important that river ecosystems are protected.

This research is also important as it addresses a research gap that exists for this topic. There is a multitude of research on the impact of drought on rivers and river ecosystems, but not specifically for the 2018 drought in the Netherlands. Existing research on the 2018 drought in the Netherlands mainly focuses on impacts of drought on drinking water services provided by rivers, and not on impacts on river ecosystems themselves.

3.3 Research question and objective

This study aims to understand how the drought in the summer of 2018 has impacted the water quality and quantity of the Dutch part of the Rhine river. To reach this aim, the following research question is formulated.

- What impact did the drought of 2018 have on the Dutch part of the Rhine river in terms of discharge, water temperature, pH, dissolved oxygen content, and ammonium concentration?

The objective of this study is to obtain a better understanding of the impact of drought on rivers, and what the implications of drought might be for the functioning of river ecosystems. The answers to the research question will provide this understanding, which will then serve as a starting point from which sustainable adaptation measures can be developed.

3.4 Scope of the study

This study will analyze water quality and quantity data of four locations along the Rhine and its distributaries. The locations are Lobith, Nieuwegein, Nieuwersluis and Andijk. A further introduction of the locations is provided in the methods section. The temporal scope of the study are the summer months (June-September) of the years 2009-2018.

4. Theory and concepts

Having introduced the scope of the research, this section is concerned with defining the key concepts that are used and describing their relationships in a conceptual framework. The impacts of the drought described in this section will be measured by analyzing the quantity and quality parameters.

4.1 Drought

When thinking of drought, one often thinks of long periods without precipitation. This is not wrong, as all droughts originate with a deficiency of precipitation. However, this definition of drought is known as a meteorological drought, in which periods of drought are identified on the basis the number of days with precipitation less than a specified threshold based on an average (Wilhite & Glantz, 1985). This definition of drought does not account for the effects of this reduced amount of precipitation on river flow. A definition that does take this into consideration is that of hydrological drought, which is the definition that is used in this study. Hydrological drought is associated with the effects of periods of precipitation deficiency on surface or subsurface water supply (Wilhite & Glantz, 1985). Hydrological droughts usually follow after a meteorological drought as it takes time for precipitation deficiencies to make their way through the various components of the hydrological system.

4.2 Habitat loss

Aquatic habitat refers to bodies of water, their soil material and nutrients that provide habitat to aquatic floral and faunal species. The size of the habitat, thus the volume of water, plays a large role in regulating the number of inhabitants (Lennox et al., 2019). When in case of a drought, this water volume suddenly decreases, this can put stress on the aquatic organisms as there is suddenly less space, nutrients and oxygen (Mulholland et al., 1997). This process is referred to as habitat loss. One form of habitat loss is habitat degradation which means that while the spatial habitat remains intact, it does no longer function properly, and it cannot serve its inhabitants (Mulholland et al., 1997).

The corresponding parameter for measuring spatial habitat loss is discharge, which is defined as the volume of water flowing through a river at any given point. During a drought, discharge usually decreases (Buras et al., 2020).

Corresponding parameters for measuring habit loss as a result of degradation are temperature, ammonium concentration and pH.

4.3 Heat stress

Heat stress occurs when river water temperatures become so high that the species that live in the water experience illnesses and, more severely, death as a result of the stress that heat exerts on the body (Lennox et al., 2019). The corresponding parameter for this is water temperature. Temperature controls the kinds of organisms that can live in rivers and lakes. All aquatic species have a preferred temperature range. As water temperatures rise or fall too far above or below this preferred range, the number of individuals of the species decreases until finally there are none (Smithson et al., 2008).

4.4 Oxygen stress

Just like life on land, aquatic life needs oxygen to survive. Oxygen enters a river mainly from the atmosphere, and in areas where groundwater discharge into streams is a large portion of streamflow, from groundwater discharge (Smithson et al., 2008). Oxygen levels depend on whether water is flowing or not, plant-growth and the temperature of the water (Huang et al., 2019). Waves and water tumbling due to it hitting obstacles mix atmospheric oxygen with river water. Oxygen is also produced by rooted aquatic plants and algae as a product of photosynthesis (Smithson et al., 2008). Oxygen levels are higher in cold, flowing water with a moderate amount of plants. Warm water holds less dissolved oxygen than cool water, and may not contain enough dissolved oxygen for the survival of different species of aquatic life (Smithson et al., 2008). Therefore, temperature has both direct and indirect impacts on aquatic life.

The corresponding parameter for oxygen stress is dissolved oxygen content.

Ammonium concentration is a secondary parameter that can indicate oxygen stress, as it exerts a demand on oxygen as it is transformed into oxidized forms of nitrogen (EEA, 2020).

4.5 Toxicity

Toxicity indicates the degree to which a substance can harm an organism. There are many substances that are toxic to aquatic life. In this study, the parameter that is used to indicate toxicity is ammonium. Ammonium (NH4+) itself is not harmful, ammonia (NH3) however, is harmful (Sawyer, 2008). The proportions of ammonium and ammonia in water are driven by pH and temperature. The chemical equation that goes with this relationship is the following:

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$$

In situations where pH is low, the reaction is driven to the right, and when pH is high, the reaction is driven to the left (Sawyer, 2008). Aqueous ammonia is also much less active at low temperatures, and more active at higher temperatures (Sawyer, 2008). This means that in situations with high temperatures and high pH, the ammonium is converted into ammonia, which then also has higher activity, and is toxic to aquatic life. In drought conditions, when water temperatures are usually high as well, this process can be extremely harmful to all vertebrates, causing convulsions, coma and death (Randall & Tsui, 2002).

The corresponding parameters for toxicity are ammonium concentration, temperature and pH.

4.6 Conceptual framework

The different concepts that are used in this thesis are combined in a conceptual framework (figure 1). In this framework, the relationship between the concepts is visualized.

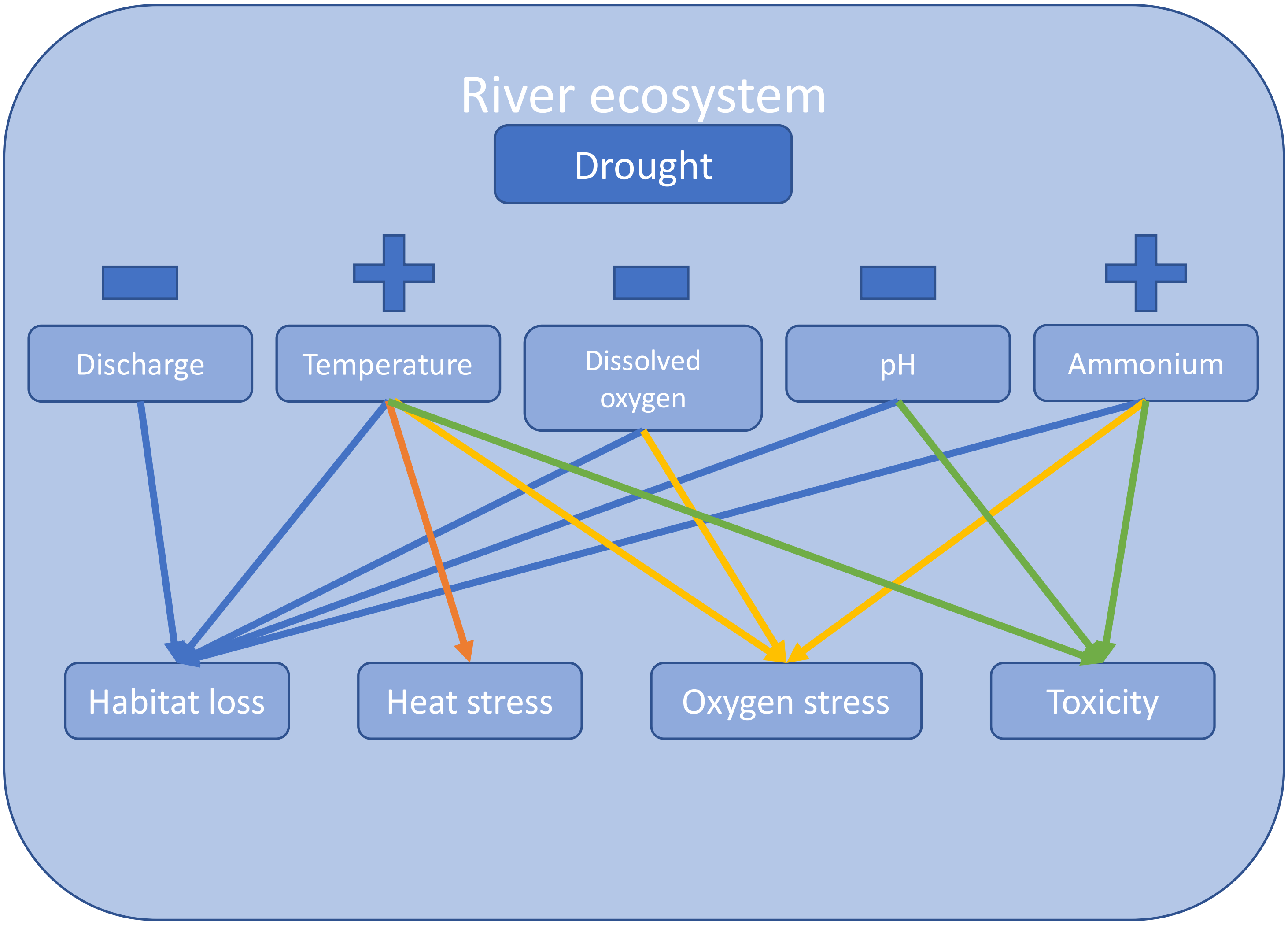

Figure 1: Conceptual framework describing the various ways a drought can impact river ecosystems.

The conceptual framework shows the various ways in which a drought can impact river ecosystems. The plus and minus signs indicate what is expected to happen to the value of a parameter during a drought. The arrows then indicate to what impact this change translates. The colors of the arrows are dependent on the impact, so it can quickly be determined which parameters influence which impacts.

Habitat loss occurs when discharge, dissolved oxygen content and pH decrease, and temperature and ammonium concentration increase. Heat stress occurs when temperature increases. Oxygen stress occurs when dissolved oxygen content decreases and temperature and ammonium concentration increase. Lastly, toxicity occurs when temperature and ammonium concentration increase and pH decreases.

5. Methods

For this study, a quantitative data analysis was carried out. The study made use of data provided by yearly reports on Rhine water quality, published by RIWA-Rijn (RIWA, 2009-2018). Subsequently, a statistical analysis of these data was carried out, using SPSS.

5.1 Data collection

Data for this study is collected from yearly water quality reports, detailing water quality of the Rhine. The organization that provided this data is RIWA-Rijn. RIWA is the Association of River Water Companies in the Netherlands, and their main focus is monitoring river water quality so it can be safely used by drinking water companies. The yearly reports contain tables of monthly means on the composition of Rhine water at four measuring locations. Many parameters are monitored by RIWA, though for this study only discharge, temperature, dissolved oxygen, pH and ammonium are studied. Links to these reports can be found in the references in section 10.1.

The measuring locations are Lobith, Nieuwegein, Nieuwersluis and Andijk (Fig. 2). Lobith and Nieuwegein measure discharge, while Nieuwersluis and Andijk do not as these measuring locations are located at larger water bodies to which the Rhine is a tributary. Figure 2 also shows a fifth measuring location, Haringvliet, but this location was only added in 2015 and was thus not included in the analysis.

The locations all have different characteristics, with different elevation levels and land use of the immediate surrounding area. Table 1 gives an overview of these characteristics for each location, which was determined by using Google Earth.

For each of the locations, parameter values are collected over a 10-year time period, stretching from 2009-2018, focusing on the summer months (June-September).

Location	Elevation	Land use
Lobith	13 meters	Residential and industrial
Nieuwegein	4 meters	Industrial
Nieuwersluis	1 meter	Agriculture
Andijk	0 meter	Agriculture

Table 1: Elevation and land use for each of the measuring locations.

Figure 2: Map of the Netherlands showing the measuring locations and their positions within the Rhine river basin.

5.2 Data analysis

The collected data on water quality and quantity was analyzed using the SPSS program (Statistical Package for the Social Sciences). To become familiar with the data, some qualitative analysis was performed before moving on to the statistical analyses. One way this was done is by creating boxplots per parameter. In these boxplots there are two boxes, one for 2009-2017 and one for 2018. Figure 3 shows an example of a boxplot.

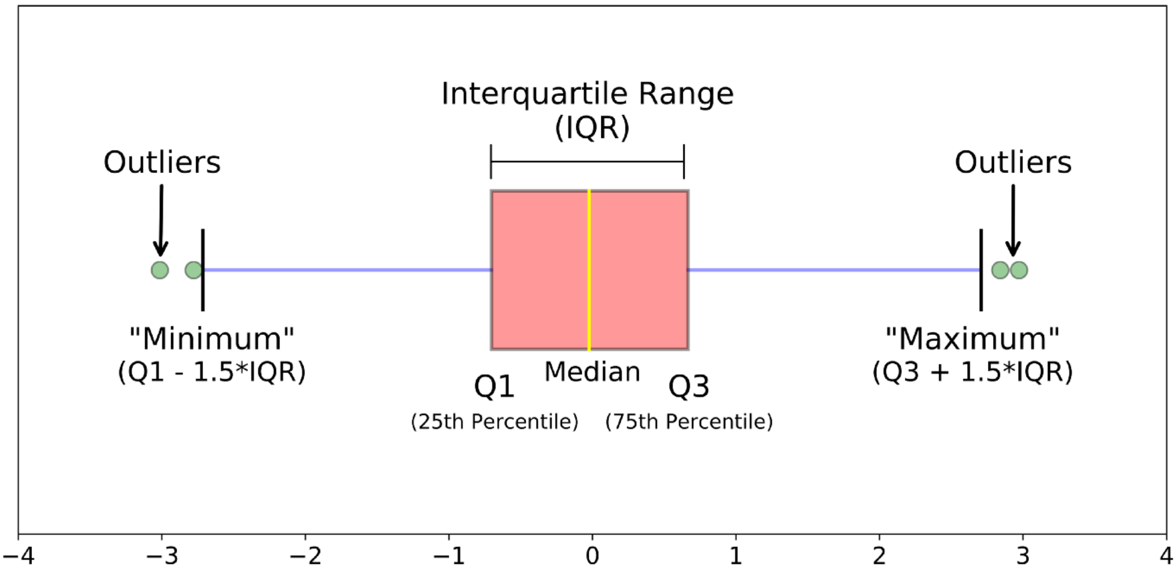

Figure 3: Example of a boxplot. Retrieved from: https://towardsdatascience.com/understanding-boxplots-5e2df7bcbd51

The middle box represents the interquartile range (IQR), which is the middle 50% of scores. Within the IQR falls the median, 50% of scores have values above the median, and 50% have values below the median. Q1, or the lower quartile indicates that 25% of scores fall below this value. Q3, or the upper quartile indicates that 75% of scores fall below this value. The whiskers on each end of the box each represent scores outside the middle 50%. Whiskers extend to a minimum and a maximum, which is located a distance of 1.5 times the IQR away from Q1 and Q3, respectively. Any values that fall outside the range of the whiskers are considered outliers.

The boxplots are useful for providing first impressions of the distribution of the data, as well as determining outliers that possibly need to be removed from the dataset. When an outlier was identified, it was only excluded if it represented an obviously unrealistic value. If not, it was still included in the analysis. An exception to this was made for the years 2010, 2013 and 2015, as these were also drought years (KNMI, n.d.) – though less much less extreme than 2018 - and the analyses were run including and excluding these years.

After exploring the data with these boxplots, normality of distribution was determined for each of the variables, using the Shapiro-Wilk test, the result of which determined to proceed with parametric or non-parametric tests.

Variables that follow normal distribution were tested using one-way ANOVA when testing for differences between all individual years. Significant differences between years were then further analyzed using Tukey's post hoc tests, to determine what years differed significantly. Additionally, 2018 was compared to 2009-2017 as a group via an independent samples t-test. This test was also used to compare 2018 to 2009-2017 while excluding the drought years of 2010, 2013 and 2015.

Variables that do not follow normal distribution were tested using Kruskal-Wallis when testing for differences between all individual years. Significant differences were then further analyzed using the Mann-Whitney U test to determine what years differed significantly. Additionally, 2018 was compared to 2009-2017 as a group via the Mann-Whitney U test as well. This test was also used to compare 2018 to 2009-2017 while excluding the drought years of 2010, 2013 and 2015.

After executing the statistical analysis, the results were interpreted in relation to the conceptual framework that was explained in section 4.6.

6. Results

6.1 Descriptive analysis

Parameter	Mean	Std. Dev.	Min.	Max.	Mean 2009-2017	Mean 2018
Discharge	971,7469	968,2769	6,31	4330,00	1004,1375	665,5500
Temperature	20,164	2,154	15,6	24,8	20,649	21,913
DO	8,4290	0,8681	6,00	11,7	8,6891	8,5000
pH	8,1444	0,2248	7,74	8,94	8,0297	7,9925
Ammonium	0,0781	0,0596	0,0135	0,4400	0,0592	0,0667

Table 2: Overview of means, standard deviation, minimum and maximum for each parameter.

Table 2 shows the overall mean values, standard deviation, mean values for 2009-2017, mean values for 2018, minimum and maximum values of each of the parameters. Figure 3 shows boxplots for each of the parameters. The boxplots contain two boxes, one for the year 2009-2017, and one for 2018. These descriptive statistics give an impression of what the dataset looks like and the general patterns that exist within the data.

For discharge, the 2018 mean is lower than both the overall mean and the mean of 2009-2017. The standard deviation of the overall mean is very large, which indicates that the data points are spread out over a large range of values; something that is supported by the large difference between minimum and maximum values. The boxplot for discharge, however, shows that the maximum value is an outlier. The two boxes also show the same distribution pattern. The median value for 2018 is slightly lower, though the difference is minimal, indicating that it is unlikely there is a difference between the years.

For temperature, the 2018 mean is higher than both the overall mean and the mean of 2009-2017. The standard deviation is not very large, which indicates that there is not much variation in the dataset. The boxplot for temperature shows a clear difference in distribution for 2018 in comparison to 2009-2017. The median value for 2018 lies just outside the interquartile range of the 2009-2017 box, indicating that there is likely to be a difference between the years.

The 2018 mean value for dissolved oxygen content falls in between the values of overall mean and the 2009-2017 mean. The standard deviation is small, which indicates little variation within the dataset. The boxplot for dissolved oxygen content shows that the interquartile range for each time period is almost the same, while the whiskers extend further for 2009-2017. The median values are almost the same, indicating that it is unlikely there is a difference between 2018 and 2009-2017. For the years 2009-2017 there are quite some outliers, although they are not unrealistic values and were therefore not excluded from further analysis.

For pH, the 2018 mean value is slightly lower than the overall mean and the mean of 2009-2017. The standard deviation is small, indicating little variation within the dataset, which is supported by the small difference between minimum and maximum values. The boxplot for pH shows quite similar distribution for both time periods, with the median value being almost the same as well. There are some outliers for 2009-2017, but as these are not unrealistic values, they were not excluded from further analysis.

The 2018 mean value for ammonium concentration falls in between the values of the overall mean and the 2009-2017 mean. The standard deviation is relatively large, which is supported by the large difference between the minimum and maximum values. The boxplots show that the distribution is not very different for 2018 compared to 2009-2017. The interquartile range is almost the same, as well as the median value, indicating that it is unlikely there is a difference between 2018 and 2009-2017. Again, there are some outliers which are not unrealistic values, and they were not excluded from further analysis.

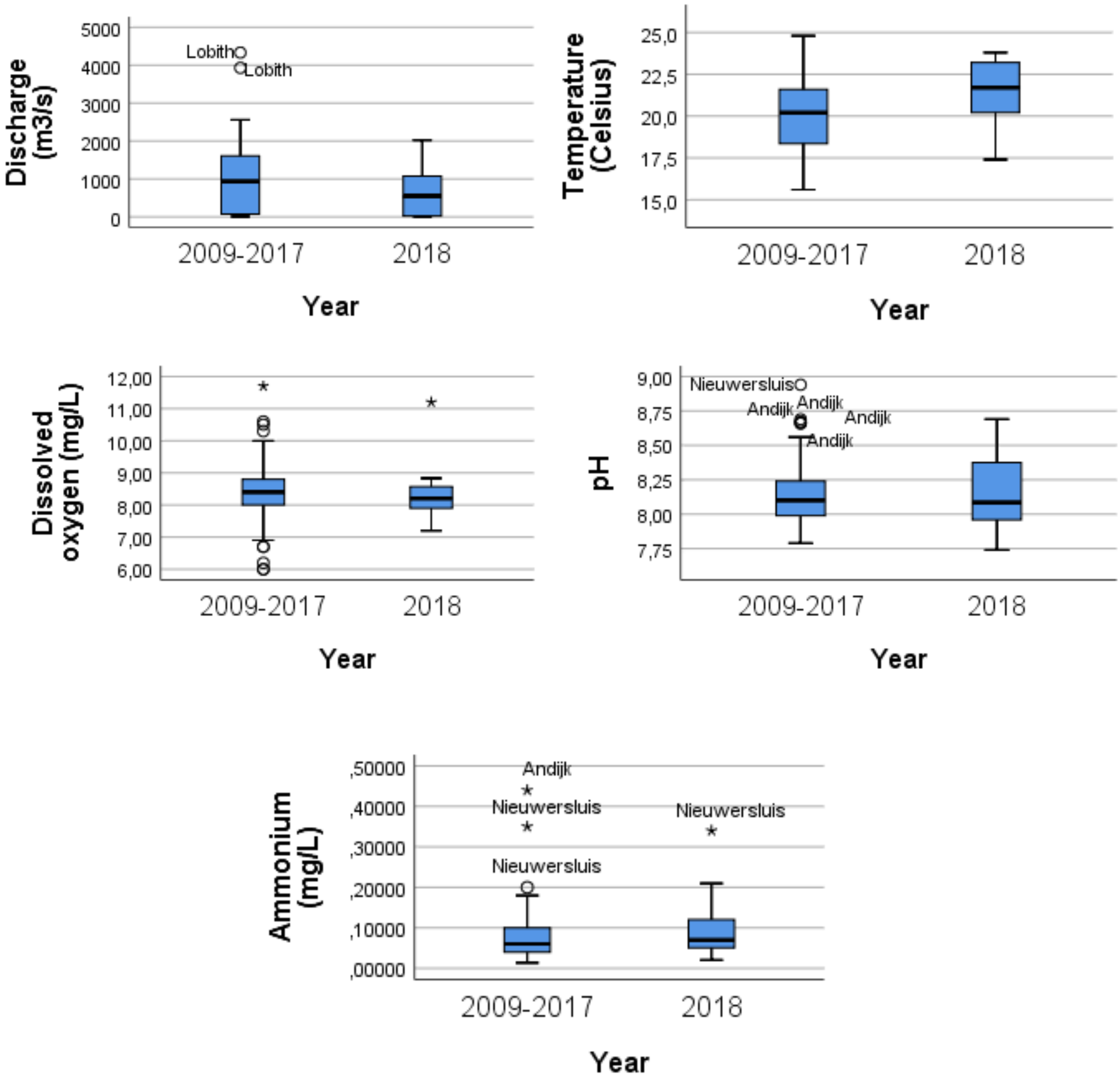

Figure 4: Boxplots showing possible differences in distribution for each of the parameters in the period 2009-2017 compared to 2018.

6.2 Statistical analysis

Firstly, the Shapiro-Wilk test was used to test for normality of distribution. From this it was determined that temperature and pH followed normal distribution, while discharge, dissolved oxygen content and ammonium concentration did not. This meant that temperature and pH were analyzed using the parametric tests as introduced in the methods section, while discharge, dissolved oxygen content and ammonium concentration were analyzed using the non-parametric tests.

No significant differences were found for the parameters discharge, dissolved oxygen content, pH and ammonium concentration when comparing the individual years, comparing 2018 to 2009-2017 and comparing 2018 to 2009-2017 while excluding the drought years 2010, 2013 and 2015. For temperature however, a significant difference (Sig.=0.011; $p<0.05$) was found between 2018 and 2009-2017. This significant difference still existed when excluding the other drought years (Sig.=0.014; $p<0.05$). It is interesting to note that the significance slightly decreases when excluding other drought years; as it would be expected that this increases the difference between 2018 and the other years, thus increasing the statistical significance.

These results are in line with the expectations following from the patterns the boxplots showed. Temperature was the only parameter that was likely to show a difference, which turned out to be a correct assessment.

7. Discussion

7.1 Impacts

In the conceptual framework, it was defined which parameters can be used to indicate the occurrence of which impacts.

All parameters can be used to indicate the occurrence of habitat loss: a decrease in discharge would point to spatial habitat loss and the other parameters to habitat degradation. The results showed that only temperature was significantly higher in 2018 than in the previous years. This is not enough to definitively state that there was habitat degradation, and it means that there was likely no habitat loss.

Temperature is the sole indicator of heat stress. As temperature was the only parameter that showed a significant difference for 2018 compared to 2009-2017, it can be stated that heat stress occurred.

For oxygen stress, the indicative parameters were temperature, dissolved oxygen content and ammonium concentration. Again, only temperature showed a significant difference. As dissolved oxygen content (the main indicative parameter for this impact) did not show a significant difference, oxygen stress likely did not occur.

Lastly, toxicity had temperature, pH and ammonium concentration as parameters. With again only temperature showing a difference, toxicity was likely not an impact of the 2018 drought.

7.2 Scientific context

These results are different from the expectations as defined in the conceptual framework and not in line with previous research on drought impacts. Buras et al. (2020) demonstrated that the 2018 drought was comparable to, if not more extreme than, the drought of 2003. Van Vliet & Zwolsman (2008) found significant deterioration of water quality of the Meuse during the 2003 drought, on the same parameters that were analyzed in this study. Although the Meuse is a different river, it is remarkable that so many significant impacts were found for 2003 and just one for 2018. An explanation for this is that the upstream area of the Rhine received sufficient precipitation for water levels downstream to not reach critical values (Waterstaat, 2018). This explains why discharge showed no significant differences. Additionally, this can explain why there was no significant difference found for ammonium concentrations, as these are largely influenced by dilution of effluents of wastewater treatment plants (van Vliet & Zwolsman, 2008). When there is enough waterflow, ammonium released from these plants is diluted, which means that ammonium concentrations are not increased.

Additionally, with discharge not showing a significant difference between 2018 and 2009-2017, it is not surprising that dissolved oxygen content and pH also did not. Hanslik et al. (2016) found a positive correlation between discharge and dissolved oxygen content, and both positive and negative correlations between discharge and pH, depending on the location. From these correlations they concluded that both dissolved oxygen content and pH are dependent on discharge. Comparing this conclusion to this present study, it is not surprising that, as there was no significant difference found for discharge, there were also no significant differences found for dissolved oxygen content and pH.

The significant differences found for temperature are in line with previous research. Wolff and van Vliet (2021) found significantly higher temperatures for both the Rhine and the

Meuse during the summer of 2018. However, they found larger impacts for the Meuse than for the Rhine, and attribute this to the Meuse being a rainfed river while the Rhine is mixed snowmelt- and rainfed. High air temperatures in the area where the Rhine originates likely caused increased snowmelt, resulting in an inflow of cool water that also reduced water level decrease (Wolff & van Vliet, 2021).

In a wider context than 2018, higher temperatures during drought conditions were also found in several other studies (Baurès et al., 2013; Hanslik et al., 2016; van Vliet & Zwolsman, 2008; Zielinski et al., 2009). In these studies, increased temperatures were accompanied by a decreased dissolved oxygen content, which is not the case in this study. However, this is likely because there was no decreased discharge.

7.3 Limitations

The main limitation of this research has been the sample size. Working with monthly averages meant that for each year only sixteen datapoints per parameter could be analyzed. While the means would have stayed the same when working with daily values, it would have impacted the distribution of the data. This could have been beneficial in obtaining more significant outcomes, as the small sample size makes the analysis vulnerable to type II errors (accepting a false null hypothesis). It is therefore important to mention that while almost no significant differences were found with this analysis, this does not mean that the differences do not exist.

Another limitation of this research lies in the influence of outside factors that are difficult to check or were not included in the scope of this research. Discharge and temperature can be checked and explained by looking at weather reports for the years that showed differences. For dissolved oxygen this is more difficult already, as it is influenced by many other factors, such as temperature, water velocity, and productivity. pH is influenced by several chemical processes and ammonium concentration is influenced by productivity as well as wastewater treatment discharge and agricultural and industrial runoff. These factors are difficult to check as there is not an archive that registers increased agricultural and industrial runoff, unless it is part of a hazard.

As for the impact defined as toxicity, the parameters that serve as indicators in this study are far from the only parameters that may cause toxic water conditions. Many chemical compounds are toxic to aquatic life in high concentrations, but they were not included in this study because this would broaden the scope, which was deemed not desirable because of limited available time. Based on the results from this analysis, toxicity was not an impact of the 2018 drought. However, multiple drought monitors published by Rijkswaterstaat in the summer of 2018 mentioned the increased presence of Cyanobacteria and botulism, and increased mortality of fish (LCW, 2018a; LCW, 2018b; LCW, 2018c). Therefore, toxicity did occur as an impact of the 2018 drought, although it was not demonstrated by this study because of the limited scope. For the next paragraph on the implications of this study, toxicity will be counted as an impact.

7.4 Theoretical implications

The main theoretical implication following from this study is that the results do not confirm the theory that the 2018 drought was exceptional or extremely impactful to the Dutch part of the Rhine river. However, as was already determined for toxicity, the parameters used in this study are not the only indicators of impacts on river ecosystems. In terms of newly discovered theoretical insights, this study has proven that the most common indicators of water quality are sometimes not sufficient to determine if there are impacts on ecosystems.

Within the broader field of sustainability, the results from this study might look hopeful at first glance, as not many impacts were determined. However, this is not the case, as it highlights the difficulty in choosing the right parameters to analyze. Even if it is known beforehand that ecosystems suffered during drought conditions, there is a long list of parameters that could have caused these impacts, as well as interaction effects between parameters that might not seem logical beforehand.

These conclusions provide points that should be addressed in future research. Firstly, future research should include analysis of all measured values instead of monthly means to determine with more certainty the impacts of the drought. Additionally, a larger spatial scope including the entire Rhine river may provide a better understanding of upstream and downstream dynamics. A larger spatial scope including the Meuse river may provide a better understanding of the influence of weather conditions. Lastly, further research should also include analysis of more parameters, so to be sure that all indicators of drought impacts are considered, and interaction effects can be established as well.

7.5 Policy implications

The lack of significant differences between 2018 and 2009-2017 can have several causes: the weather circumstances in the upstream part of the Rhine provided a buffer to the downstream part, the limitations of the research caused type II errors, or measures taken by Dutch authorities were sufficient to relieve drought impacts. The former two causes were already discussed, but the third cause provides an interesting aspect to explore as well.

In periods of drought, the Dutch Ministry of Infrastructure and Water Management publishes so called 'drought monitors' on a weekly basis, which contain information on the current state of the drought and its effects on weirs, open water, groundwater, soil, drinking water services and inland shipping. It gives a national overview of the situation as well as discusses regional situations if they are critical. However, it also mentions measures taken by authorities to relieve the effects of the drought. From July 18th, 2018 and onward, the reports mention that there is a withdrawal ban on surface waters, which includes the Rhine and its distributaries (LCW, 2018a; LCW, 2018b; LCW, 2018c). They also mention the opening of the Irenesluizen to keep salinity levels in the Lek and the Amsterdam-Rijnkanaal within reasonable values, as well as the closing of the sluices in the Afsluitdijk which prevents water in the Ijsselmeer from going into the sea (LCW, 2018a; LCW, 2018b; LCW, 2018c). The opening of the Irenesluizen, which are located just before the measuring location Nieuwegein, meant that discharge at this location increased. The closing of the Afsluitdijk possibly impacted measurements at Andijk, although this is difficult to determine exactly without further research, as it is not directly affected, like discharge.

From the lack of significant differences, it follows that these measures were successful in at least partly mitigating the impacts of the drought on ecosystems. Spatial habitat loss in particular was prevented by the well-executed management of water levels through the sluices. Impacts that were present are heat stress and toxicity. Therefore, it is necessary that additional measures are taken to relieve the river ecosystems of these impacts. The focus of these measures should mainly be on mitigating temperature increases of river water, as this parameter influences heat stress and is a driver in physical and chemical processes that cause toxic conditions. An added effect of these measures would be that river water can still be used to cool electricity plants, which would benefit society as well.

8. Conclusion

This study aimed to find an answer to the following research question:

> What impact did the drought of 2018 have on the Dutch part of the Rhine river in terms of discharge, temperature, pH, dissolved oxygen content, and ammonium concentration?

The parameters mentioned in the research question were indicators of four different impacts: habitat loss, heat stress, oxygen stress and toxicity. From the results of the data analysis, it can be concluded that heat stress was the only impact of the 2018 drought. However, due to limitations of the design of the study, several parameters indicating toxicity were not included. Reports of high values of toxins, along with reports of increased fish kill led to the conclusion that, while it does not follow from the results of this analysis, toxicity was in fact an impact of the 2018 drought as well. It can be concluded with fair certainty that habitat loss was not an impact of the 2018 drought as water levels were maintained through management of sluices. There was also no evidence of oxygen stress.

While these results might show that the 2018 summer drought did not impact the Dutch part of the Rhine river as severely as expected, it is still important to develop further adaptation and mitigation measures. This will provide much needed protection to river ecosystems that will experience increased stress in the future, as droughts are more often to occur as a result of the changing climate. These river ecosystems must be protected, because they support many of earth's processes and provide services that society cannot live without.

9. Acknowledgements

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10. References

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