Spreading of the runoff times in the Dutch Rhine delta

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image: vb&t groep

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Preface

This is the final report on my bachelor thesis carried out at Rijkswaterstaat Oost-Nederland between the 26th of October 2020 and the 15th of January 2021. Due to the global Covid-19 pandemic the entire research was carried at home. In this section I want to thank both Anouk Bomers from the University of Twente and Daniël van Putten from Rijkswaterstaat for the time and effort they have spent to provide me with feedback during the last couple of weeks. Their help has been invaluable and I am very grateful for it.

Jeroen Bod
Vorden, January 2021

Abstract

The aim of this research is to obtain continuous relationships between runoff times and water levels in the Dutch Rhine delta. A custom made methodology was used to determine the runoff time of individual discharge waves by observing the duration for which these waves stay above certain distances underneath the peak water level value. The shift of these time periods between water level measuring stations is then used to calculate runoff time values. Water level data collected between 1985 and 2019 was used to determine runoff times between Lobith and other measuring station in the delta. Additionally runoff times have been determined between successive measuring stations as well. The results show that floodplains have an increasing effect on runoff time while the weir management in the delta and lateral inflow from the Twente Canal and the Old IJssel river cause the increased spreading of runoff times of individual discharge waves.

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1 Introduction

Since ancient times humans have built settlements close to rivers all around the world. Rivers have been a major factor in the establishment and growth of human civilization. They have been used for agricultural purposes, raising livestock and also fulfil an important role in our transportation systems. Hence a lot of urban centres can be found close to rivers these days (Jinxin et al., 2015).

However, besides all the benefits that rivers have offered us, they also embody a source of danger. Floods caused by rivers have been happening before humans existed and it is expected that this threat will increase in the future due to climate change. Areas not protected from flooding can receive significant damage during a flood event but protected areas are not excluded from this danger. These areas are often economically developed and a flood event can thus cause even more damage than in unprotected areas (Gaál et al., 2015). Macro-stability, overflow and piping are examples of possible failure mechanisms.

If humans want to receive the benefits from river basins while keeping themselves and their economic assets safe, a clear understanding of river dynamics is needed. This understanding allows humans to build protective structures and anticipate possible future threats. One of the tools that can be used for anticipating events in the future is the runoff time or travel time of a discharge wave. The runoff time describes the time that has passed when a body of water travels from one place to another. This information can be useful if one wants to predict when a flood wave will arrive at a certain location along a river.

This type of knowledge, concerning river behaviour, also plays a significant role in the Netherlands. A large part of the country makes up the delta where the river Rhine, Meuse and Scheldt all flow out into the North sea. The Dutch have a well-known history in water management since large parts of the country are vulnerable to floods. Knowing the runoff times between locations is useful information for those who rely on the benefits of the rivers but it is also important for those who live in floodable areas.

1.1 Problem definition

In the current situation, the available methods to determine runoff times often produce a single runoff time value for a large water level range. When no external factors that can influence the runoff time are present, these methods produce fairly accurate results. However, these conditions are often not met which leads to misleading runoff time results that are obtained due to the presence of factors that influence the river flow at specific water levels. Examples of these factors are weir management, flood plains and upstream traveling waves. A methodology that can be used to obtain an accurate relation between water levels and runoff time is currently missing due to these influencing factors.

1.2 Research questions

The objective of this research is to determine the spreading of the runoff times in the Dutch Rhine delta as a function of the water level. The main research question directly follow from this goal:

- ***What are the expected runoff time values at different water levels in the Dutch Rhine delta?***

Due to the availability of the water level data that has been collected in the study area, the obvious path towards answering the main question is to examine individual discharge events that have occurred in the past. With enough data, these individual cases can be used to sketch a bigger picture about what is the expected spreading of runoff time values. Two sub questions have been formulated that will help to answer the main research question:

  - *How can the runoff time of an individual water level peak or valley be determined?*
  - *How can runoff time values obtained from individual water level peaks and valleys be combined to obtain a relation between runoff time and water level?*

1.3 Scope

The scope of this research is limited in size and depth due to the limited time period of 10 weeks that is available to conduct the entire research. As stated before, the study area coincides with the Dutch Rhine delta but only partially so. The parts of the delta located in the west of the Netherlands beyond Zaltbommel and Hagestein will not be taken into consideration in this research due to tidal wave influences that make it infeasible to determine runoff times.

1.4 Study area

An overview of the project area can be seen in Figure 1. The Rhine river, coming from Germany, enters the Netherlands near Lobith in the east. Due to its geographical location, Lobith is an import point in the Dutch Rhine delta. It is used as a reference point in most research. After Lobith the Rhine bifurcates into the Pannerden Canal and the river Waal. The Pannerden Canal is rather short (only 6 kilometre) and continues as the Nederrijn towards Arhem. A side branch of the Nederrijn, the IJssel river, starts here. The IJssel continues in the northern direction and will finally flow into Lake IJssel. The Old IJssel and the Twente Canal merge with the IJssel near the cities of Doesburg and Zupthen respectively. These two flows thus contribute to the total discharge of the IJssel river. The Nederrijn flows in the western direction until the river is crossed by the Amsterdam-Rhine Canal. After that the river is known as the Lek. The Amsterdam-Rhine Canal is a branch of the river Waal and crosses the Nederrijn near Wijk bij Duurstede. The river Waal flows from the Pannerdense Kop near Germany towards the west and turns into the Boven Merwede near the city of Gorinchem.

Three sluices are located on the Nederrijn and the Lek. These can be found near the cities of Driel, Amerongen and Hagestijn. They are also shown in Figure 1 with a purple icon. Two sluices are located on the Amsterdam-Rhine Canal. These are known as the Prince Bernhard sluice near Tiel and the Princes Marije Sluice near the village of Rijswijk (province of Utrecht).

Figure 1 - Study area

1.5 Structure of the report

The remaining of this report is structured in the following way. In chapter 2 previous attempts to determine runoff times in the Dutch rhine delta will be discussed as well as some theory about runoff times. Chapter 3 gives a step by step description of the methodology that was used in this research. All the obtained results will be presented in chapter 4. The validation for some decisions made with regard to the methodology are included in this chapter as well. A discussion of the results is given in chapter 5 followed by the conclusion in chapter 6. Two appendices containing all the obtained relations between water level and runoff time can be found at the end of this report.

2 Background knowledge

This chapter gives insights into previously conducted research and what the shortcomings of these attempts were. Evaluating what has been established in the past can help to avoid issues that held back those particular attempts to quantify runoff time values. Some theory about runoff times and how to determine a runoff time value will also be briefly discussed.

2.1 Previously conducted research

In 1985 Rijkswaterstaat published a report that contained runoff time values that were determined based on measurement data gathered between 1970 and 1984 (De Vries, 1985). Discharge waves with a value of at least 3000 m^3/s near Lobith were used for the analysis. The amount of the data available for this report was not very substantial and the findings only indicated the runoff times associated with high discharge events.

In 1992 multiple tracer tests were conducted to validate the so called "Rhine alarm model version 2.1". The concentration of the tracer (chloride) was measured at Lobith and Hagestein. The time between the peaks in concentration at both locations were used to calculate the runoff time. Only 17 runoff times have been determined during this study and the amount of spread was quite significant (multiple days) (van Mazijk & Wuijts, 1995).

In "*Betrekkingslijnen Rijntakken versie 2018*" (by van der Veen & Agtersloot, 2019) the authors have made an attempt to calculate the runoff times in the Dutch Rhine delta but they ran into a problem that effected the results significantly. One of the factors that had a major influence on the results is the three weirs that are present in the delta (see Figure 1). The weir near Driel normally allows an output of 30 m^3/s which consequently means that peaks in the water level observed upstream of Driel are not visible downstream.

In "*Betrekkingslijnen Rijntakken versie 2018*", the authors compared the water levels at Lobith with the water levels at other locations in the delta. Those two variables can be put in a graph to see how well they are correlated. This is done in Figure 4 and Figure 5. In Figure 4 the time shift is 0 hours. This means that every point in the figure represents a water level at Lobith and the water level near Zupthen that occurred at the same moment. In Figure 5 a shift of 17 hours is applied. So every point represents a water level measurement near Lobith and the water level measurement near Zupthen 17 hours after that. By changing the time when the water levels where measured at a certain measuring station compared to Lobith, the point cloud in the graph will change. The idea is that the correlation between the water levels is the highest when the time shift is equal to the runoff time. By calculating R^2 values with the use of a third degree polynomial correlations were obtained. The best correlations found were used to determine the runoff times. R^2 is known as the coefficient of determination and is a statistical tool used to show how well an independent and a dependent variable are correlated (Zhang, 2016).

$$R^2 = 1 - \frac{\sum(y_i - \hat{y})^2}{\sum(y_i - y_a)^2} \qquad \text{Equation 1}$$

Where in this case:
R^2 is the coefficient of determination.
y_i is the water level at Lobith (m+ NAP)
$\hat{y}$ is the expected value from the polynomial
y_a is the average y value

The datapoints in Figure 5 are more closely packed around the polynomial than the datapoints in Figure 4. This is confirmed by the R^2 value of 0.94 which is higher than the 0.92 value in the first graph.

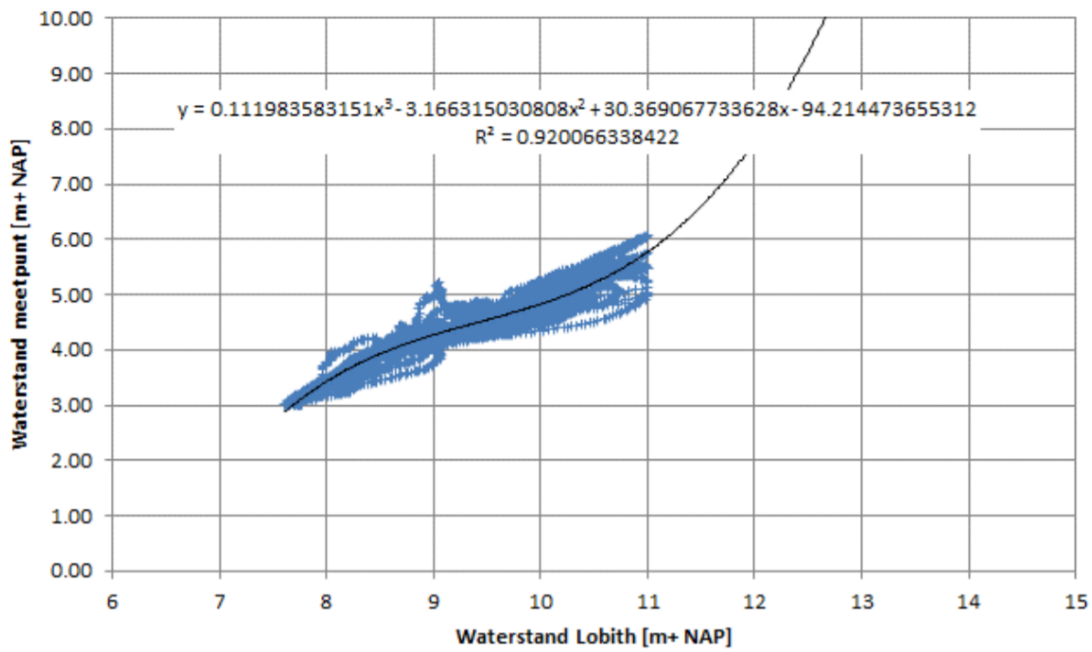

Figure 2 - Runoff time measuring point Zutphen-noord-grens (0 hours)

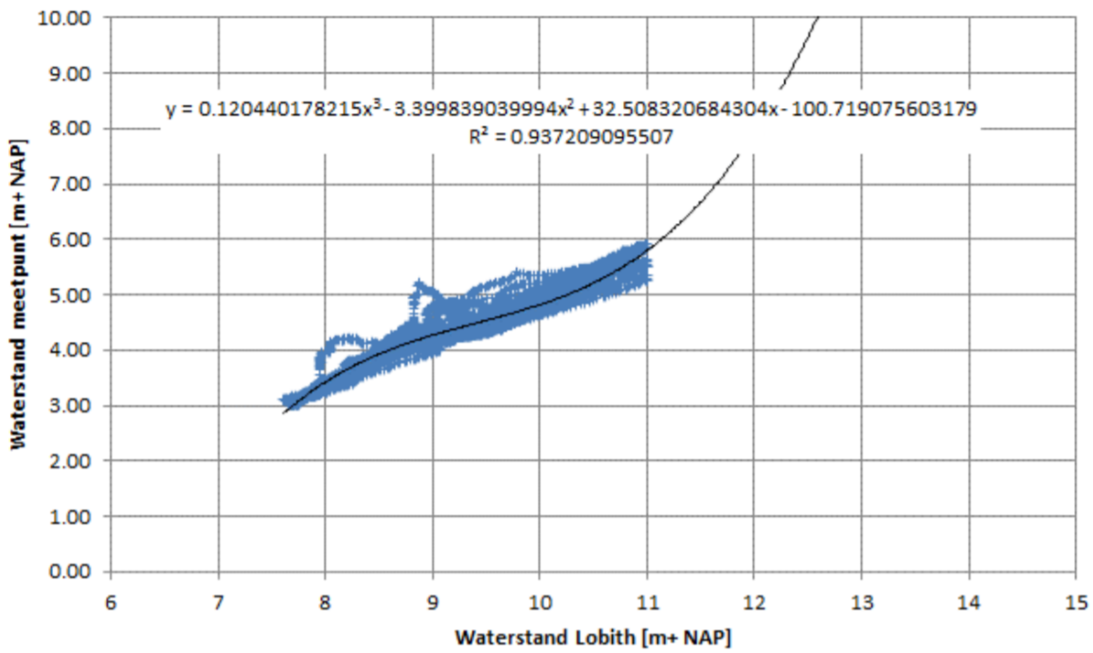

Figure 3 - Runoff time measuring point Zupthen-noord-grens (17 hours)

This method thus works well when no artificial manipulation of water levels is present which is unfortunately not the case in the Dutch Rhine delta. The influence of the weir management leads to unrealistic results for those measuring stations that are affected by it. Another shortcoming of this method is that it produces two runoff time value for two large water level domains instead of a continuous relation between runoff time and water level. One of these domains consists of water levels below 11 m and the other consists of water levels above 11 m. Additionally the runoff times calculated for the water level domain above 11 m have model calculations as input instead of actual water level measuring data.

2.2 Theoretical framework

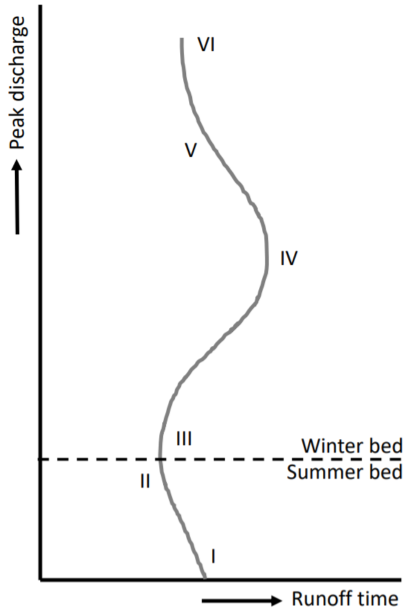

Figure 4 - Adjusted image from the report "Looptijden hoogwatergolven op de Rijn" by de Vrees in 1985 showing the theoretical relation between peak discharge and runoff time

An important factor that influences the runoff time is the profile of the river bed. The profile of a river bed can cause the runoff time to increase when the discharge increases. The theoretical relationship between runoff time and peak discharge influenced by the river profile can be seen in Figure 4 (De Vries, 1985). The different phases in the figure are:

I. The runoff time will decrease when the discharge increases since the water can flow more freely in the summer bed
II. The summer bed of the river is almost entirely filled with water. The flow speed is maximal and the runoff time minimal.
III. The winter bed starts to fill up. The water meets resistance from the winter bed which causes the runoff time to decrease when discharge increases.
IV. The runoff time is maximum due to winter bed resistance.
V. The relative amount of friction is decreasing when the discharge increases. The river can flow more freely and the runoff time will thus decrease.
VI. The maximum peak discharge is reached. The effect of friction in the winter bed is minimal and thus the runoff time is also minimal.

Figure 5 depicts a typical cross section of a river. In most river systems the speed of a flood wave is approximately equal to the wave propagation speed. The speed of a flood wave is the speed at which a body of water travels where the wave propagation speed is the speed at which wave characteristics travel (A wave can propagate in a material without the material moving at the same speed). The following equation can be used to approximate the wave propagation speed (Richards et al., 2012).

$$c = \sqrt{g \times \frac{A}{B}} \qquad \text{Equation 2}$$

Where:
c is the wave celerity (m/s)
g is the acceleration due to gravity (m/s^2)
A is the cross sectional area of the flow (m^2)
B is the width of the flow cross section at the surface (m)

The equation follows the behaviour of the theoretical relation shown in Figure 4.

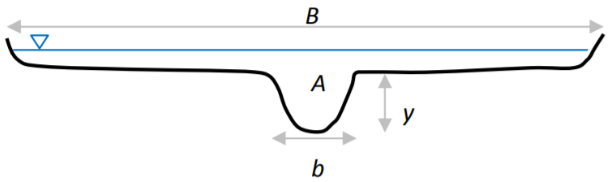

Figure 5 - Typical cross section of a river

Determining runoff times is usually done by tracking “characteristics” of discharge waves over time. Peaks and valleys (maxima and minima) are the most useful characteristics since they are most easy to point out. The inflection point is also a characteristic that could be used but it is also far less suitable since it is more susceptible to influencing factors that can change the water level.

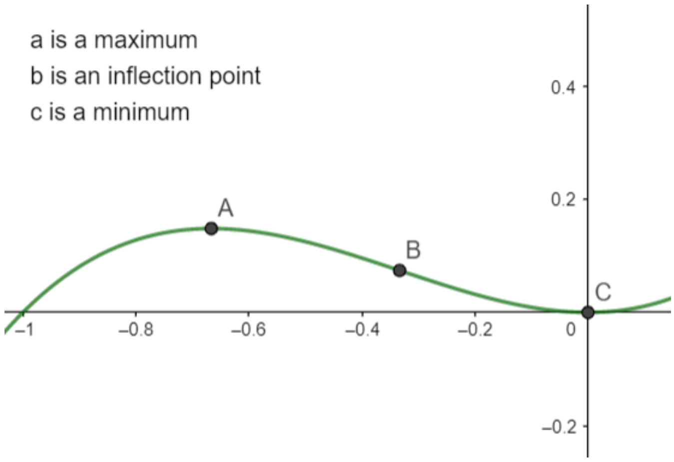

Figure 6 - Examples of water level characteristics

Another method that can be used, makes use of a triangular hydrograph as can be seen in Figure 7. This method does not compare the minimum and maximum values but rather looks at the centroid of the triangular hydrograph. This point is more stable than the peak value of a discharge wave and is therefore often used to determine runoff times (Granato, 2012). However, since the method follows the centroid of a body of water, discharge values are needed as input. The discharge is only measured at 5 different locations in the study area compared to 32 locations where the water level is measured. Therefore, the triangular hydrograph is not suitable.

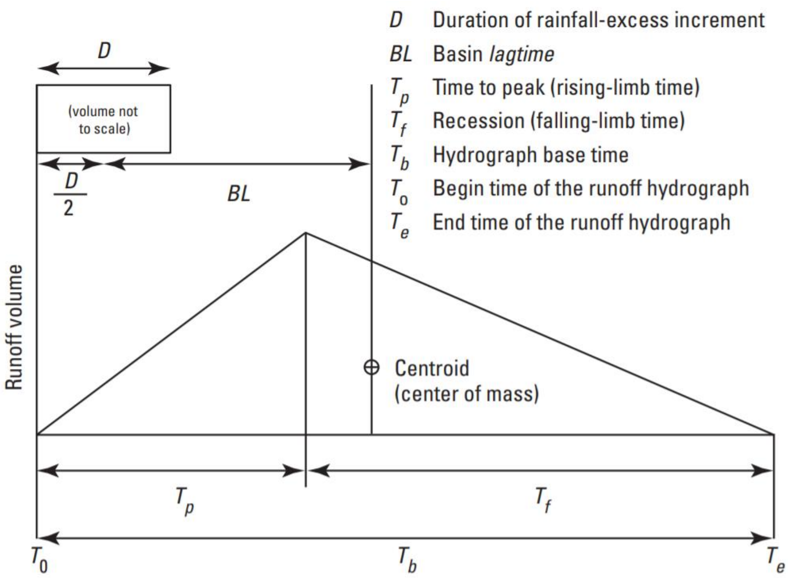

Figure 7 - Triangular hydrograph approach

3 Methodology

The methodology (see flow chart in Figure 8) applied in this research links water level peaks and valleys between different measuring stations and determines the runoff times for individual discharge events. The combined runoff times of these individual events will give insight into the expected runoff times at different water levels. The runoff time will be determined between the measuring station of Lobith (a reference location for water management in the Rhine delta) and all other measuring stations. Additionally, the runoff time will be determined between the nearest upstream and downstream measuring station for every station. Since the distance between successive measuring stations is shorter, water level peaks will deform less. This makes it easier to determine the relation between runoff time and water level.

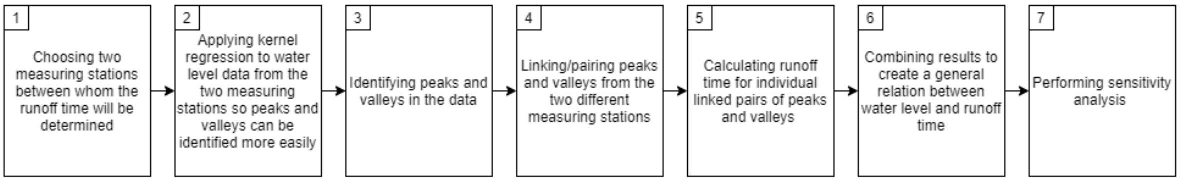

Figure 8 - Flow chart of the methodology

The different steps of the methodology are:

1. The two stations between whom the runoff time will be determined have to be chosen.
2. Kernel regression will be applied to smoothen the data so peaks and valleys can be identified more easily. This will be explained in section 3.2.
3. Peaks and valleys are identified and isolated from the data. See section 3.3.
4. The same peaks and valleys at both measuring stations will be paired. See section 3.3
5. The runoff time of individual discharge waves (the linked peaks and valleys are the minimum and maximum values of these waves) will be calculated. See section 3.4.
6. All the individually calculated runoff times will form a point cloud. This point cloud will be used to derive the relation between the runoff time and the water level between the two stations. See section 3.5.
7. Two important parameters are used in the methodology. The sensitivity analysis will show the influence of these parameters when they are altered. See section 3.7.

3.1 Data gathering

Before the methodology itself is described thoroughly, the data used and where it is was collected within the study area will be elaborated upon. The data consists of water level measurements conducted between 1985 and 2019 (No model calculations have been used since they do not always represent what happens in reality). Water level measurements are used instead of discharge measurements due to a lack of available discharge data. The discharge is only measured at 5 locations in the study area. Hourly water level data is collected by Rijkswaterstaat between 1985 and 2011. From 2011 and onwards the collected data consists of 10 minute values. Initially, only the 10 minute values collected between 2011 and 2019 were used. However, the amount of data available for high discharge events was insufficient within this time period. Only 18 discharge waves with a water level higher than 13 m at Lobith were observed in this period. This is also exactly the domain of water levels at which the floodplains start to fill and influence the runoff time. Therefore hourly data collected between 1985 and 2009 is used to create a complete picture of the expected runoff time values for water level of +10 m NAP and higher at Lobith. Data from before 1985 exists (some measurements date back till 1901) but the amount of data collected since 1985 is sufficient for the purpose of this study. Unfortunately some stations in the study area have only measured water levels on a daily basis in the 1985 till 2009 period. These stations are located near: Dodewaard (1985

– 2000), Tiel (1988 – 1990), Grebbe (1985 – 2006), Deventer (1985 – 1996), Wijhe (1985 - 2006) and Katerveer (only in 1985). The missing hourly values for these stations have been supplemented with interpolated values based on the daily measurements as well as measurements from other stations. Water level data collected in 2010 is not used since that year is the transition period between hourly collected data and data that is collected every 10 minutes. The time needed to organize the data for the analysis was considered to be not in balance with the benefits it would provide since the amount of data available is already sufficient.

The 1985/2009 data is used to obtain runoff times between Lobith and all the other measuring stations in the study area directly. The 2011/2019 data will be used in two different ways. Firstly by linking all the measuring stations directly to Lobith and secondly for the linking of consecutive stations. This means that every station is linked to the nearest upstream and downstream measuring station.

There are 32 measuring stations within the study area that report the water level for their respective location every 10 minutes. The location of each of these stations are given in Figure 9. Three of these stations come in pairs and are given a purple colour in the figure. These stations are located on the Nederrijn and the Lek near the before mentioned weirs (see paragraph 2.2). They measure the upstream and downstream water level.

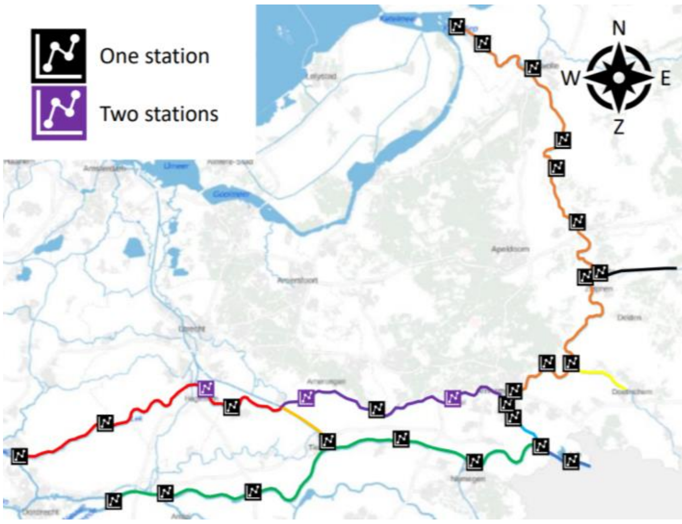

Figure 9 - Measuring stations within the study area

The first sub question that will help answer the main question of this research is *"How can the runoff time of an individual discharge event be determined?"*. The sections below will discuss the step by step process that was carried out to determine the runoff time for individual discharge waves. The steps are accompanied with information and examples that will justify the proposed methodologies.

3.2 Applying kernel regression to water level data

When two water level measuring stations are chosen, the next step is to apply kernel regression to the water level data. The main idea of kernel regression is to fit a line through a set of data points that best describes the overall trend in the data. The value of a point on this line is obtained by taking a weighted average of the data surrounding that particular point. Points close by will get a higher weight than those located further away since it is assumed that close by points are a better estimation of the trend at the evaluated location. The reason we do this becomes clear when we look at the water level graph depicting the peak of a discharge Figure 10. Since the water level is measured every 10 minutes and not continuously, there is not a smooth line representing the water level but rather a fluctuating one. Additionally the water level is measured in whole centimetres. It is not obvious from this data when the exact peak of the wave is passing by. The true peak is probably located somewhere between the 16:14 and 01:50 but a separate strategy is required to estimate this value.

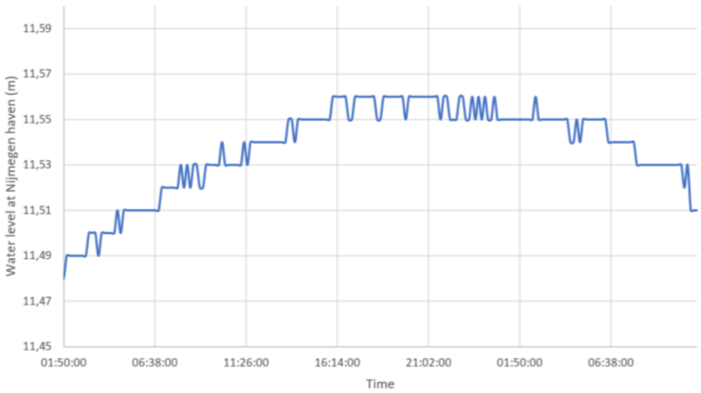

Figure 10 - Water level Nijmegen haven (January 27-28 2018)

The Nadaraya-Watson estimator is the function that is used to calculate the regression values (Munk-Nielsen, 2016). The estimator looks like this:

$$h(x) = \frac{1}{N}\sum_{i=1}^{N} w_i y_i \qquad w_i \equiv \frac{K\left(\frac{x_i - x}{b}\right)}{\frac{1}{N}\sum_{j=1}^{N} K\left(\frac{x_j - x}{b}\right)} \qquad \text{Equation 3}$$

Where:
h is the regression value at x
x is the time
N is total number of measurements
w is the weight factor
y is the actual measurement
b is the bandwidth
K can be any function that uses what is between brackets as input

The Gaussian function will be used for K since it allows the estimator to give higher weights to nearby data points. A graph of this function can be seen in Figure 11.

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{\frac{-x^2}{2}} \qquad \text{Equation 4}$$

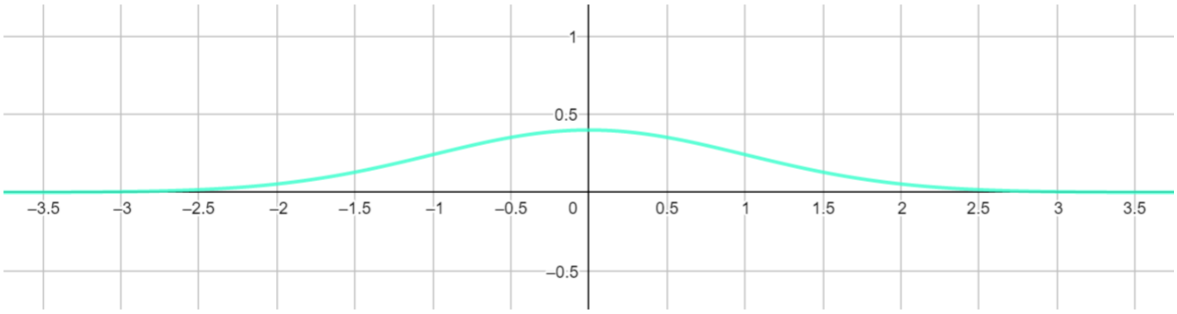

Figure 11 - The Gaussian function

The value of b (the bandwidth) in equation 3 can be manipulated to change the weights for the data points and thus also the regression value. By lowering the value of b the relative weights of nearby data points will increase while those who are further away will decrease. The consequences of this are that a small value of b can cause overfitting of the data while a large value can cause underfitting. When b approaches zero the regression line will directly link the data points while a b value that approaches infinity will be a flat line at the height of the average.
Normally the value of N in equation 3 is the size of the entire data set. The data collected between 2011 and 2019 contains more than 400.000 water level measurements. The code that is used for this research to calculate the kernel regression values has to run multiple days if every data point is considered. In order to keep computation times reasonably low, the amount of considered data points for the regression is limited to 100 points (16.7 hours for data collected every 10 minutes and 100 hours for the hourly data) before and 100 points after the point being evaluated. However, this does not have any significant effect on the regression values since the weight of the data values at the end of the domain (100 before and after the evaluated point) is already smaller than the weight of values at which the regression value is calculated by a factor of 10^{240}.

The water level graph in Figure 10 together with two regression lines can be seen in Figure 12. The effect of a lower or higher value of b can clearly be seen in the figure. The blue line with a bandwidth of 7 is more sensitive to local variations than the orange line with a bandwidth of 20. The bandwidth value of 20 is used for this particular reason. The regression line should fit the measurement data reasonably well but should also not fluctuate a lot due to local variations. The procedure discussed in section 3.4 determines for what period of time a water level peak stays above a certain distance underneath the peak at two measuring stations and uses that information to determine runoff times (the shift between the middle points of these two time periods equals the runoff time). A small local variation, which can more easily happen with a lower bandwidth, might thus be problematic when evaluating at a certain distance x underneath the peak since the height of the peak itself can change when the bandwidth changes. This can clearly be seen in Figure 13.

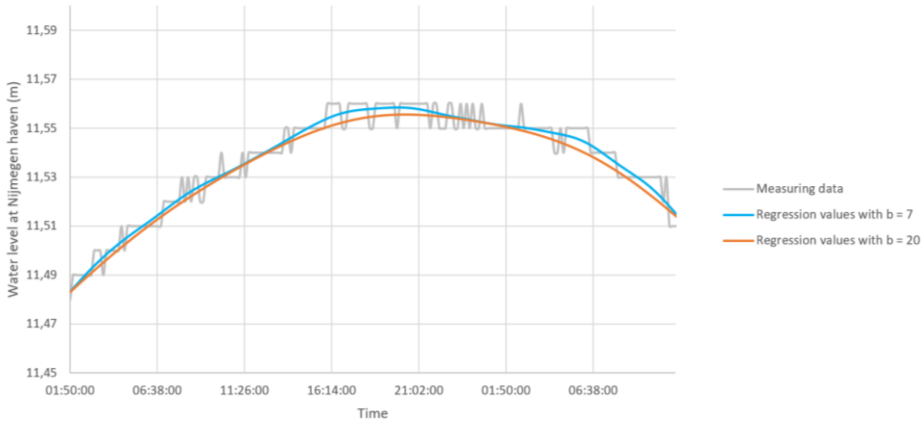

Figure 12 - Regression lines through water level data (Nijmegen haven, January 27-28 2018)

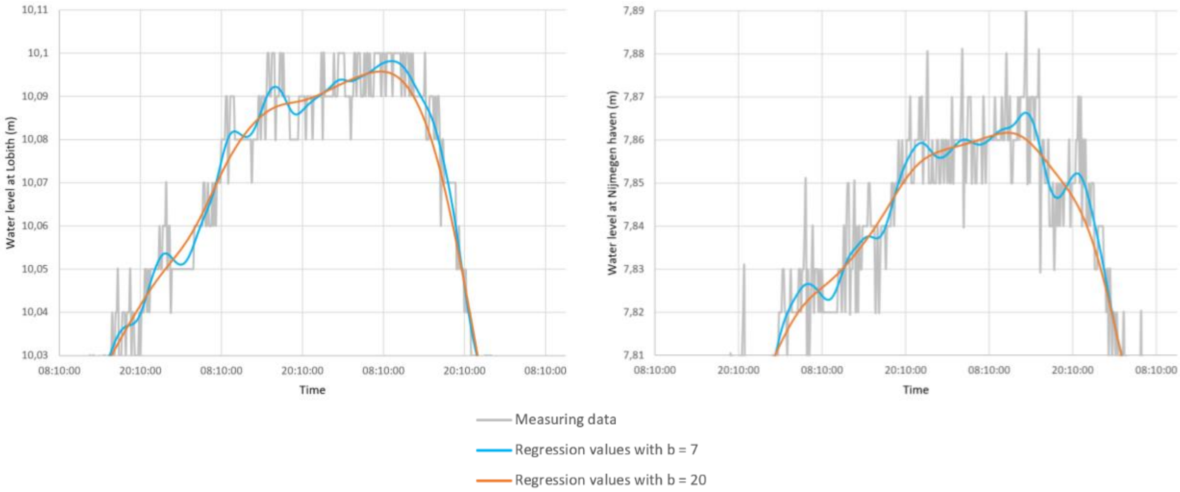

Figure 13 - Effect of regression bandwidth at Lobith (left) and Nijmegen (right)

The graphs in Figure 13 show how the shape of the discharge wave remains roughly similar between Lobith and Nijmegen with a bandwidth value of 20 and that small local variations start to appear when this value is lowered to 7. However, since the regression lines are almost equal when the water level is steeply rising or falling, a large effect on the determined runoff times caused by the chosen b value is not expected. During the sensitivity analysis this minor effect will be quantified. Only when the shape of the discharge wave is very asymmetrical like in Figure 13 will this phenomena have any significant effect. Most discharge wave are more symmetrical in shape around the peak.

3.3 Linking peaks and valleys

The final part of the method that is used to calculate the runoff times is implemented in a Matlab script. This script contains multiple steps that need to be executed before runoff time values are obtained. All these steps will be elaborated upon in to the following sections.

The regression lines can now be used to isolate the peaks and valleys. In Figure 14 the regression lines obtained from the water level data of the year 2018 is presented for the measuring stations near Lobith and Nijmegen. The purple and orange dots represent the peaks and valleys that will be isolated and linked by using the methodology described on the next few pages. The data presented in these two figures was used to calibrate the parameters in the script. First all suitable peaks were manually chosen. After that the parameters of the script were manipulated until the list of linked peaks matched the manually created list.

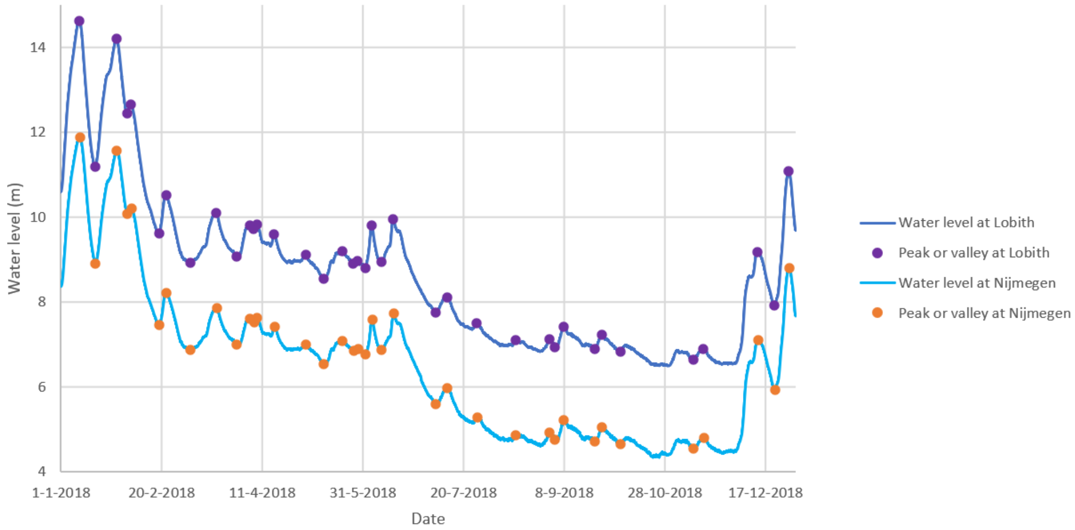

Figure 14 - Water levels at Lobith and Nijmegen in 2018

We first isolate the peaks and valleys from the data. The script that is used to do this completes a couple of intermediary steps before the peaks and valleys are isolated and linked. The peaks and valleys of the upstream measuring station will be identified first. In this case Lobith is the upstream station.

- For every data point the script checks if that data point is a peak or valley by comparing its value with the neighbouring values. Peaks and valleys are then saved separately.
- Then the script checks for every peak and valley if that particular peak or valley is a local peak or valley within a certain time domain. The domain is 50 hours before and after the evaluated point.
- To ensure that only significant peaks and valleys are used in the analysis, the script checks how much the water level has changed 50 hours before and after the peak/valley. On both sides this difference should be at least 5 cm in the same direction. If this criteria is not met, the peak/valley is not used in next steps of the analysis. This criteria is added to make sure that the characteristics of the peak/valley will be visible at the next measuring station as well. When the water level has only risen by 0.5 cm 50 hours after a valley, the characteristics of the valley will easily be flattened out over time. The value of 5 cm will not be used for every measuring station but only for Lobith. For the other stations this value is reduced by a certain factor due to the flattening effect of discharge waves. The value used at Doesburg for instance is equal to 3.67 cm. How this factor is determined for every measurement stations individually will be elaborated upon in section 3.4.

The parameter values used in the above described methodology were chosen after an evaluation of the peaks in Figure 14 that were linked with methodology. With the used parameter values no wrongly linked pair of peaks or valleys are present. One can argue that there are two possible combinations visible in Figure 14 that could potentially be linked but are not with the current parameter values (which means that approximately 5% of all linkable peaks do not get linked between Lobith and Nijmegen). While this might be true, this does not form a substantial problem since multiple years of water level data are used for the analysis. Therefore, enough results will be gathered for the final analysis. Missing out on a few possible combination is more desirable than including all possible combination with the risk of linking peaks and valleys that should not be linked.

By carrying out the above mentioned steps the script creates a list of the highest peaks and lowest valleys within a 100 hour domain for the entire data set. These peaks and valleys will then be linked to the same peaks and valleys at the other measuring station. This is done in one single step. For every peak at the first measuring station the script will identify the highest point within a certain time domain at the second station. When dealing with a valley, the lowest point will be identified. The size of the domain is chosen after an iterative process. The size of the domain has to be limited in order to avoid that completely unrelated peaks get linked with each other. When enough peaks are linked at different water levels, the range of runoff times will become clear. According to this range the domain can be altered if that is needed. For instance, if the domain is between 0 and 30 hours and the results show that the upper bound of the range of runoff times at certain water levels is close to 30 hours, the domain can be increased to for instance 40 hours. The results in Figure 15 between Lobith and Nijmegen suggest that the range of runoff time values is between approximately two and twelve hours for the entire water level range. Choosing a domain that evaluates peaks at for instance 30 hours after a peak/valley at Lobith seems thus rather pointless. With this step completed, all suitable peaks and valleys are linked. The validation for this part of the methodology is given in section 4.1.

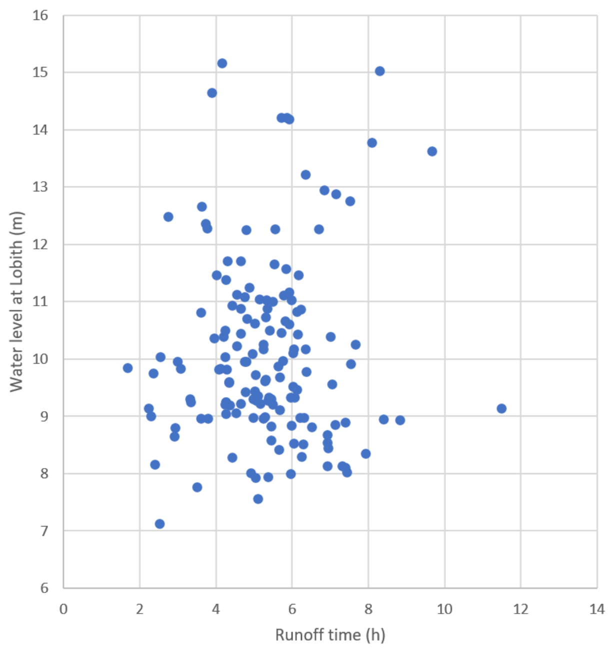

Figure 15 - Spreading of runoff times (Lobith – Nijmegen, 2011 – 2019)

3.4 Calculating the runoff time

The next step in the methodology is to examine for all linked peaks and valleys how long the delay is. Figure 16 illustrates how the runoff time is determined. The script looks for how long the water level stays above 1, 2, 3, 4 and 5 centimetres below the peak. The middle point of this time range will then be compared with the middle point obtained at the second station.

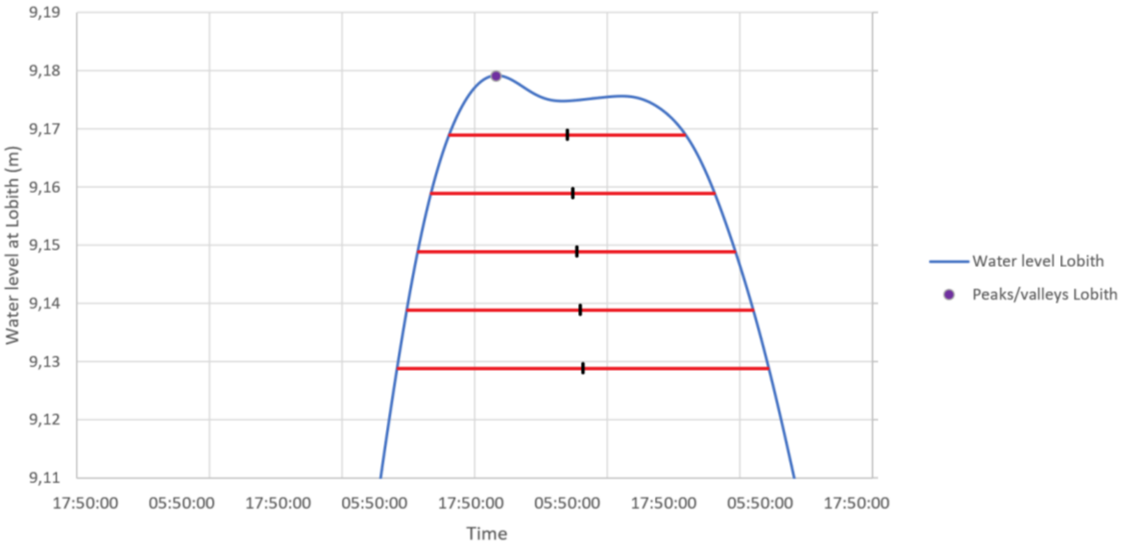

Figure 16 - Water level durations (Lobith and Nijmegen haven, December 10-14 2018)

When looking at Figure 17 and Figure 18 it will become clear why we are looking underneath the peak instead of at the peak value itself. By only looking at peak value we will obtain misleading results. Figure 17 suggests that the runoff time between the two peaks is 8.2 hours and Figure 18 suggests a runoff time of 1.0 hour.

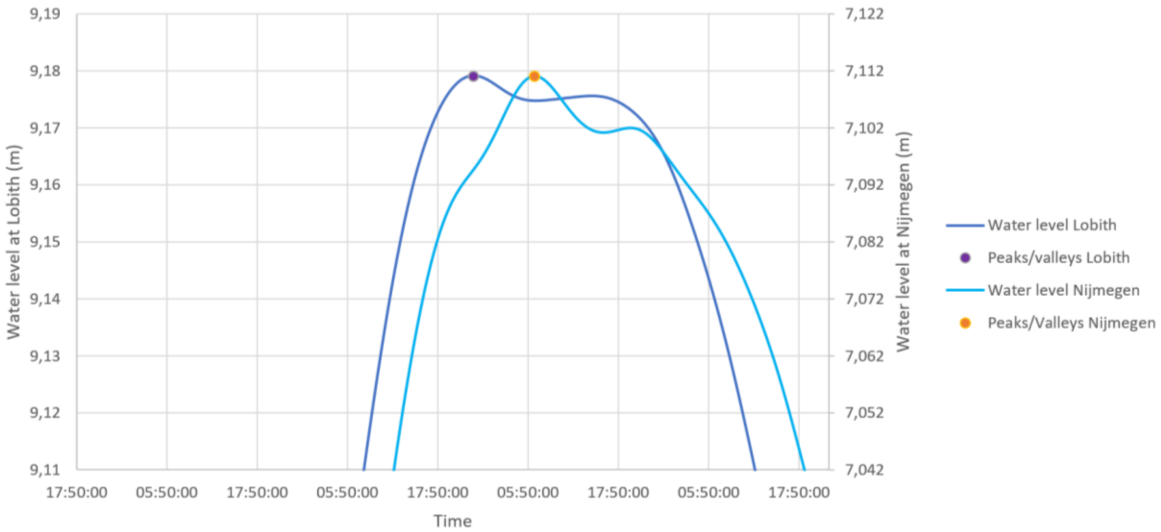

Figure 17 - Shape of discharge peak - part 1 (Lobith and Nijmegen haven, December 10-14 2018)

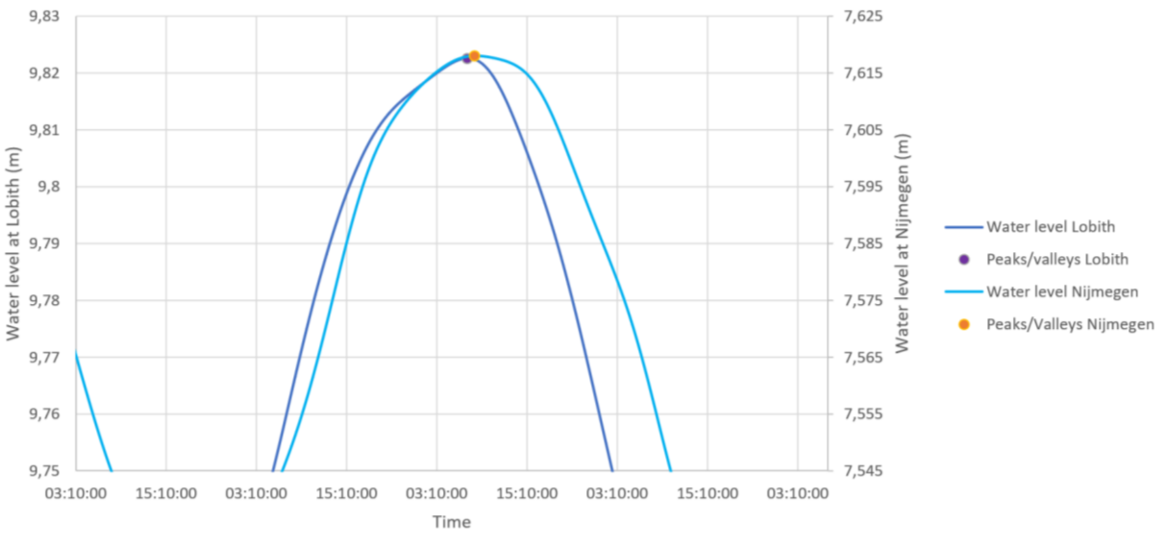

Figure 18 - Shape of discharge peak - part 2 (Lobith and Nijmegen haven, April 6-10 2018)

Both discharge waves have changed a substantial bit in shape between Lobith and Nijmegen when only the section between the peak and approximately 1 cm underneath the peak are considered. However, a couple centimetres below the peak not a lot has changed. The average runoff time at 1 to 5 centimetres below the peak for the first figure is 4.3 hours and for the second figure this value is 4.0 hours. Looking below the peak will thus give more consistent results than when only the peak is considered. The runoff time is thus calculated by looking for which duration a discharge peak stays above a certain distance below the peak value. However, the distance used underneath the peak will not be the same for every measuring station. The distance underneath the peak will be become smaller for measuring stations that are located further downstream. The reason for this is the following. Discharge waves tend to flatten out while they move downstream. This means that a feature visible at a certain distance x underneath the peak will not be visible at the same distance underneath the peak elsewhere downstream. This principle is illustrated in Figure 19 and Figure 20.

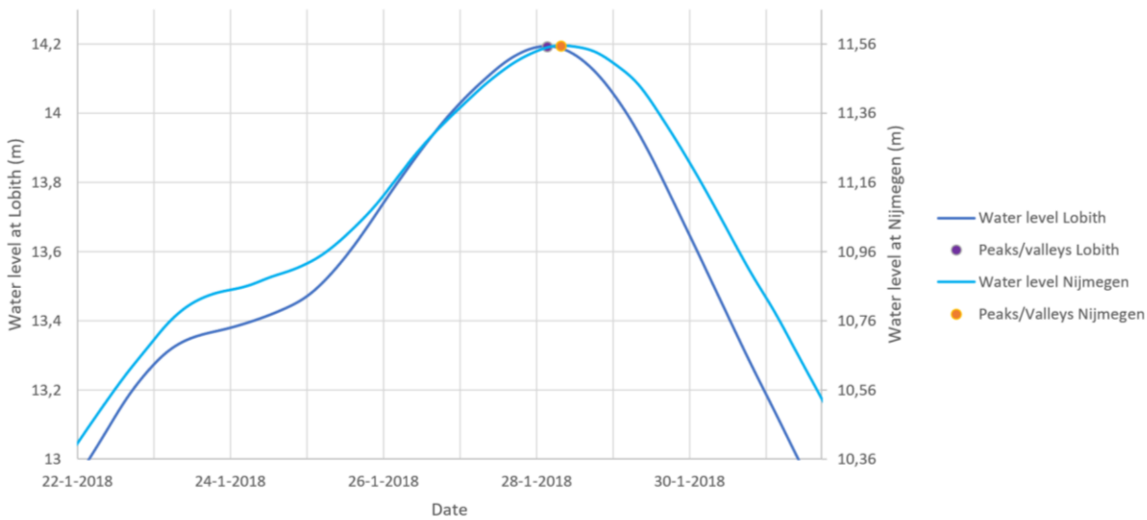

Figure 19 - Flattening of a discharge wave between Lobith and Nijmegen

The dark blue line represents the water level at Lobith while the light blue line represents the water level at Nijmegen. The size of the domain of both y axes is the same but shifted and the values are chosen in such a way that both peaks end up on a horizontal line. On the left side of the figure, both lines tend to flatten a little bit around the 24^{th} of January. However, the light blue line is positioned higher up the y-axis than the dark blue line. This is due to the flattening of the discharge wave between Lobith and Nijmegen.

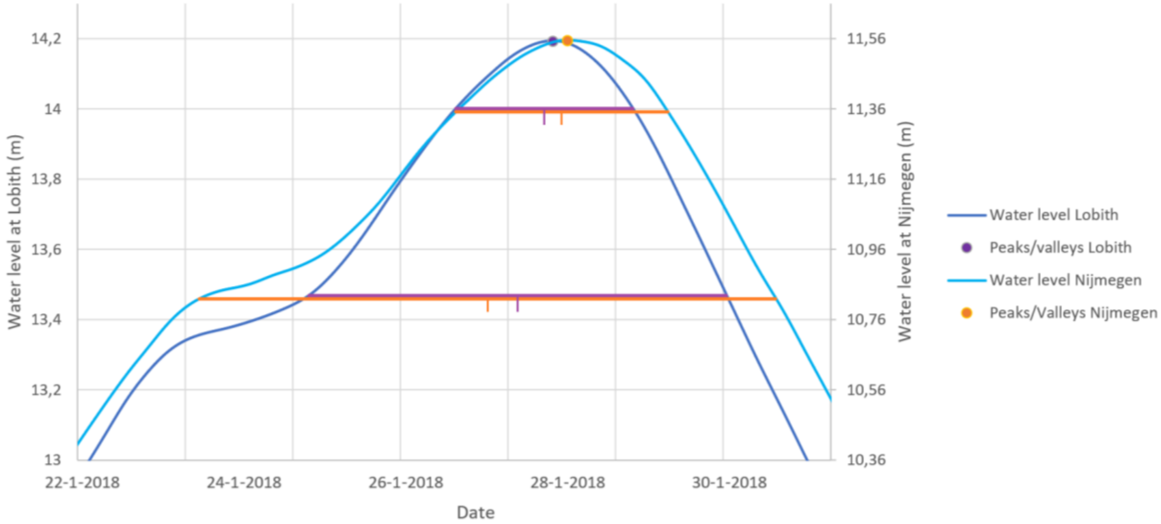

Figure 20 - Effect of flattening on determining the runoff time

In Figure 20 the possible problem that can arise becomes clear. 20 cm underneath the peaks the runoff time is positive since the middle of the orange line is on the right of the middle of the purple line. However, at a little over 50 cm underneath the peaks the runoff time becomes negative. At this height the water level at Nijmegen has already flattened while this has not yet happened at Lobith. These types of features in water level graphs can thus end up creating misleading results.

One possible solution is thus to reduce height underneath the peak at the second measuring station with a certain constant. In Figure 20 this could for instance mean that the runoff time at Nijmegen is not determined around 10.81 m but rather at 10.96 m while Lobith is still evaluated at 13.48 m. This will give a more realistic runoff time value since the shape of the discharge above these two heights is similar at both measuring station.

One way to determine the size of this constant is to use relation lines (“betrekkingslijnen” in Dutch). Relation lines indicate an expected water level at station y given a known water level at station x. The relation line between Lobith and Nijmegen is given in Figure 21 (van der Veen & Agtersloot, 2019).

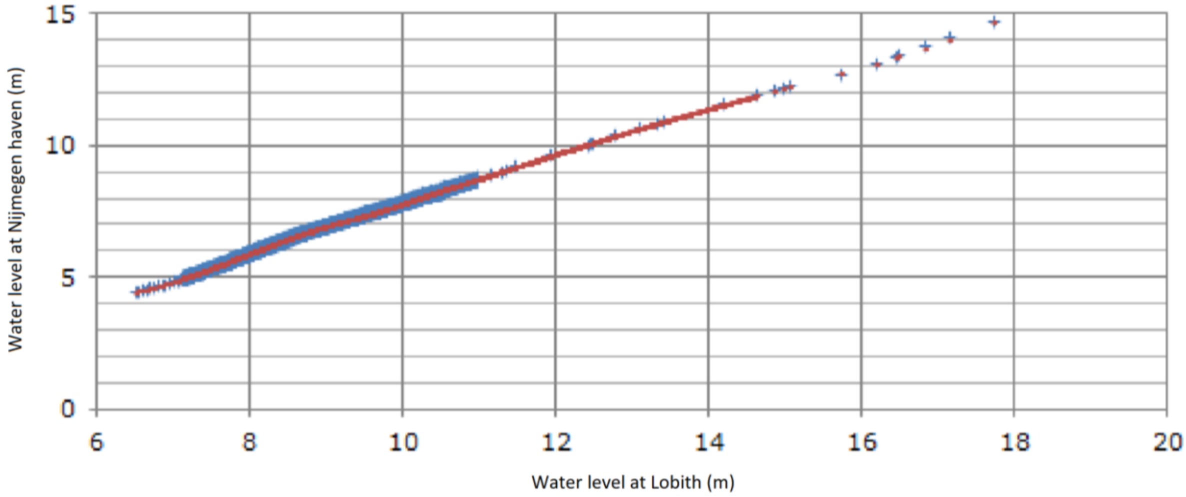

Figure 21 - Relation line Lobith - Nijmegen haven

The slope of the relation line is a suitable value for the constant since it indicates how much the water level at Nijmegen changes given a one meter water level change at Lobith. In other words: the slope of the line describes to what extend a discharge wave will flatten. Since the slope of the line is equal to 1.09, the distances underneath the peaks at Nijmegen will be shortened with a factor of 1.09 compared to Lobith. 5.0 cm underneath the peak at Lobith equals 4.6 cm underneath the peak at Nijmegen.

There are two aspects that need to be taken into account when using these relation lines. The first of which is that not all of these lines are as straight as the one shown in Figure 21. The weir management in the delta, the presence of Lake IJssel and tidal waves result in relation lines that have interesting features.

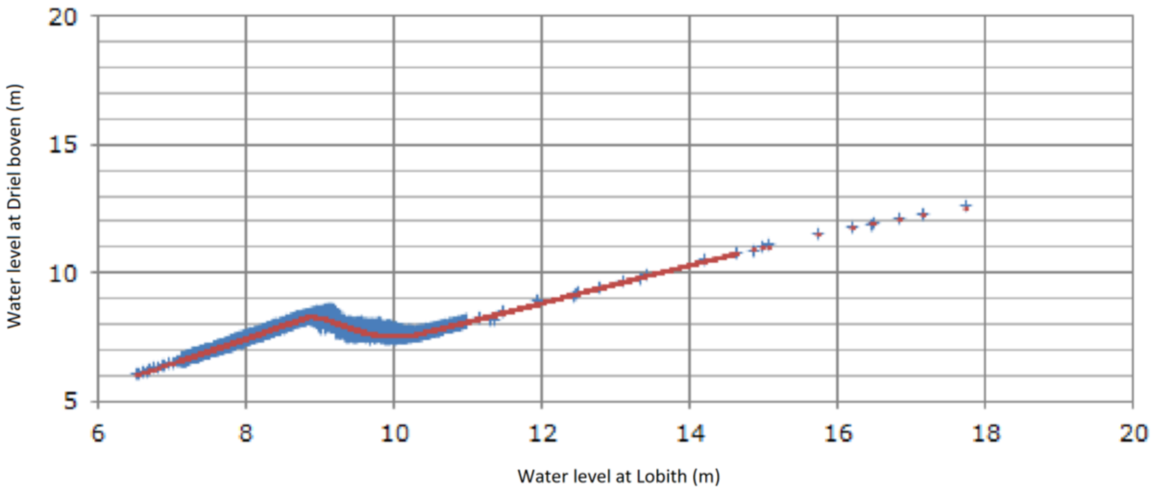

Figure 22 - Relation line Lobith - Driel boven

The influence of the weir management at Driel can clearly be seen in Figure 22 by the dip in the relation line between a 9 and 10 meter water level at Lobith. The constant will therefore be determined by evaluating the relation line above a 12 meter water level at Lobith. The stations downstream of Driel have similar relations lines.

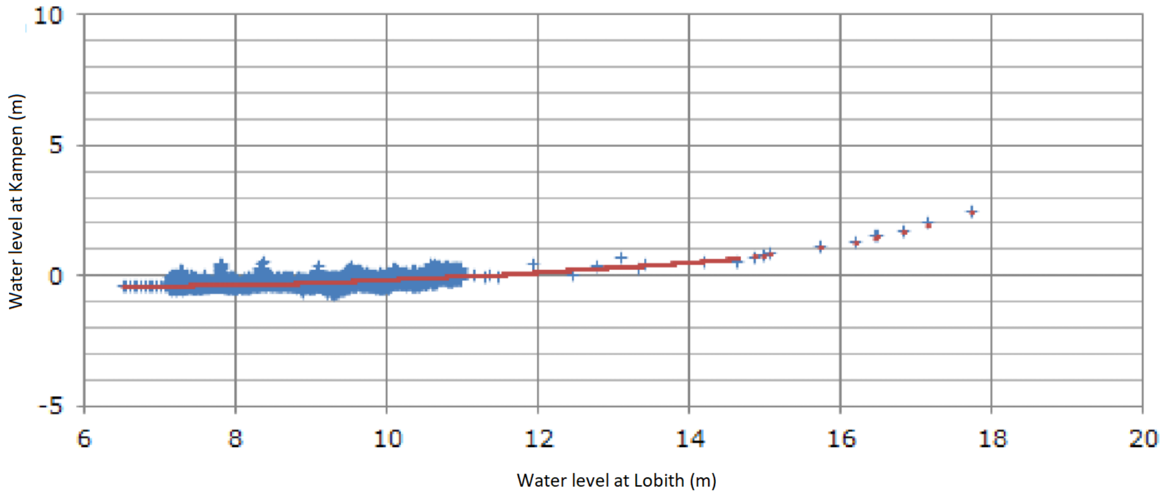

Figure 23 - Relation line Lobith - Kampen

Figure 23 shows the influence of Lake IJssel on the relation line between Lobith and Kampen. At lower water levels the relation line flattens since the water level at Kampen is more dependent on water coming from Lake IJssel than discharge waves coming from Lobith. The constant will therefore be determined by evaluating the relation line above a 12 meter water level at Lobith. This effect is visible at Katerveer and the measuring stations downstream of Katerveer (The relation line between Lobith and Kampen is shown in Figure 23 since the effect is more distinct than between Lobith and Katerveer).

Zaltbommel is the only station for which the constant will only be determined above a 10 meter water level at Lobith. The influence of tidal waves makes it impossible to determine runoff times at lower water levels with the used methodology. The influence of tidal waves on the relation line are only relevant at lower water levels.

The second aspect that needs be taken into account and that also ties into the first one, is that different constants will be needed for different water level heights. Since the data between 1985 and 2009 will be used to analyse high discharge events, the constant used at some measuring stations will be different from the one used for the 2011 – 2019 data. The constant used for the 2011 – 2019 data will be determined by evaluating the entire domain of the relation line while the constant used for the 1985 – 2009 data will be determined by only evaluating water levels above 12 m at Lobith. All the measuring stations together with the constants derived from the relation lines are listed in Table 1 in section 4.2.

The runoff time will not be calculated at just one distance underneath the peak value but instead at five different distances. At Lobith this will be 1 till 5 cm underneath the peak and at other stations these distances will be reduced with the constants mentioned in section 4.2. The average of these five runoff time values will be the runoff time for the particular discharge wave in question. One criterium that has to be met, is that no individual runoff time value may differ more than 1 hour from the average value. If this is not the case, the runoff time value will be calculated with 4 values instead of 5. This will then be done with the combination of the 4 values with the smallest difference with the average value. When no combination of 4 values can be made that meets the criterium, all combinations of 3 values will be checked following the same procedure. When no combination of 3 values can be made, the runoff time will not be calculated and therefore not be used in the final analysis. Section 4.3 provides a justification for the 1 hour criterium used here.

An additional criterium has been used to calculate the runoff times for the water level peaks in the data collected between 2011 and 2019. The data collected between 1985 and 2009 is only used in combination with the previously mentioned criterium. The second criterium is used to ensure that a water level peak maintains a similar shape between two measuring stations. The time period during which the water level stays above a certain height underneath the peak level is used as input. The black and purple line in Figure 24 are a visualisation of this time period. Similar to the first criterium, the second criterium is evaluated at 5 different distances underneath the water level peak. The value calculated at these 5 different distances is the duration at the downstream stations divided by the duration at the upstream stations (B/A in Figure 24). The criterium then states that all these obtained values should not differ more than 0.05 with the average of the 5 values.

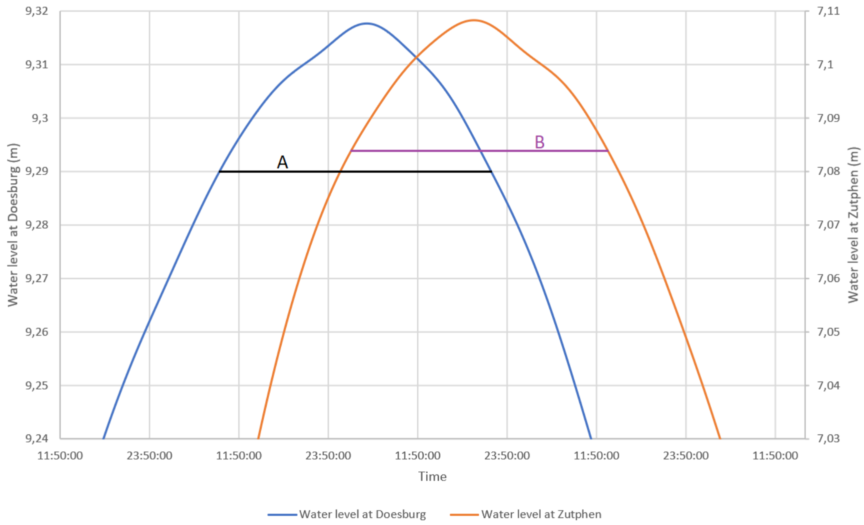

Figure 24 - Visualisation of the second criterium used to calculate runoff times

It is important to mention that the second criterium was not meant to be used in the final analysis because a good substantiation for doing so is missing. Parts of the data have been analysed with this criterium due to human error. A comparison between the results obtained by both using and not using the second criterium is given in section 4.4.

3.5 Obtaining general relation between water level and runoff time

Now that the runoff times of all the individual discharge waves have been determined, the last step is to combine those results to get a general relation between water level and runoff time (answering the second sub question of this research). The runoff times of all the individually linked peaks together with the recorded height of the discharge peaks are plotted in a scatter plot like in Figure 25.

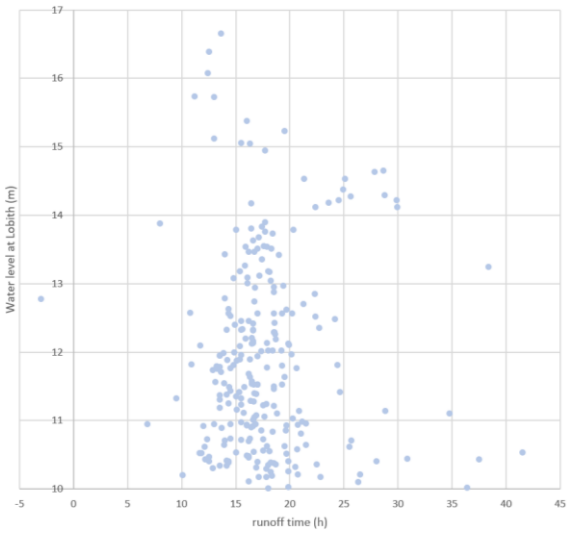

Figure 25 - Water level and runoff time point cloud (Lobith Zalbtommel 1985 - 2009)

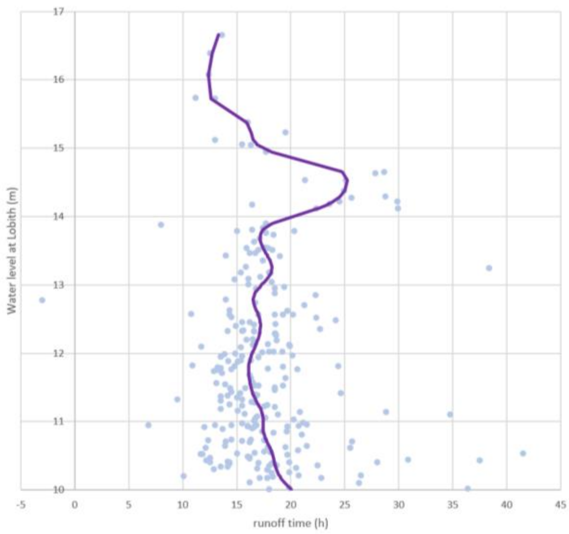

Figure 26 - Regression line added to point cloud (Lobith Zaltbommel 1985 - 2009)

The Nadaraya-Watson estimator (see equation 3) is used to construct a regression line through the point cloud. An example of this is given in Figure 26. Just like in section 3.2 the Gaussian function (see equation 4) will be used for K since it allows the estimator to give higher weights to nearby data points. The bandwidth b in equation 3 is determined with the use of Jackknife cross-validation. The main idea of Jackknife cross-validation is to find a balance between bias and variance (Munk-Nielsen, 2016). If the bandwidth is to large the regression line will underfit the data which can be seen as a large bias. If the bandwidth is to small the regression line will overfit the data and thus make it to susceptible to local variance. The Jackknife cross-validation equation is constructed like this (Munk-Nielsen, 2016):

$$CV(b) = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{h}_{[i]}(x_i)^2$$

Equation 5

Where in this case:
CV is the Jackknife cross-validation criterium which should be minimized.
N is total number of data points.
y is the determined runoff time belonging to a single point in the point cloud.
$\hat{h}$ is the expected value based on the Nadaraya-Watson estimator where observation i is not used to make the prediction.

Overfitting of the data will get punished by Jackknife cross-validation since the difference between the observed y and expected y, based on the Nadarya-Watson estimator when observation i is left out, will increase when the bandwidth gets too small.

Some data points in Figure 26 are located quite far away from the regression line and the other data points as a whole. To make sure that as many incorrectly estimated runoff times are not used in the construction of the regression line, the top 5% data points that deviate the most from the regression line will be removed from the data. A new regression line will then be constructed with the remaining data (see Figure 27).

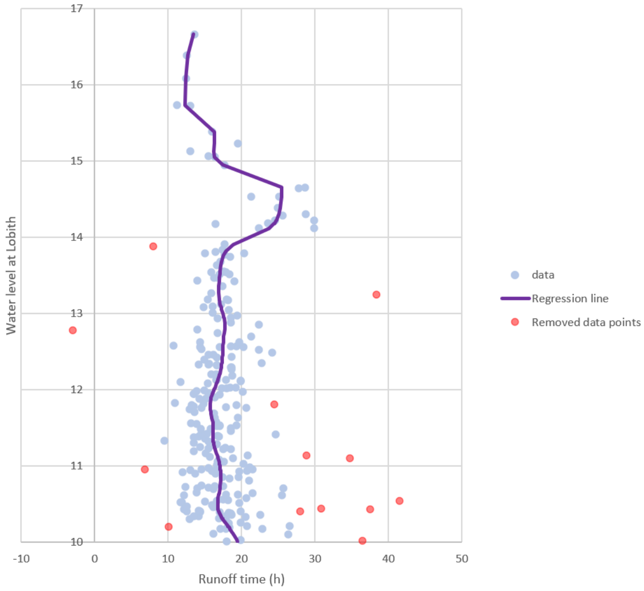

Figure 27 - Regression line after removing outliers (Lobith Zaltbommel 1985 – 2009)

3.6 Confidence interval around regression line

The very last step will be to construct a confidence interval (95%) around the regression line. This confidence interval is obtained by applying a method called bootstrap. With bootstrap a separate set of data is created in which the data points are random copies of the original data set. The method starts by picking a random data point from the data set after which it is copied to the bootstrap sample. This is repeated till the size of the bootstrap sample is equal to the size of the original data set (Fook Chong & Choo, 2011). Because every data point is picked randomly, the chances are very high that some data points will be copied multiple times while others are not copied at all. In order to create a confidence interval, multiple of these bootstrap samples have to be created. For every single bootstrap sample the Nadaraya-Watson estimator (see equation 3) is then used to create a regression line (Chen, 2017).

$$\bar{\hat{m}}^{*}_{h,B}(x) = \frac{1}{B}\sum_{l=1}^{B} \hat{m}_h^{*(l)}(x) \qquad \text{Equation 6}$$

$$\widehat{Var}_B\big(\hat{m}_h(x)\big) = \frac{1}{1-B}\sum_{l=1}^{B}\left(\hat{m}_h^{*(l)}(x) - \bar{\hat{m}}^{*}_{h,B}(x)\right)^2 \qquad \text{Equation 7}$$

Where:
B is number of bootstrap samples.
x is the water level.
$\hat{m}_h^{*(l)}(x)$ is the regression value of bootstrap sample l at x.
$\bar{\hat{m}}^{*}_{h,B}(x)$ is the average regression value of all bootstrap samples at x.
$\widehat{Var}_B\big(\hat{m}_h(x)\big)$ is the variance of the regression value of all bootstrap samples at x.

The confidence interval can then be calculated with Equation 8. For the equation to be true it is important to under smooth the data (Chen, 2017). Therefore the bandwidth used for the bootstrap samples is 4 times smaller than the ideal bandwidth obtained from Jackknife cross-validation.

$$\hat{m}_h(x) = \pm z_{1-\frac{\alpha}{2}} \sqrt{\widehat{Var}_B\big(\hat{m}_h(x)\big)} \qquad \text{Equation 8}$$

Where:
$\hat{m}_h$ is the confidence interval
z is the confidence coefficient
$\widehat{Var}_B\big(\hat{m}_h(x)\big)$ is the variance of the regression value of all bootstrap samples at x.

A total of 500 bootstrap samples are used to calculate the final confidence interval (see Figure 28) since the confidence interval does not converge any further when more than 500 samples are used.

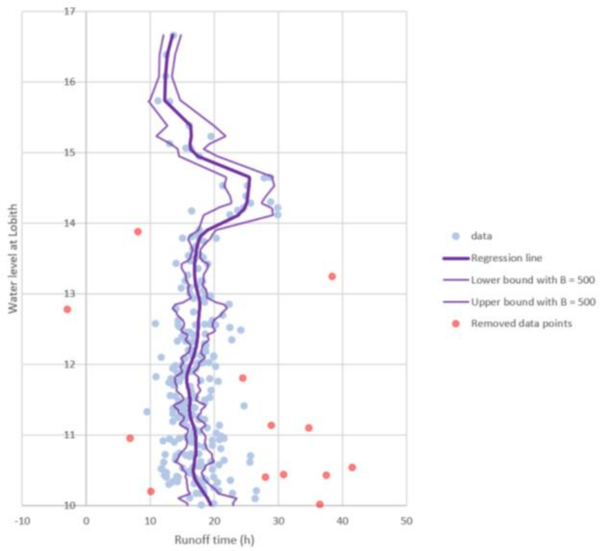

Figure 28 - Confidence interval with 500 bootstrap samples

3.7 Sensitivity analysis

There are two important parameters that have be described earlier on in this chapter. These are the kernel regression bandwidth used to smoothen the water level data (discussed in section 3.2) and the constant that is used to reduce the distance underneath the peak at which the runoff time is calculated. A sensitivity analysis will be conducted to see how the final relation between the runoff time and the water level is influenced when the values of these parameters are altered. The sensitivity analysis will be conducted with the data collected between 2011 and 2019 at Lobith and Nijmegen. In the base scenario, the kernel regression bandwidth and the constant have a value of 20 and 1.096 respectively. Four other scenarios will be evaluated in which the value of one of the two parameters is either increased or decreased. For the kernel regression bandwidth these values are 7 and 33. For the constant these values are 1.04 and 1.15. The results for this are given in section 4.7.

4 Results

The structure of the results chapter is following: Section 4.1 shows the validation step for the method which is used to link individual discharge waves between measuring stations. Section 4.2 provides an overview of the different value for the constant introduced in section 3.4. In section 4.3 a justification is given for the criterium used to calculate runoff time of individual discharge waves. In section 4.5 we will take look at water level graphs of individual discharge waves with unusual runoff times. This will give more insight into the possible flaws of the methodology. Section 4.6 shows the relations obtained between runoff time and water level at a few selected measuring stations. Finally, in section 4.7 the results of the sensitivity analysis are given.

4.1 Linking of peaks – validation

The script was calibrated with the data collected by the measuring stations near Lobith and Nijmegen in 2018. Water level data collected near Doesburg and Zutphen in 2011 was used to validate the script. Doesburg and Zutphen were chosen since they are located in another part of the study area where the water levels are influenced due to the inflow of the Old IJssel and the Twente Canal. Since these conditions are very different, it is expected that the method will work well for the entire research area if it performs well between Doesburg and Zutphen. In Figure 29 and Figure 30 the peak and valleys that are linked by the script, using the same parameter values that were used during the calibration, are visualised. As the figures show, no peaks or valleys were wrongfully linked with one another.

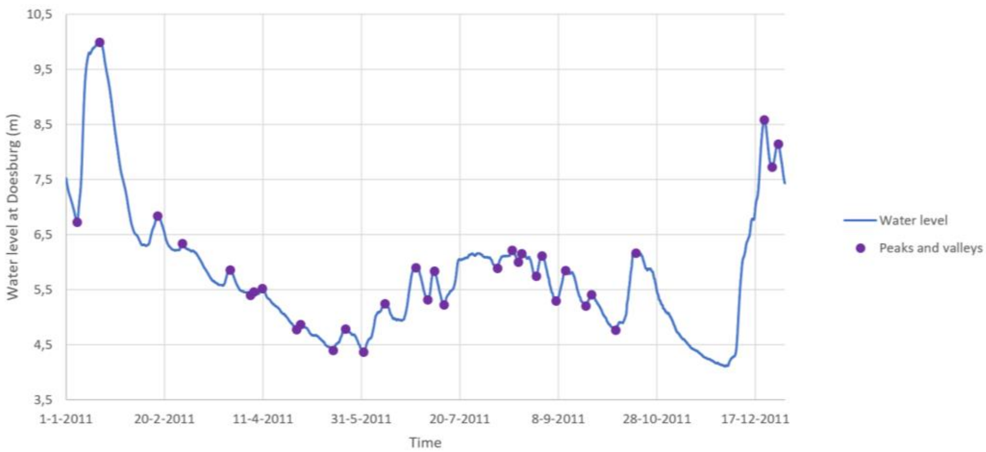

Figure 29 - Water levels at Doesburg in 2011 with isolated peaks and valleys

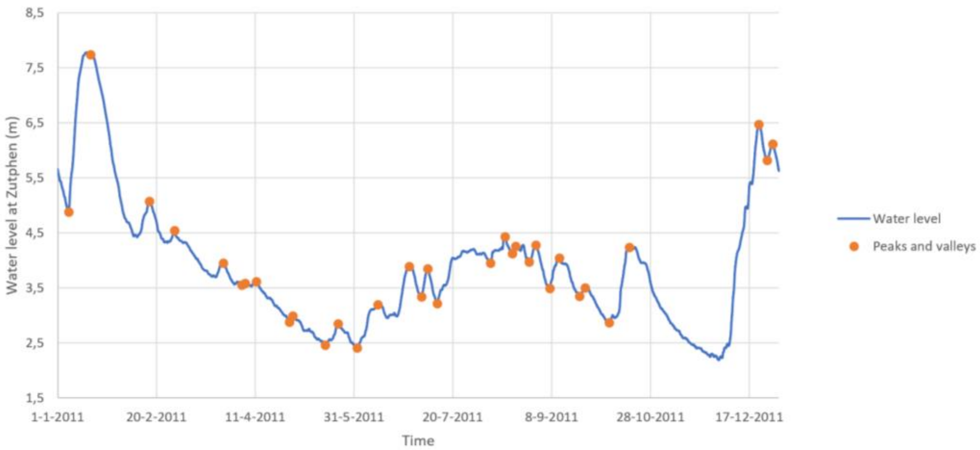

Figure 30 - Water levels at Zutphen in 2011 with isolated peaks and valleys

The peak and valley around the 4th and 6th of April are not clearly visible in Figure 29 and Figure 30 due to the length of the y-axis. Figure 31 and Figure 32 provide a better view of the situation. The figures show that the peak and valley visible at Doesburg are still visible at Zutphen and can therefore be linked. However, the effect of the lateral inflow is also clearly visible in the figures. There is some significant distortion visible in Figure 32 that is not present in Figure 31 . Although questions can definitely be raised about linking these peaks and valleys, the effects on the final results will be marginal. Peaks and valley like these are exceptions and additionally 5% of the most deviating results will not be taken into account during the final analysis.

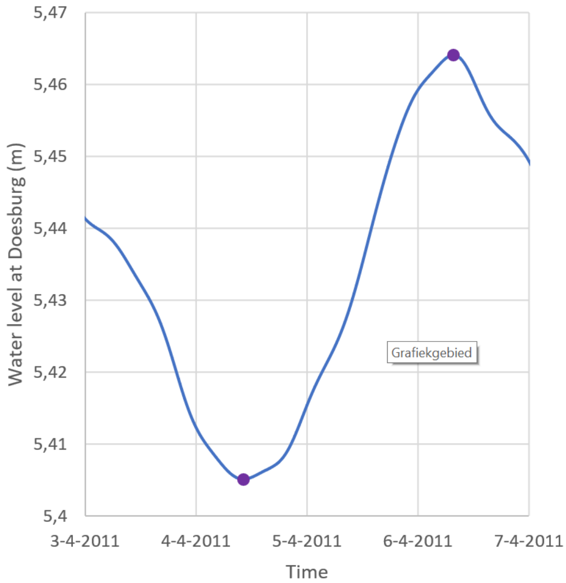

Figure 31 - Peak and Valley at Doesburg

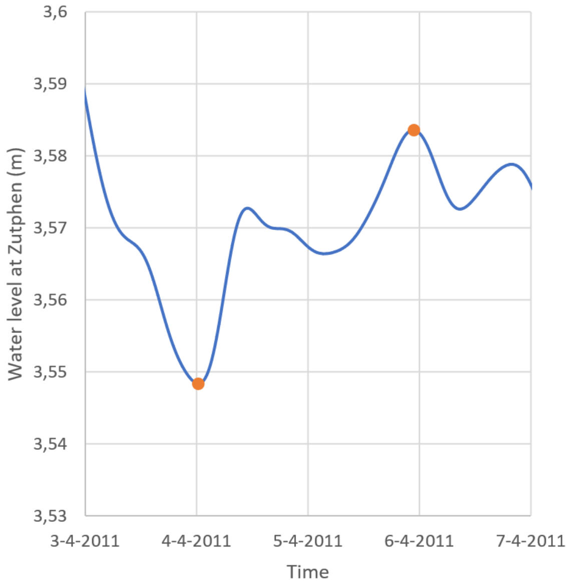

Figure 32 - Peak and Valley at Zutphen

4.2 Constants obtained from relation lines

Table 1 shows the different values used for the constant obtained from the relation lines that is used to reduce the distance underneath the water level peak at which the runoff time is determined.

Table 1 - Constants obtained from slope of relation line for each measuring station

Measuring station	Constant with regard to Lobith (used with 2011 – 2019 data)	Constant for +12m water level at Lobith (used with 1985 – 2009 data)
Pannerdense Kop	1,067	1,119
Nijmegen haven	1,096	1,143
Dodewaard	1,171	1,324
Tiel	1,176	1,256
Zaltbommel	-	1,172
Looveer Huissen	1,258	1,351
IJsselkop	1,288	1,339
Driel boven	1,495	1,495
Grebbe	1,324	1,324
Amerongen boven	1,397	1,397
Culemborg	1,215	1,215
Hagestein boven	1,141	1,141
Westervoort	1,399	1,603
De Steeg	1,492	1,972
Doesburg	1,464	1,995
Zutphen	1,566	2,397
Deventer	1,540	2,075
Olst	1,729	2,189
Wijhe	1,838	1,956
Katerveer	2,427	2,427
Kampen	2,494	2,494
Keteldiep	4,575	4,575

4.3 Justification for first criterium used in runoff time calculation

The justification for the value of 1 hour used in the criteria can be seen in Figure 33. The figure shows the confidence interval of the mean runoff time for all linked peaks and valleys between Lobith and Nijmegen in the period between 2011 and 2019. A low value will result in a wider confidence interval since substantially less linked peaks and valleys will meet the criteria. For higher values the amount of peaks and valleys that meet the criteria will be larger but the standard deviation of the runoff time will also increase. With a value of 1 hour the perfect balance between these two aspects is obtained. Figure 33 shows this since the confidence interval is the smallest when the criteria value is approximately 1 hour. This does not prove that the value of 1 hour is the optimal value to use for every measuring station but it at least shows that the value is a reasonable choice.

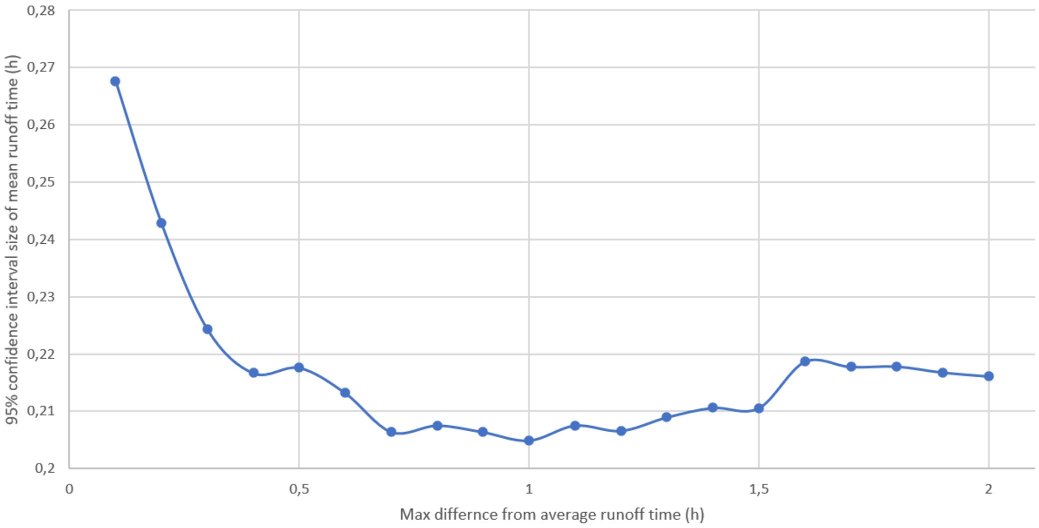

Figure 33 - Confidence interval for different values of runoff time criteria

4.4 Runoff times obtained when second criterium is excluded

Figure 34 and Figure 35 show the results obtained when the second criterium (meant to only include water levels peaks that maintain their shape between two measuring stations) is used and not used.

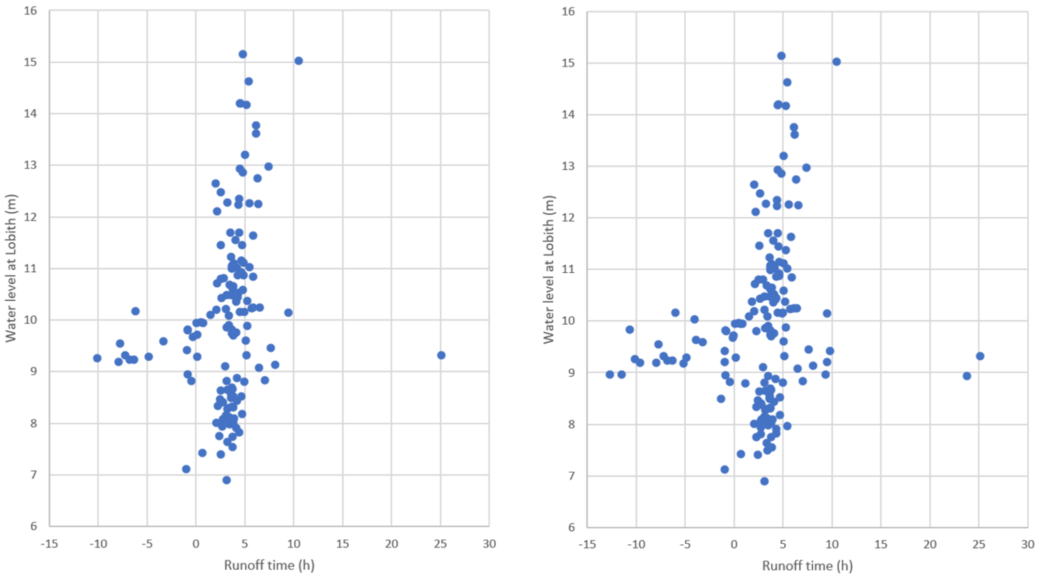

Figure 34 - Runoff time results between Lobith and IJsselkop. With use of second criterium (left) and without use of second criterium (right)

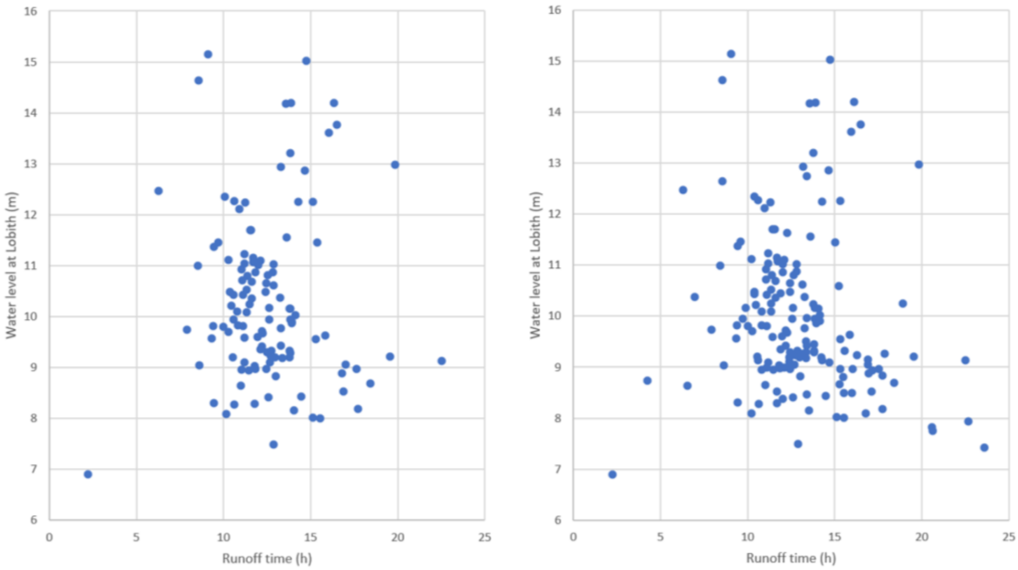

Figure 35 - Runoff time results between Lobith and Tiel. With use of second criterium (left) and without use of second criterium (right)

Both figures show that some spread is eliminated by using the second criterium. However, a substantial amount of data points that do not add to the spread are also removed. This is most noticeable in Figure 35 between a water level of 8 and 10 m at Lobith.

4.5 Shapes of individual discharge waves with unexpected runoff times

In this section we will take a look at the actual shape of discharge waves for which runoff times are determined. Visualising these waves will give more insight into the performance of the methodology. The discharge waves discussed here have been observed between Westervoort and Doesburg, Doesburg and Zutphen as well as IJsselkop and Driel boven. These locations where chosen because there is a significant amount of spread in the results with sometimes extremely large and even negative runoff times. Figure 36 shows the discharge valleys for which the runoff time is determined between Westervoort and Doesburg in the time period 2011 till 2019. Figure 37 is similar but shows the discharge peaks instead. From both figures the individual discharge waves with the lowest and highest runoff time are coloured orange and they are visualised in Figure 38 till Figure 41.

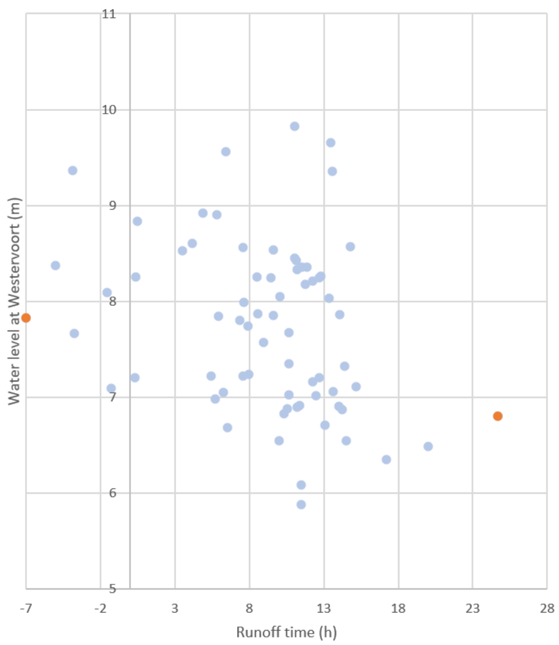

Figure 36 - Point cloud of water level valleys (Westervoort - Doesburg, 2011 - 2019 data)

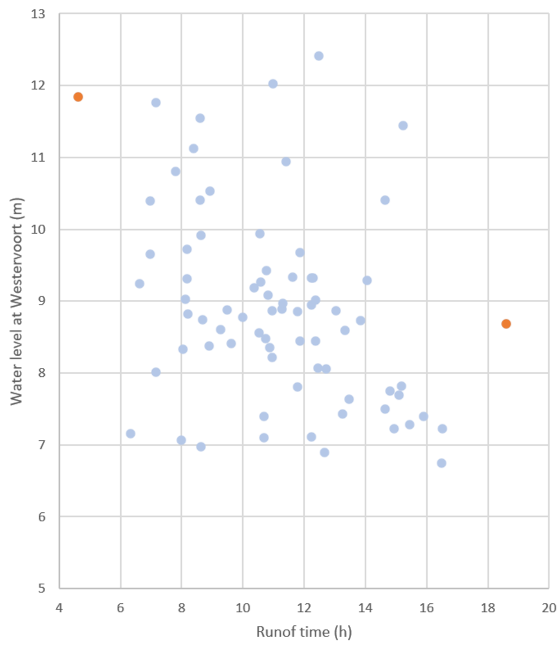

Figure 37 - Point cloud of water level peaks (Doesburg - Zutphen, 2011 - 2019 data)

The calculated runoff time for the discharge valley in Figure 38 is -7 hours. Initially one would expect that there is a mistake in methodology leading to this results. The figure however shows that the valley at Doesburg happens earlier in time than the valley at Westervoort. A discharge wave coming from the Old IJssel river is the most likely explanation for this phenomena. If such a wave arrives just before the actual valley at Doesburg, the valley will happen earlier in time.

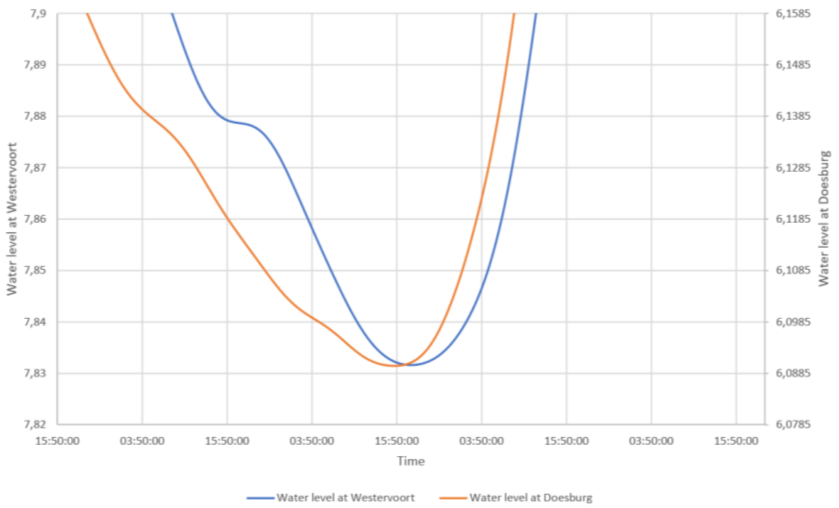

Figure 38 - Water level valley at Westervoort and Doesburg (October of 2015)

The calculated runoff time for the discharge valley in Figure 39 is 24.7 hours. Both graphs have very similar shapes and the runoff time thus seems to be calculated correctly.

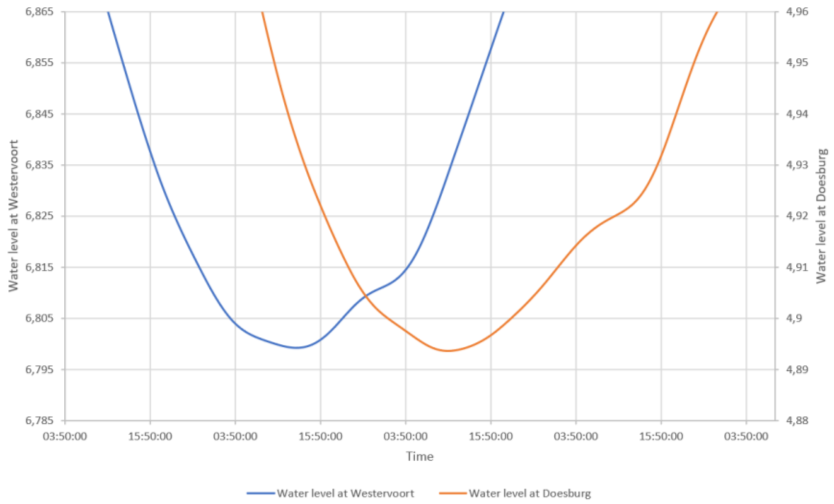

Figure 39 - Water level valley at Westervoort and Doesburg (August of 2015)

4.6 hours is the calculated runoff time for the discharge peak in Figure 40. The peak seems to have flattened quite a lot between the two stations but due to the symmetrical shape of the discharge wave this does not have a lot of influence on the calculated runoff time.

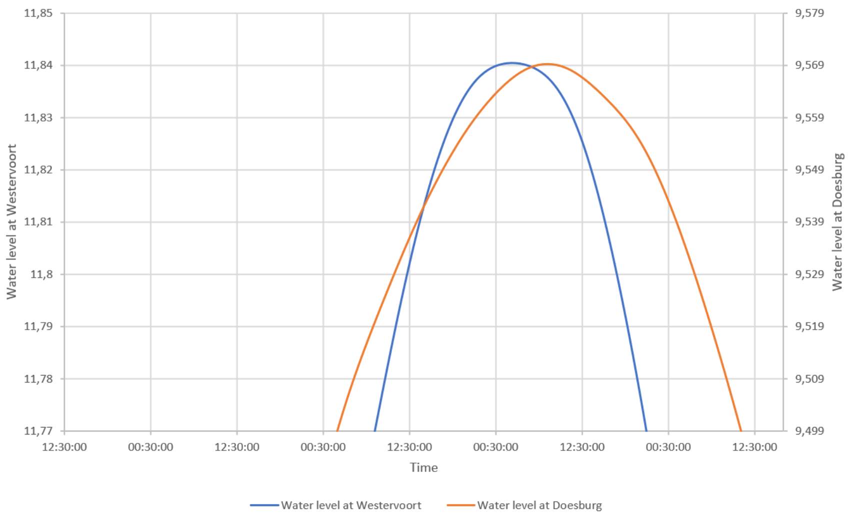

Figure 40 - Water level peak at Westervoort and Doesburg (December of 2011)

Figure 41 shows a discharge peak with a calculated runoff time of 18.6 hours. The discharge wave is very similar in shape at both stations and thus the calculated runoff time seems correct.

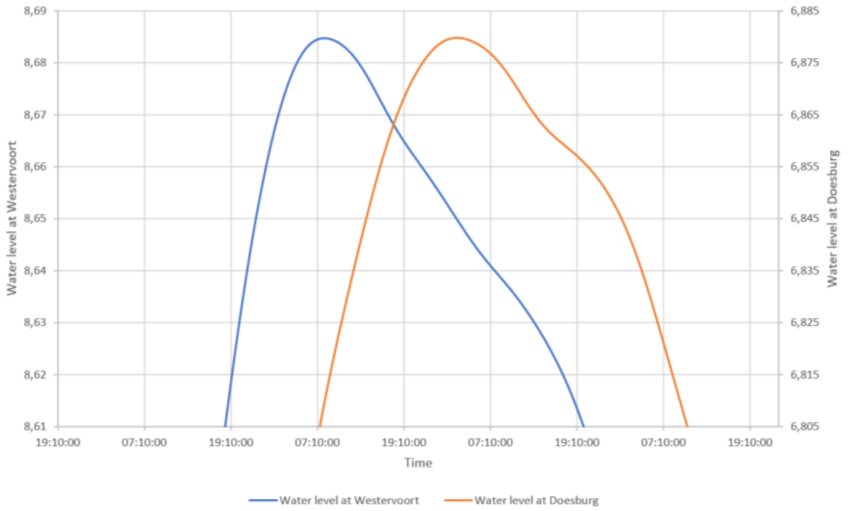

Figure 41 - Water level peak at Westervoort and Doesburg (June of 2012)

Figure 42 and Figure 43 show the runoff time calculated for individual water level valleys and peaks observed at Doesburg and Zutphen between 2011 and 2019. Again the water levels corresponding the lowest and highest runoff time in both figures will be discussed in further detail.

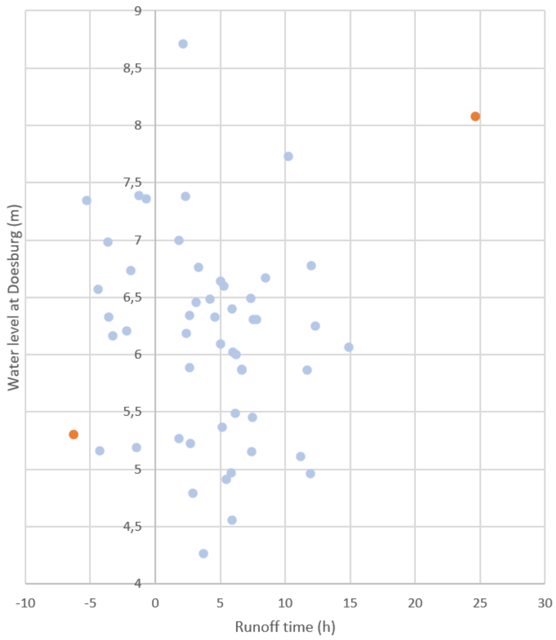

Figure 42 - Point cloud of water level valleys (Doesburg - Zutphen, 2011 - 2019 data)

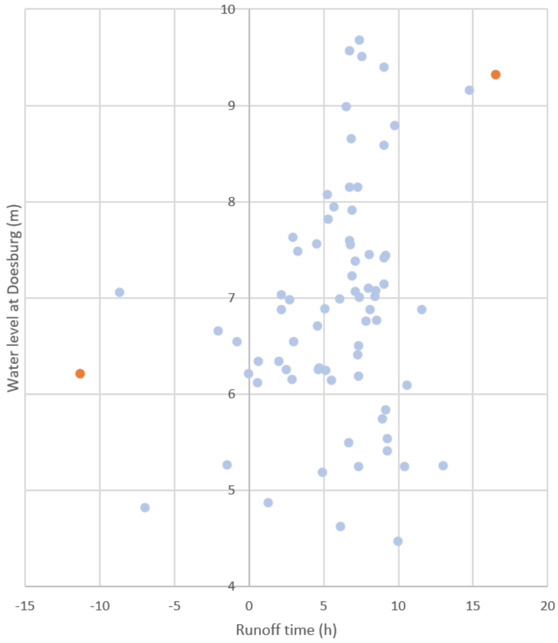

Figure 43 - Point cloud of water level peaks (Doesburg - Zutphen, 2011 - 2019 data)

The calculated runoff time for the water level valley in Figure 44 is -6.3 hours. The peak of the discharge wave at Zutphen arrives later than at Doesburg but the water level at Doesburg does not decline as fast. A discharge wave from the Old IJssel river arriving at Doesburg just after the peak could be a potential explanation for this but it remains speculation.

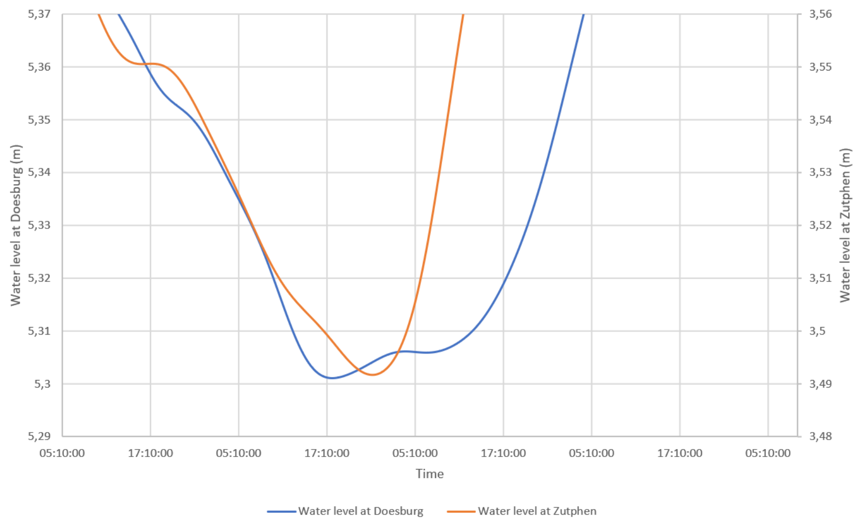

Figure 44 - Water level valley at Doesburg and Zutphen (August of 2011)

Figure 45 shows how the runoff time is mistakenly determined to be 24.7 hours. A small peak possibly caused by water coming from the Twente Canal and arriving at Zutphen delays the lowest water level valley by multiple hours. Coincidentally, the shape of the water level graph is similar in shape to the water level graph of Doesburg.

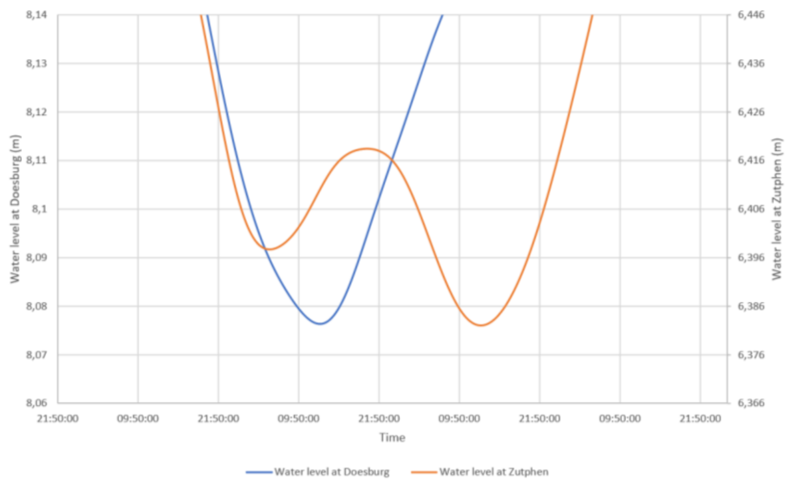

Figure 45 - Water level valley at Doesburg and Zutphen (January of 2018)

The runoff time calculated for water level peak in Figure 46 is -11.3 hours. The water level at Zutphen tends to decline more rapidly than the water level at Doesburg. This is unexpected behaviour since Zutphen is located downstream of Doesburg and discharge waves tend to flatten when the travel downstream.

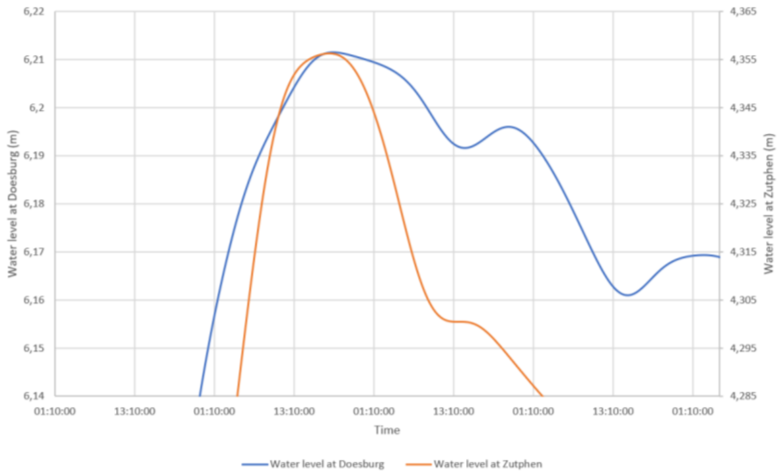

Figure 46 - Water level peak at Doesburg and Zutphen (April of 2014)

The runoff time belonging the water level peaks in Figure 47 is 16.5 hours. The almost identical shape of the two graphs gives no reason to doubt that this is a very good approximation of the actual runoff time.

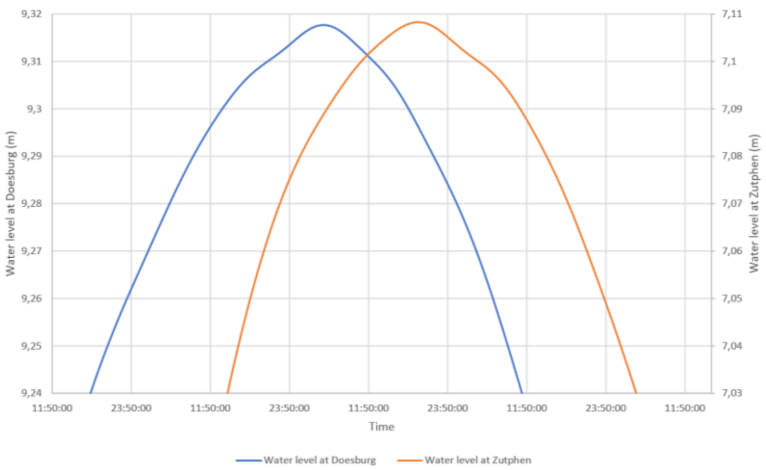

Figure 47 - Water level peak at Doesburg and Zutphen (May of 2013)

Figure 42 and Figure 43 show the runoff time calculated for individual water level valleys and peaks observed at IJsselkop and Driel boven between 2011 and 2019. Both figures show the increased amount of spread between roughly 8 to 9.5 meter of water level at IJsselkop. The peaks and valleys with the lowest and highest runoff time will be discussed at in more detail.

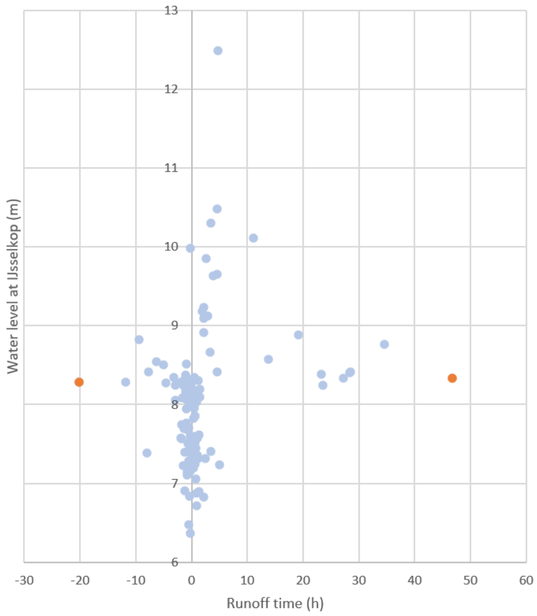

Figure 48 - Point cloud of water level valleys (IJsselkop – Driel boven, 2011 – 2019 data)

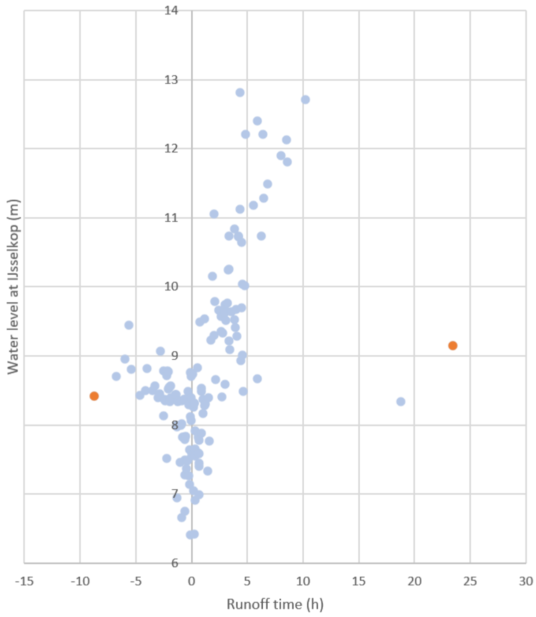

Figure 49 - Point cloud of water level peaks (IJsselkop - Driel boven, 2011 - 2019 data)

A runoff time of -20.1 hours belongs to the two linked valleys in Figure 50. The figure shows the impact of the weir management on the water levels. The water level at Driel boven is rising much faster than the water level at IJsselkop. This gives the impression that a discharge wave is arriving at Driel boven and afterwards at IJsselkop while in reality no such discharge wave exists.

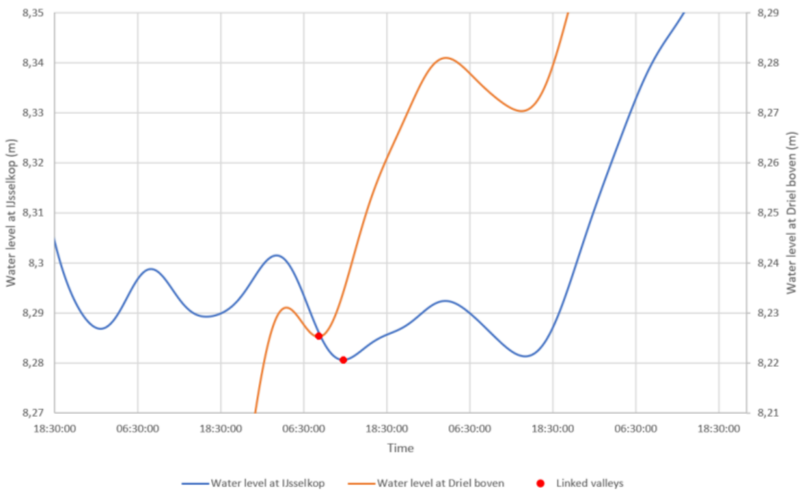

Figure 50 - Water level valley at IJsselkop and Driel boven (July of 2017)

Figure 51 shows an equally strange situation caused by weir management. A 46.7 hours runoff time is calculated for the two valleys in the figure. In reality the valley at Driel boven occurs before the valley at IJsselkop occurs. These two valleys were not linked since the other valley at Driel boven is at a lower water level. A steep decline in the water level at Driel boven, caused by in increased throughput at the weir, is the reason these two valleys were linked.

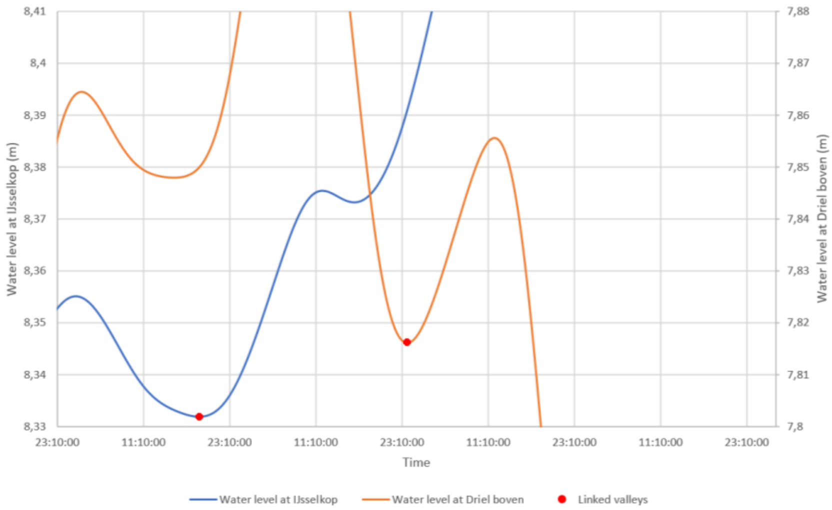

Figure 51 - Water level valley at IJsselkop and Driel boven (February of 2011)

The runoff time calculated for the water level peaks in Figure 52 is -8.7 hours. The figure shows that a water level peak is present a Driel boven before the other water level peak is present at IJsselkop. The adjustment of the discharge throughput at the weir is the most likely explanation for this phenomena.

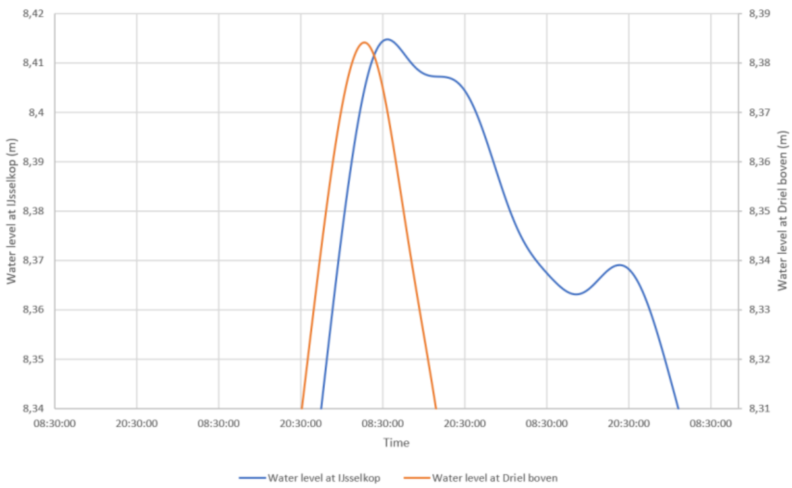

Figure 52 - Water level peak at IJsselkop and Driel boven (July of 2013)

23.9 hours is the calculated runoff time between the two water level peaks in Figure 53. The two peaks seem to be correctly linked at first sight. However, the three small peaks at the bottom of the figure show that the weir at Driel is adjusting the water level artificially. The runoff time of almost 24 hours is mostly likely a results of this.

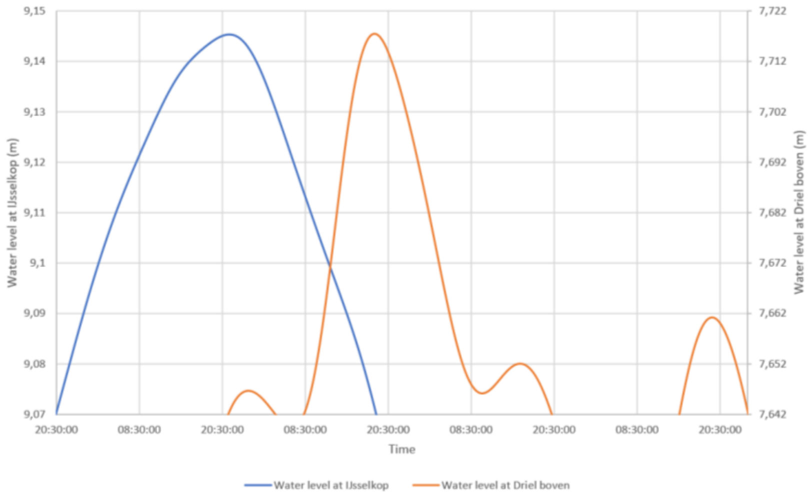

Figure 53 - Water level peak at IJsselkop and Driel boven (September of 2012)

4.6 Relation between runoff time and water level for a few selected measuring stations

In this section, the runoff time results obtained between a few selected measuring stations in the study area will be discussed. The selected stations are located in different parts of the study area so that the various factors that influence the runoff time can all be seen and discussed. The locations of these measuring stations can be seen in Figure 54. The results for all the measuring stations individually are given in the appendix (page 54). In this section the results for the two different datasets are presented separately. This is done to show the added value of including the water level data measured between 1985 and 2009. The results for the combined datasets are presented in the appendix.

Figure 54 - Measuring stations for which the relation between runoff time and water level is discussed

The relation between the runoff time and the water level between Lobith and Nijmegen is shown in Figure 55 and Figure 56. The most striking feature in these two figures is the increase of the runoff time above a water level of 13 m at Lobith and a later decrease just below 15 m of water level. In this water level range the river water flows into the floodplains. When the floodplains start to fill the amount of friction per volume of water will increase and thus slow down the discharge wave. When the floodplains are filled even further the amount of friction per volume of water starts to decrease again and runoff time will decrease as well.

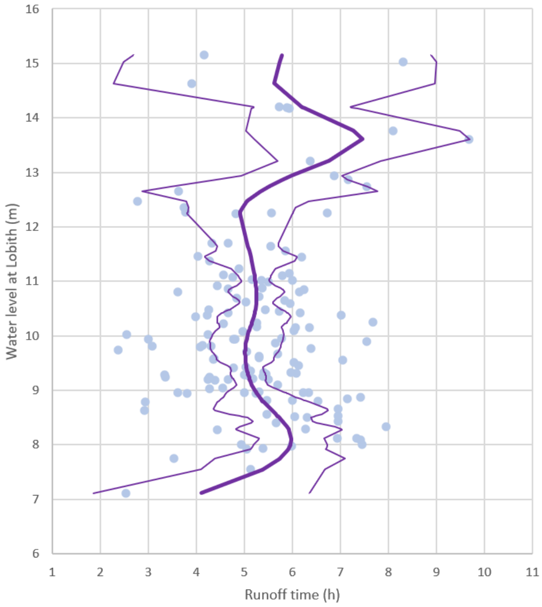

Figure 55 - Relation between runoff time and water level (Lobith - Nijmegen haven, 2011 - 2019 data)

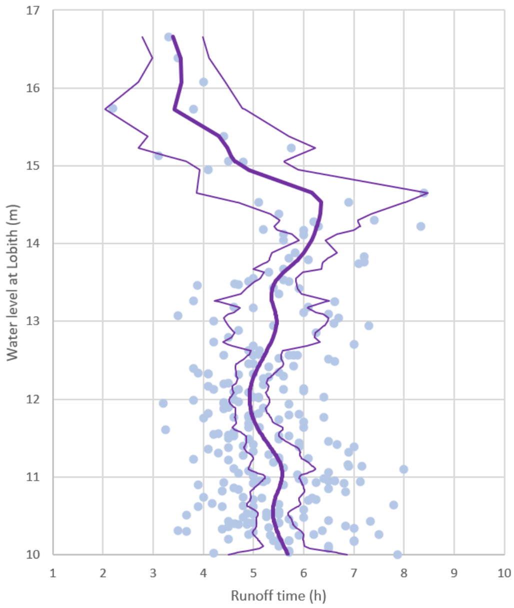

Figure 56 - Relation between runoff time and water level at high discharges (Lobith - Nijmegen haven, 1985 - 2009 data)

Figure 57 and Figure 58 show the runoff time-water level relation between Lobith and Driel. Due to the presence of the weir near Driel, calculated runoff times are often far from the actual runoff time value. This can clearly be seen in Figure 57 at the water level range of 9 to 10 m. At water levels above 10 me the weir will open completely making it possible to determine the relation far more accurately. In Figure 58 a similar relation can be seen as is shown in Figure 56. Here, the effect of the floodplain increasing the runoff time of discharge waves is even more distinct than near Nijmegen.

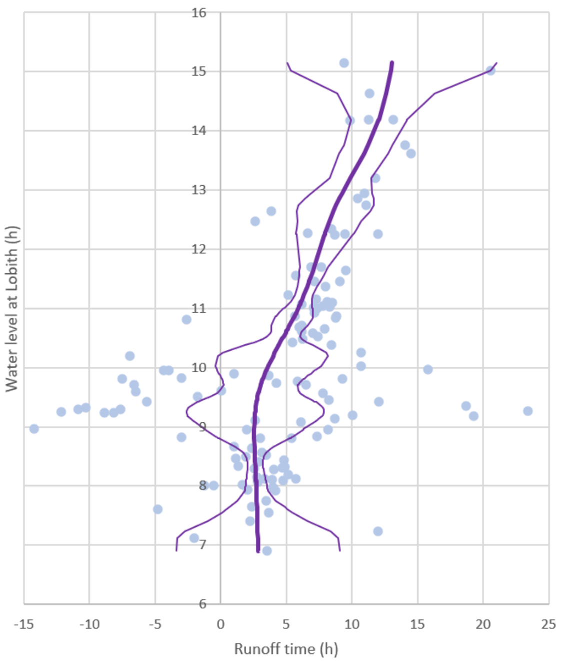

Figure 57 - Relation between runoff time and water level (Lobith - Driel boven, 2011 - 2019 data)

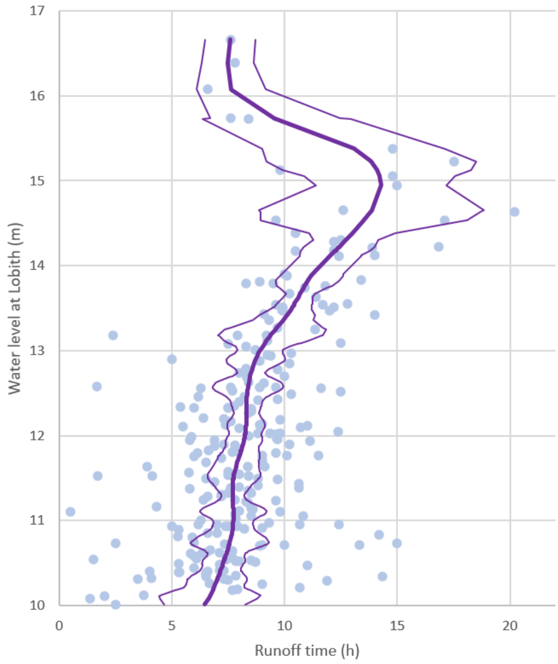

Figure 58 - Relation between runoff time and water level at high discharges (Lobith - Driel boven, 1985 - 2009 data)

The results obtained between Lobith and Doesburg are given in Figure 59 and Figure 60. Figure 59 gives the misleading suggestion that the runoff time is lower around a water level of 9 m compared to higher and lower water levels. What actually happens is that the weir management on the Nederrijn is operating in such a way that the discharge on the IJssel remains constant. The system observes the discharge coming from Lobith and the weirs are adjusted based on this input. The actual expected runoff time is probably similar to the values obtained around 8 and 11 m which is approximately 17 hours. The effect of the floodplains in Figure 60 is far more subtle than in Figure 56 and Figure 58. The most striking thing is the spread in the point cloud of individual discharge waves. The lateral inflow of the Old IJssel river is most likely the cause for this increased spread compared to Nijmegen and Driel. When water gets added to the system, the peak of a discharge wave can be delayed or arrive earlier in time depending on when the water enters the system. Since this effect works in two directions the regression line will still be good approximation of the actual expected runoff time when no lateral inflow is present.

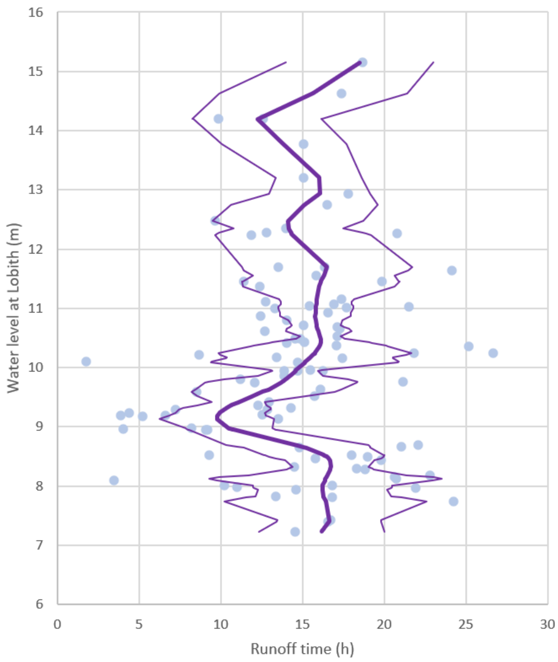

Figure 59 - Relation between runoff time and water level (Lobith - Doesburg, 2011 - 2019 data)

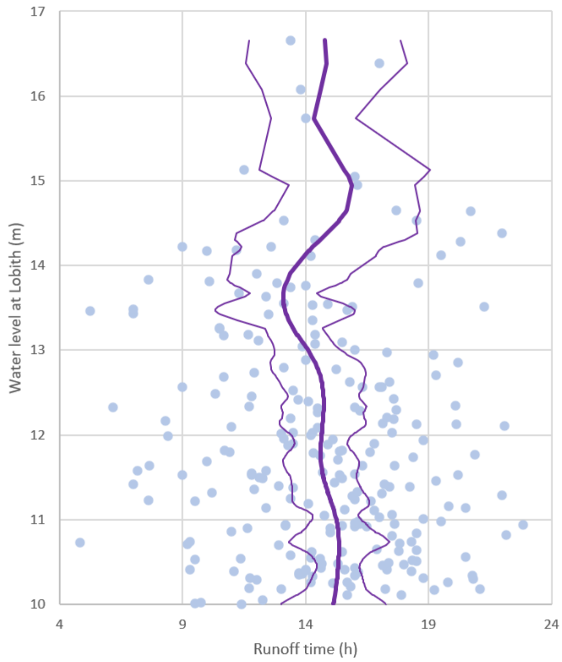

Figure 60 - Relation between runoff time and water level at high discharges (Lobith - Doesburg, 1985 - 2009 data)

Figure 61 shows the point cloud representing all the individual discharge waves for which a runoff time is determined between Wijhe and Katerveer. The point cloud looks very different compared to the ones we have seen previously. Above a water level of 3 m at Wijhe the average runoff time is 6.7 hours which seems like a plausible result. Below this water level and especially below a water level of 1 m at Wijhe, a lot of negative runoff time results can be seen. This is most likely due to the influence that the dynamics of Lake IJssel have on both of these measuring stations. It is expected that the strong winds above the lake push water into the IJssel river creating waves that travel upstream. The point spread in Figure 61 is thus probably a mix of downstream traveling waves coming from the upstream areas and upstream traveling waves coming from Lake IJssel.

Figure 61 - Relation between runoff time and water level (Wijhe – Katerveer, 2011 – 2019 data)

4.7 Sensitivity analysis results

This section contains the results of the sensitivity analysis.

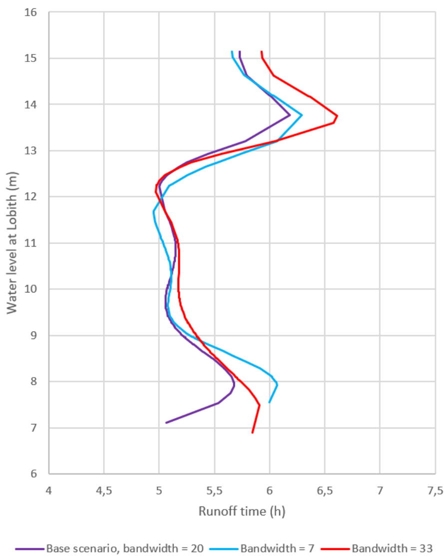

Figure 62 - Change of regression line by altering regression bandwidth value

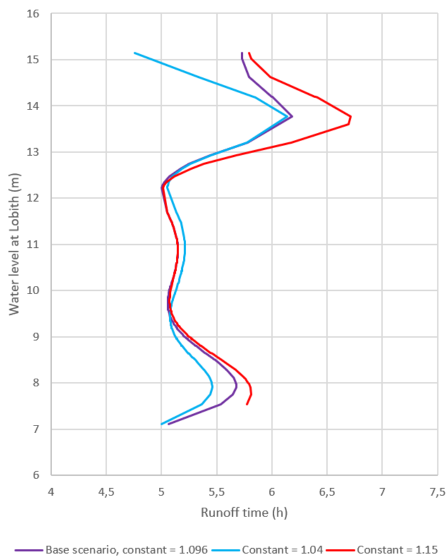

Figure 63 - Change of regression line by altering the distance underneath the peak at which the runoff time is determined

Figure 62 and Figure 63 show the regression lines for the base scenario as well as the scenarios in which the parameter values are reduced and increased. It can clearly be seen that regression lines are very similar to the base scenario in 9 to 13 m water level range. Below 9 m and above 13 m the regression lines start to deviate significantly from the base scenario. The amount of discharge peaks width a maximum height below 9 meter and above 13 is substantially lower than in between those two water levels. This explains why the regression lines deviate a lot at the ends of the spectrum. The absence of one data point has a significant effect on regression line that is constructed.

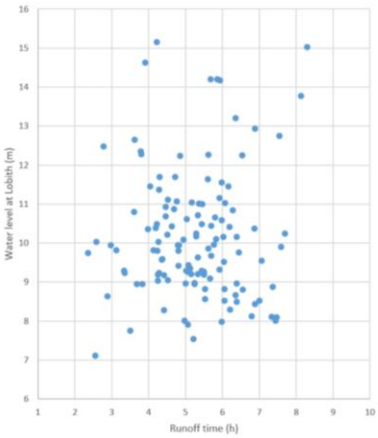

Figure 64 - Point cloud of discharge peaks - Base scenario

When we look at the point clouds in Figure 64 till Figure 68 we can see that the data points above 13 m do not change a lot in the different scenarios. The biggest contribution to the differences in Figure 62 and Figure 63 is absence of some data points. The absence of a data point between water levels of 9 and 13 m is less visible in the regression lines due to the larger number of data points in this range.

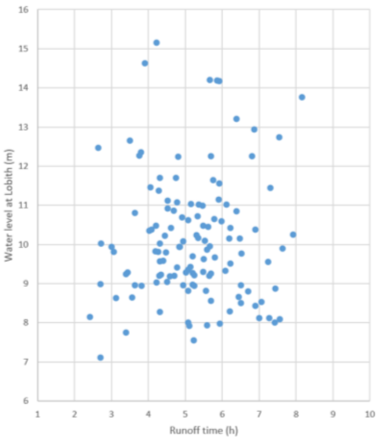

Figure 65 - Point cloud of discharge peaks - Constant = 1.04

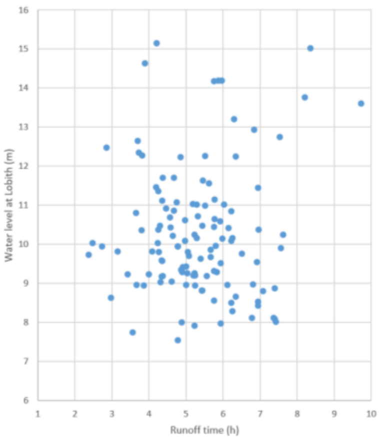

Figure 66 - Point cloud of discharge peaks - Constant = 1.15

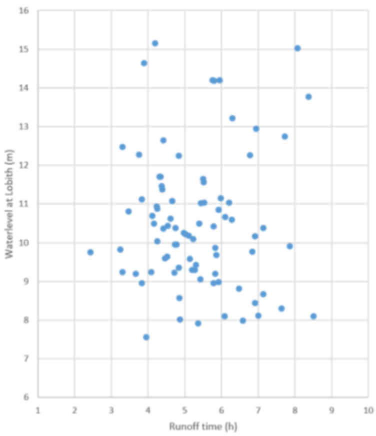

Figure 67 - Point cloud of discharge peaks - Bandwidth = 7

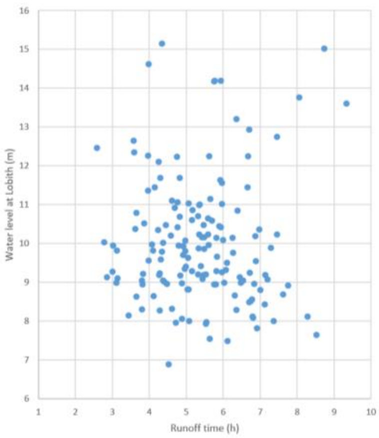

Figure 68 - Point cloud of discharge peaks - Bandwidth = 33

In Table 2 the average runoff time value at three different water level domains for the five different scenarios are given. Table 3 shows the standard deviations. The averages and standard deviations are calculated with the data points presented in Figure 64 till Figure 68.

Table 2 - Average runoff time in hours at three different water level domains for five scenarios

Water level domain	Base scenario	Constant = 1.04	Constant = 1.15	Bandwidth = 7	Bandwidth = 33
Below 9 m	5.62	5.35 (-4.8%)	5.80 (+3.2%)	6.06 (+7.8%)	5.76 (+2.5%)
Between 9 and 13 m	5.04	5.12 (+1.6%)	5.05 (+0.2%)	5.00 (-0.8%)	5.15 (+2.2%)
Above 13 m	5.52	5.35 (-3.1%)	5.74 (+4.0%)	5.74 (+4.0%)	5.65 (+2.4%)

Table 3 - Standard deviation in hours at three different water level domains for five scenarios

Water level domain	Base scenario	Constant = 1.04	Constant = 1.15	Bandwidth = 7	Bandwidth = 33
Below 9 m	1.37	1.54 (+12.4%)	1.29 (-5.8%)	1.32 (-3.6%)	1.38 (+0.7%)
Between 9 and 13 m	1.03	1.03 (+0.0%)	1.03 (+0.0%)	1.02 (-1.0%)	1.06 (+2.9%)
Above 13 m	1.67	1.60 (-4.2%)	1.89 (+13.2%)	1.64 (-1.8%)	1.87 (+12.0%)

Based on these results, the effects of altering the two parameters on the determined relationship between the water level and runoff time is substantial when a small amount of data points is used. With larger datasets the effect are minor. Only a maximum difference of 7 minutes on an average value of 5 hours is observed in the 9 to 13 m water level range. The standard deviation changes quite significantly for some of the scenario's at water levels below 9 m and above 13 m. Between 9 and 13 m the standard deviation, just like the average values, does not deviate a lot.

5 Discussion

In this chapter the results are interpreted and compared with those from the report "*Betrekkingslijnen Rijntakken versie 2018*" by van der Veen & Agtersloot. The limitations of the methodology will be discussed as well. After evaluating the results there seem to be four main factors that influence the relations obtained between runoff time and water level in the study area. Those four factors are:

- **Floodplains:** When water enters the floodplains due to water level rise, the runoff time of a discharge wave starts to increase. The surface of the floodplain provides added friction which causes the discharge wave to slow down. When the floodplains fill even further a point will get reached where friction per volume of water is maximized. Beyond this point the runoff time will start to decrease again.
- **Weir management:** The active wear management in the study area has significant influence on the calculated runoff time of individual discharge waves. The measuring stations located on the Nederrijn river experience an increased amount of spread in calculated runoff time for water level peaks between 9 and 10 m at Lobith. The influence can also be seen on the Pannerden Canal as well as on the IJssel river. The results show a large decrease of runoff time in those parts of the study area. The effect is visible in the results up until the measuring station near Doesburg.
- **Lateral inflow:** The inflow of water from the Twente Canal as well as the Old IJssel river creates a lot of spreading of runoff times for the measuring stations located on the IJssel. The added volumes of water from both flows can increase or decrease the runoff time of single discharge wave by multiple hours. Since the effect works in two directions, the relation between runoff time and water level can still be determined.
- **Lake IJssel:** Upstream travelling waves coming from Lake IJssel can reach as far as the measuring station near the city of Deventer. The results belonging to the measuring stations in this part of the delta are thus a combination of upstream and downstream traveling waves.

The main difference between the approach used in this research and the work done by van der Veen & Agtersloot in 2019 is that the runoff time is calculated for discharge waves individually instead of calculating it for entire water level domains directly. The advantage of this is that a continuous relation between runoff time and water level can be obtained. Another significant difference is that the runoff times in this research are also calculated between successive measuring stations instead of only using Lobith as a starting point. Measuring between successive stations is more accurate since water levels peaks are less likely to lose their characteristics over shorter distances resulting in fewer wrongly linked peaks.

In this research runoff time values have been calculated by observing for which duration discharge waves stay above a certain height underneath the water level peak and by comparing these results between two measuring stations. Due to flattening of discharge waves the distance underneath the peak at which the runoff time is determined differs for every station. The reality is that not every discharge wave flattens at the same rate. This means that the distance underneath the peak value should also differ for every discharge peak. The used methodology does not address this issue since it uses the same value for every discharge wave. I would thus recommend to develop a methodology which can be used to change this distance for individual water level peaks. The relation between water level and runoff time is not expected to change a lot but it could significantly decrease the amount of spread in the runoff time results. Using an incorrect distance will either results in an overestimation or an underestimation of the runoff time of an individual water level peak. The results for asymmetric water level peaks are especially sensitive to this effect.

Section 4.5 shows the methodology can produce misleading runoff time results when a discharge wave has some particular features. Although not ideal, most of these values are not used when calculating the final relation between runoff time and water level since the 5% most divergent results are removed beforehand.

Although unintended, the water level data collected between 2011 and 2019 was analysed with a criterium that isolates water level peaks that maintain a similar shape between measuring stations. There is not good substantiation for the use of this criterium. However, it is expected that the obtained relations between runoff time and water level is similar with and without the use of the criterium for three reasons. The data collected between 1985 and 2009 has not been analysed by using the criterium. Secondly, the results indicate that effect of using the criterium is minimal at higher water level peaks since these higher peaks tend keep their shape more often compared to lower water level peaks. Thirdly, the individual water level peaks that get removed by using the criterium, seem to be located quite uniformly in the data. The regression lines will thus be calculated with a smaller amount of data but they are expected to be roughly similar in shape.

The results of the sensitivity analysis indicate that the final results are not very sensitive to slight alterations of the kernel regression bandwidth, which is used to smoothen the water level data, when enough data is available. Slightly changing the distance underneath the water level peak at which the runoff time is calculated also has minimal effect for larger datasets. The results at the ends of the water level range are more susceptive due to the rather small amount of available data. The runoff times calculated for individual discharge waves do not tend to change much when the parameter values are altered. The rather strict criterium used to determine if a discharge wave will be considered in the final results has far more influence. Deleting a data point when only a small portion of data is available at a certain water level will obviously have more influence than when the dataset is larger.

When comparing the obtained relations between runoff time and water level for the different used data sets, it seems that the effect on the runoff time caused by the floodplains happens at higher water levels with the data collected between 1985 and 2009 than with the data collected between 2011 and 2019. A possible cause for this shift could be the erosion of the river bed happening in the upstream areas of the delta. Although plausible, more research is needed to test this hypothesis.

The results show that the quality of the results decreases when the water level decreases or when the distance over which the runoff time is determined increases. Discharge waves with lower water level peak values often represent a smaller body of water. This means that characteristics of such a discharge wave can change more easily when it moves downstream compared to a larger body of water. A larger distance between two measuring stations will also allow for more deformation of a discharge wave since it will take longer to travel from A to B. This explains why the results show an increased spreading of the runoff time at lower water levels and over longer distances.

6 Conclusion

The aim of this study was to determine the relationship between water level height and runoff time in the Dutch Rhine delta. The main research question was formulated in the following way:

What are the expected runoff time values at different water levels in the Dutch Rhine delta?

The most important finding is that the water level height has little impact on the runoff time at the normal water level range. However, runoff times do increase during large discharge events with high water levels. When the floodplains start to fill up the runoff time increases significantly due to the extra amount of friction that a discharge wave then will encounter. Other identified factors that influence runoff times in the delta are weir management and lateral inflow. The weir management in the delta results in increased spreading of runoff time on the Nederrijn river and a decreased runoff time on the Pannerden Canal and IJssel river. Lateral inflow from the Twente Canal and the Old IJssel river causes increased spreading of runoff times on the IJssel river.

The methodology applied in this research has two significant limitations. The first one is the quality of some of the water level data that is used. The data collected between 1985 and 2006 are supposed to be hourly measurements of the water level. However, some stations have measured water levels on a daily basis instead of an hourly basis. These sections of the data have been supplemented with interpolated values based on measurements from other stations. The other limitation can be found in the obtained relations between runoff time and water level. The weir management in the study area has such a major influence on the water levels that the calculated runoff times for some water levels at some stations is not representative for what would actually be observed without the presence of the weir management.

Besides providing a more detailed overview of the runoff times in the Dutch Rhine delta, this research introduces a methodology that can be applied elsewhere in the world to obtain similar results. Other already existing methods are used to calculate runoff times for entire water level ranges. The methodology formulated in this research can be used to obtain a continuous relation between water level and runoff time which makes it easier to identify the effects that individual factors like weir management and floodplains have on the runoff time.

A possible direction for future research would be to find correlations between the spreading of runoff times and possible factors that cause this to happen. Although this research offers expected relations between runoff time and water level it does not provide tools to make a more accurate prediction about the runoff time of a future flood wave. When the effects of factors like for instance wind, lateral inflow and the shape of a discharge wave are quantified, one might be able to narrow down the expected runoff time range of a particular discharge wave. Another direction for research, which could possibly improve the used methodology, would be to use to discharge data instead of water level data. By using discharges one can track volumes of water between measuring stations which is expected to give more reliable results than water level data can provide.

7 References

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Richards, Z., Gray, S., Varga, I., & Babister, M. (2012). How much time do we have? The variability of riverine flood wave routing speed. *Floodplain conference*, (pp. 1-7). Sydney.

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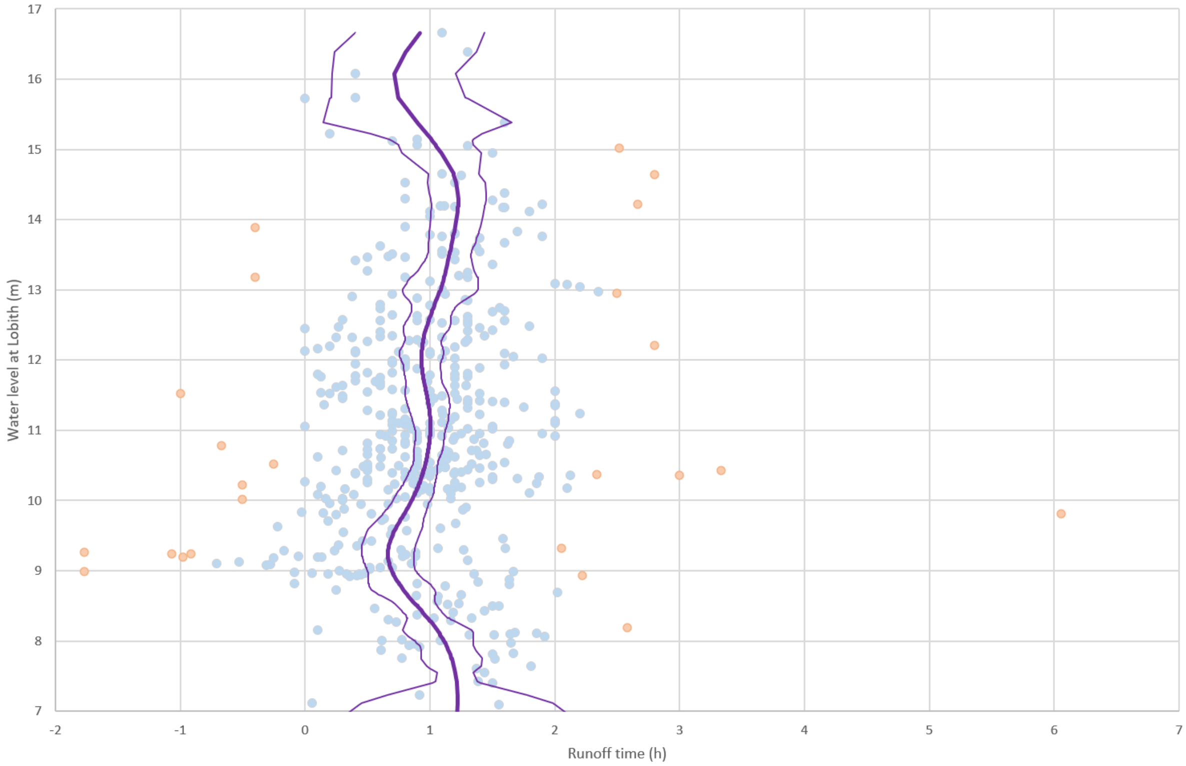
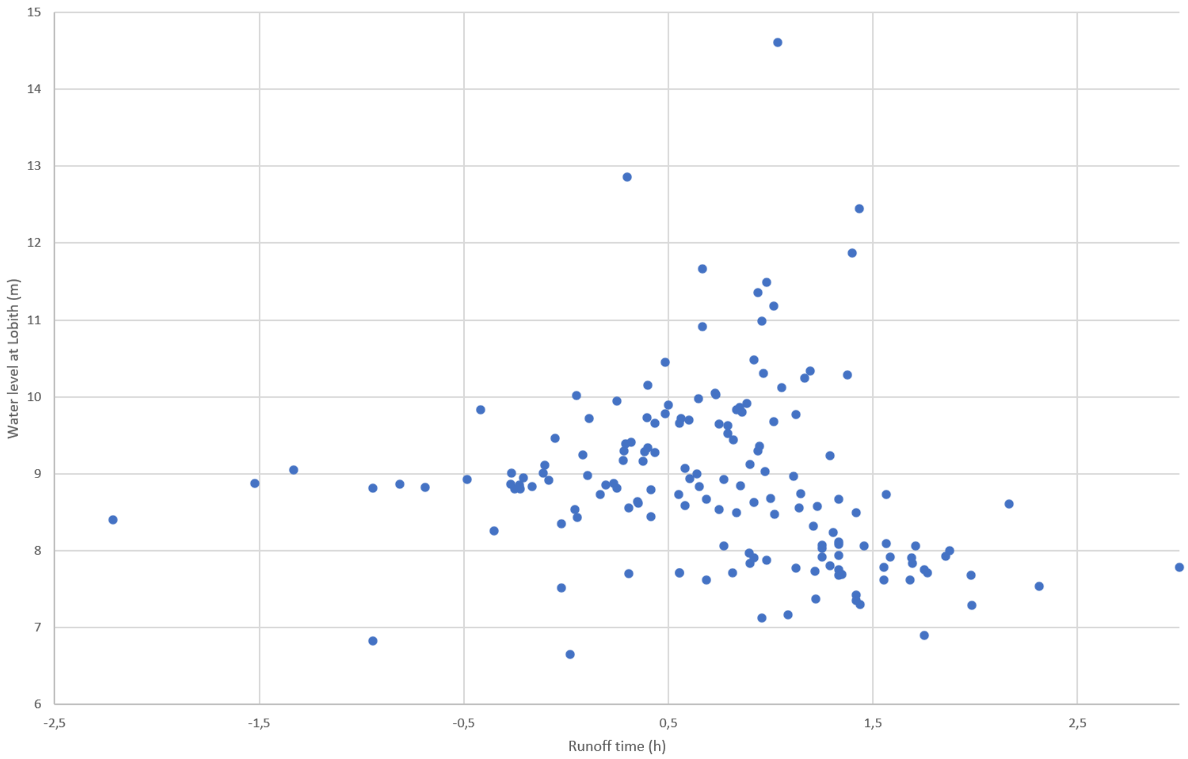
8 Appendix

The figures in the appendix that show the runoff time - water level peak relation between measuring stations in the study area contain a point cloud and a regression line. The regression lines are constructed based on the blue data points. The orange data points are excluded because they are either part of the 5% most deviating results or they are located in a water level range where the spread is considered to be too large. The titles of the figures indicate the two measuring stations, if peaks or valleys have been linked and the years in which the water level data that is used has been measured. The runoff time results for water level valleys are only presented for measuring stations where a relation between runoff time and water level is visible.

Lobith – Pannerdense kop

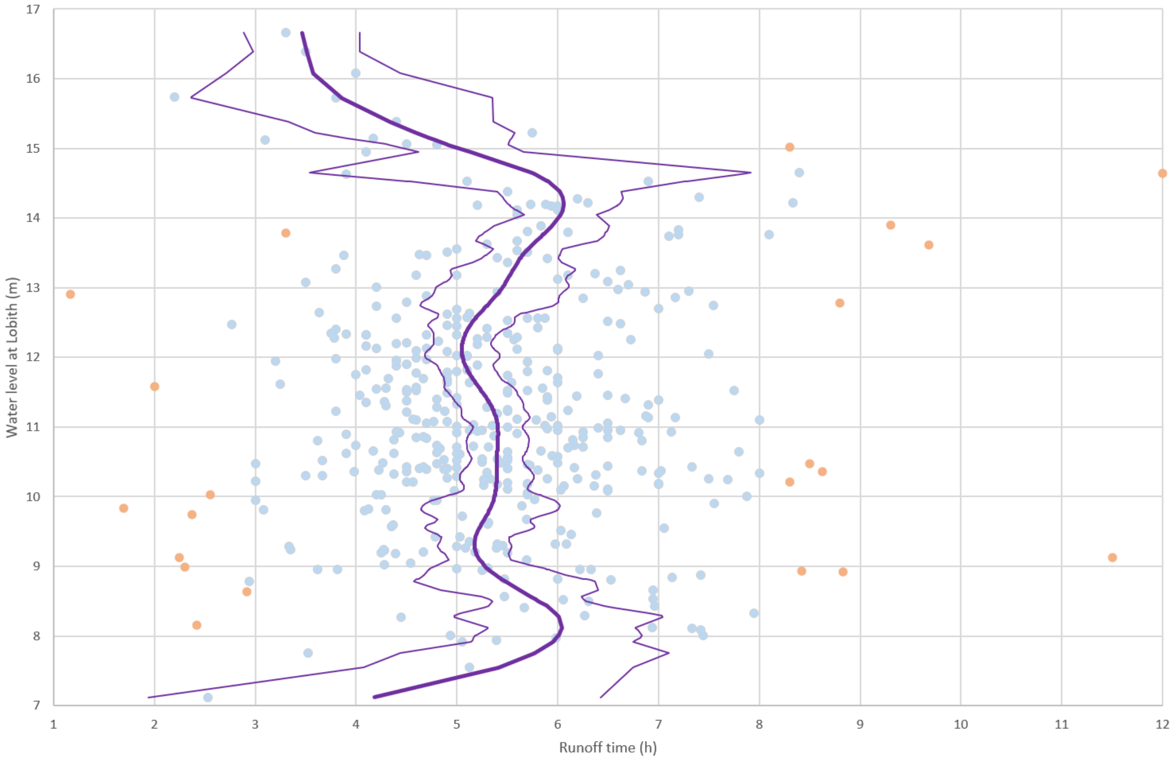


Appendix figure 1 - Lobith and Pannerdense kop (peaks, 1985 - 2019)

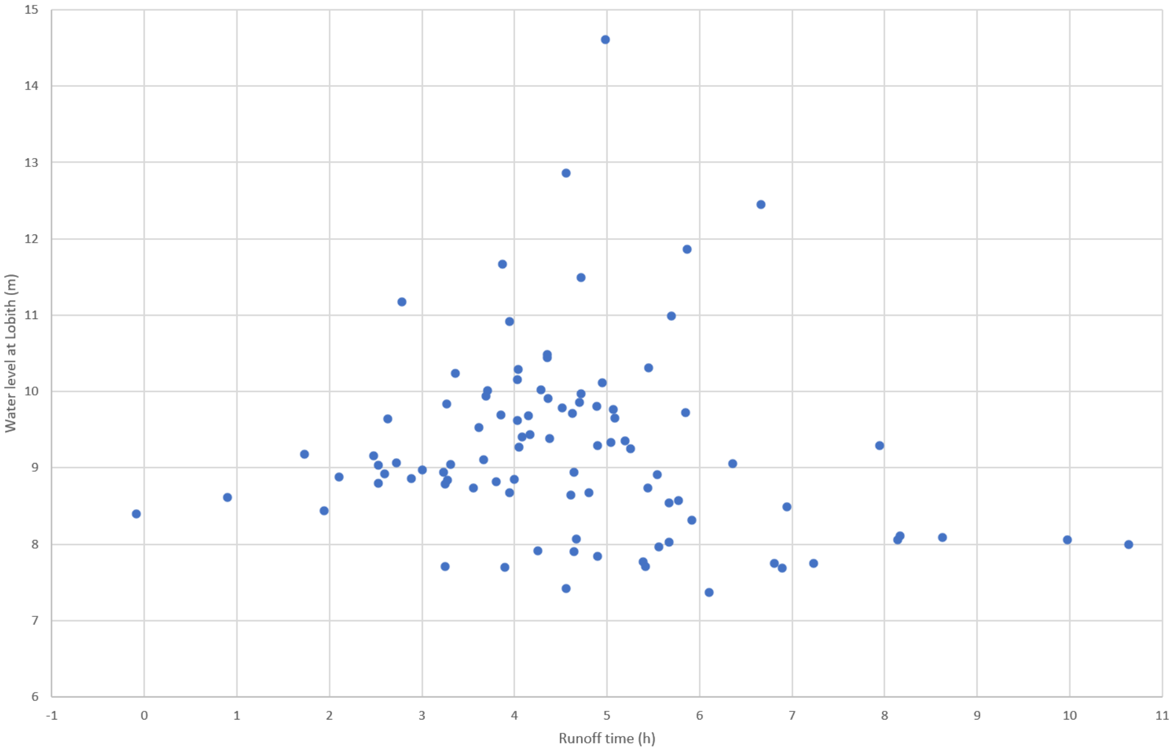


Appendix figure 2 - Lobith and Pannerdense kop (valleys, 2011 - 2019)

Lobith – Nijmegen haven

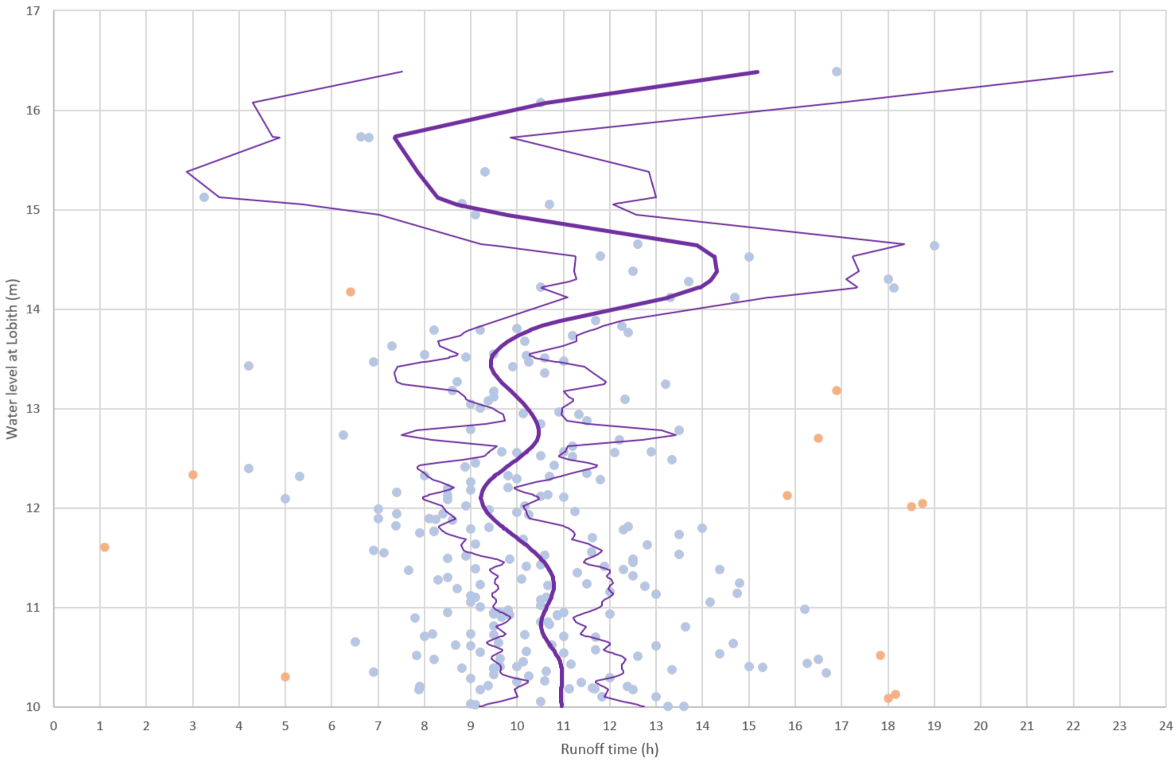


Appendix figure 3 - Lobith and Nijmegen haven (peaks, 1985 - 2019)

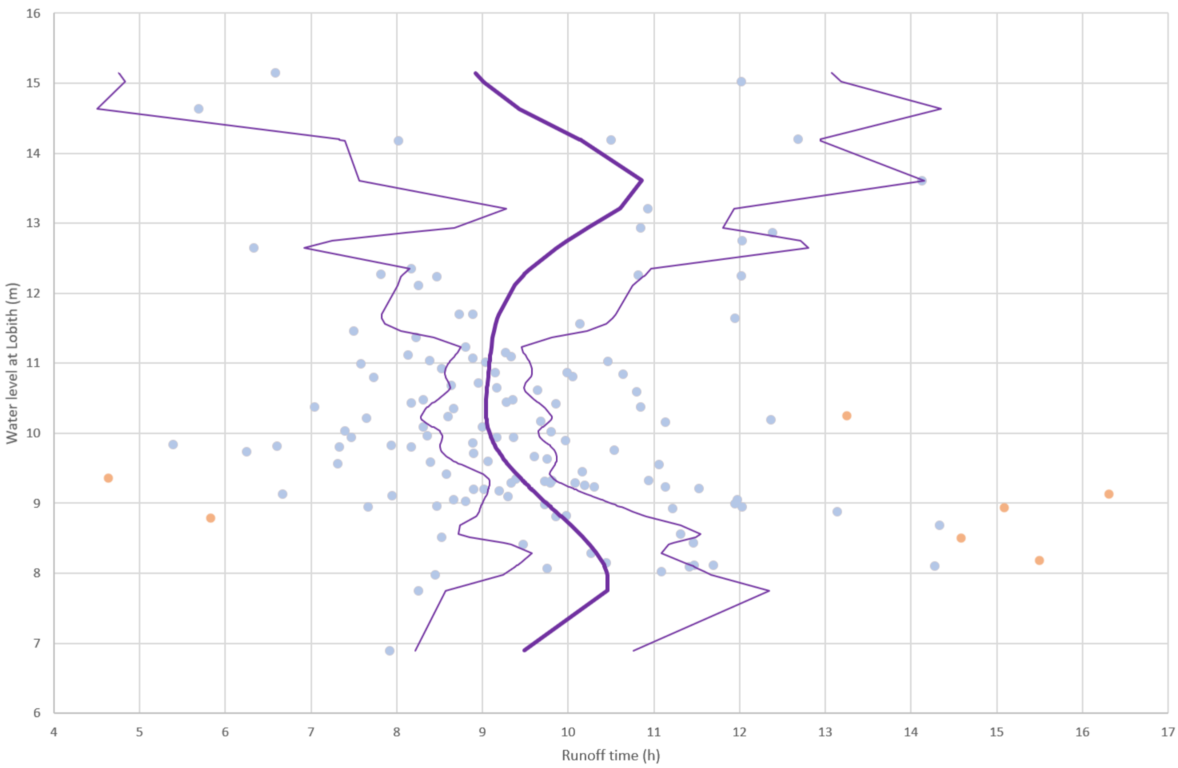


Appendix figure 4 - Lobith and Nijmegen haven (valleys, 2011 - 2019)

Lobith – Dodewaard

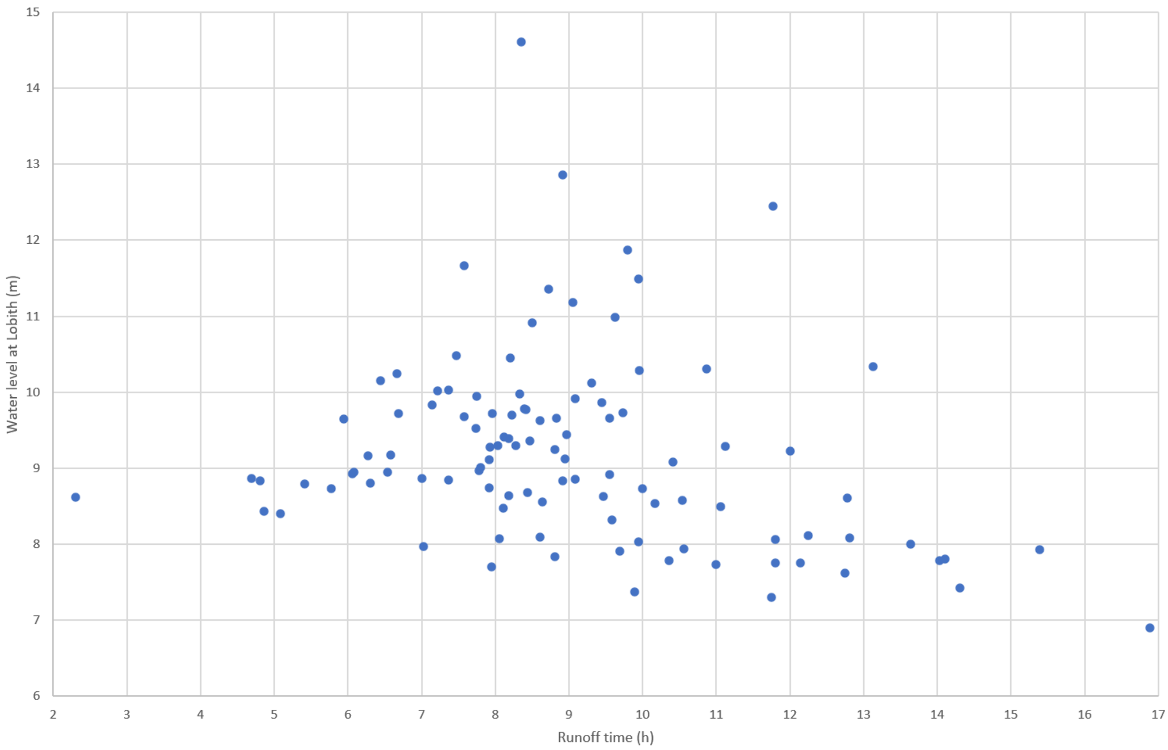


Appendix figure 5 - Lobith and Dodewaard (peaks, 1985 - 2009)



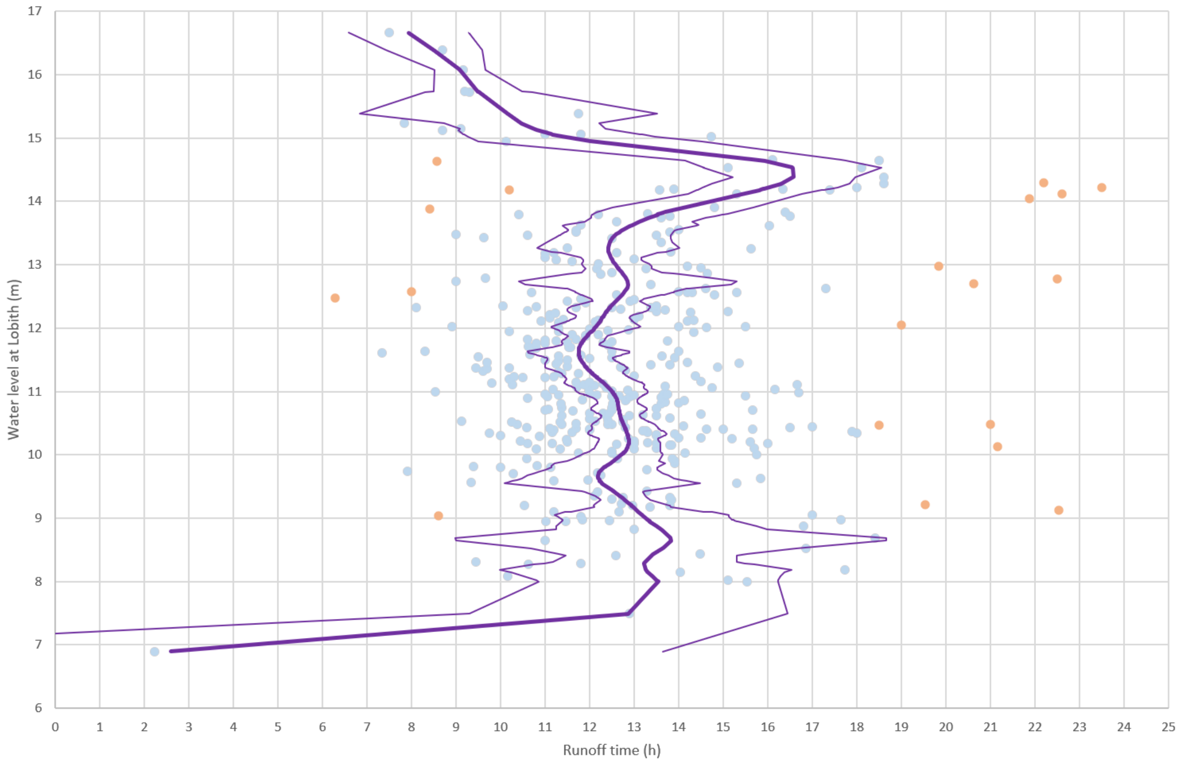
Appendix figure 6 - Lobith and Dodewaard (peaks, 2011 - 2019)

**Between 1985 and the year 2000, the water level measurements were conducted once a day. Hourly values were created for this time period by using interpolation techniques. For this reason it was decided to present the results for the two datasets separately.*

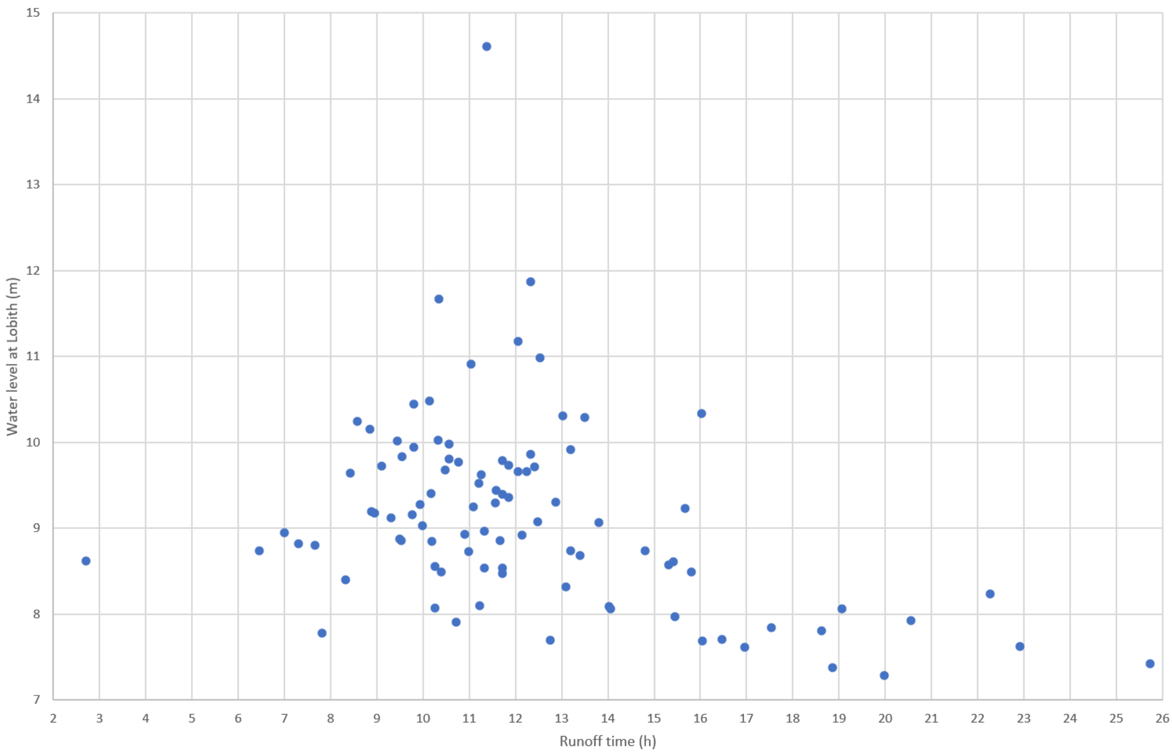


Appendix figure 7 - Lobith and Dodewaard (valleys, 2011 - 2019)

Lobith – Tiel

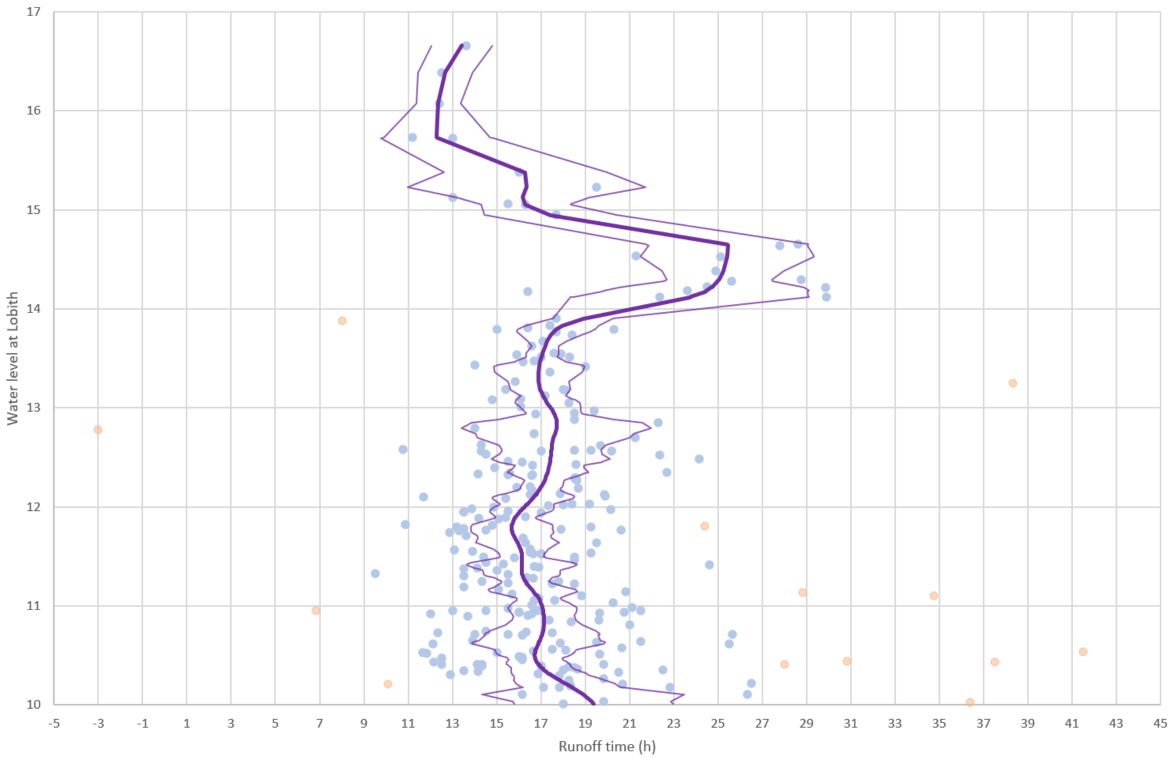


Appendix figure 8 - Lobith and Tiel (peaks, 1985 - 2019)



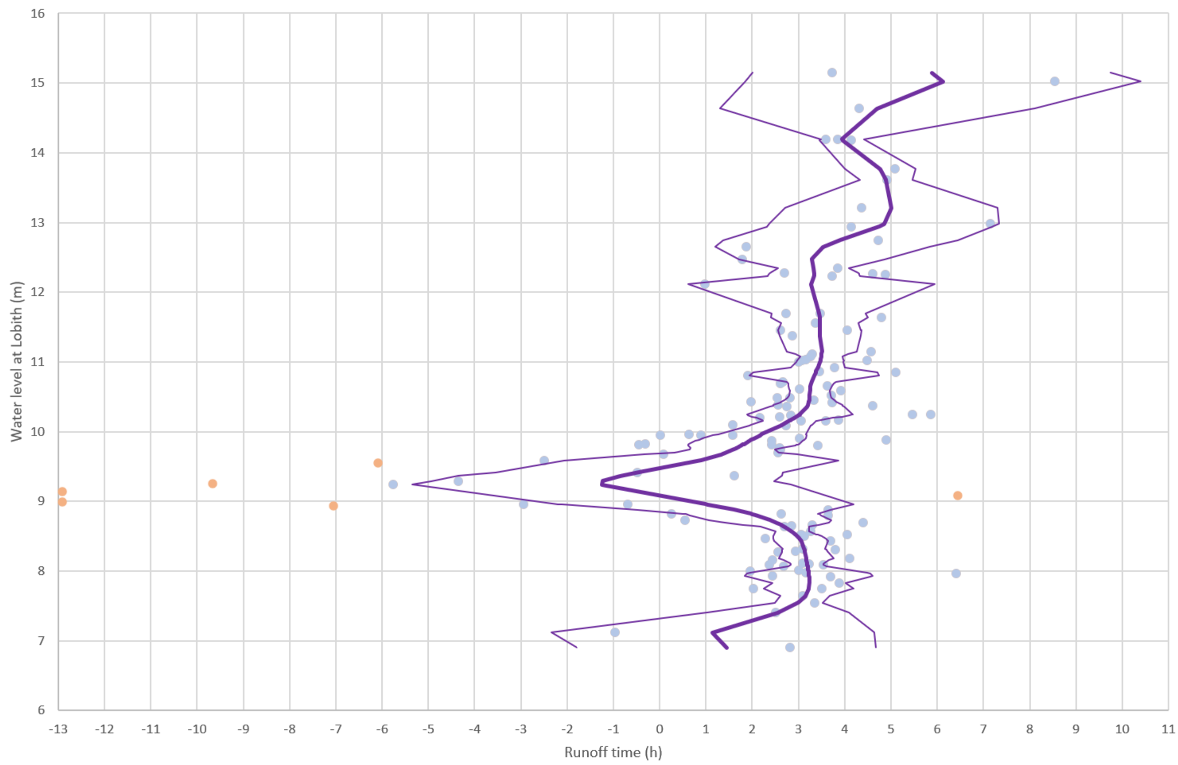
Appendix figure 9 - Lobith and Tiel (valleys, 2011 - 2019)

Lobith – Zaltbommel

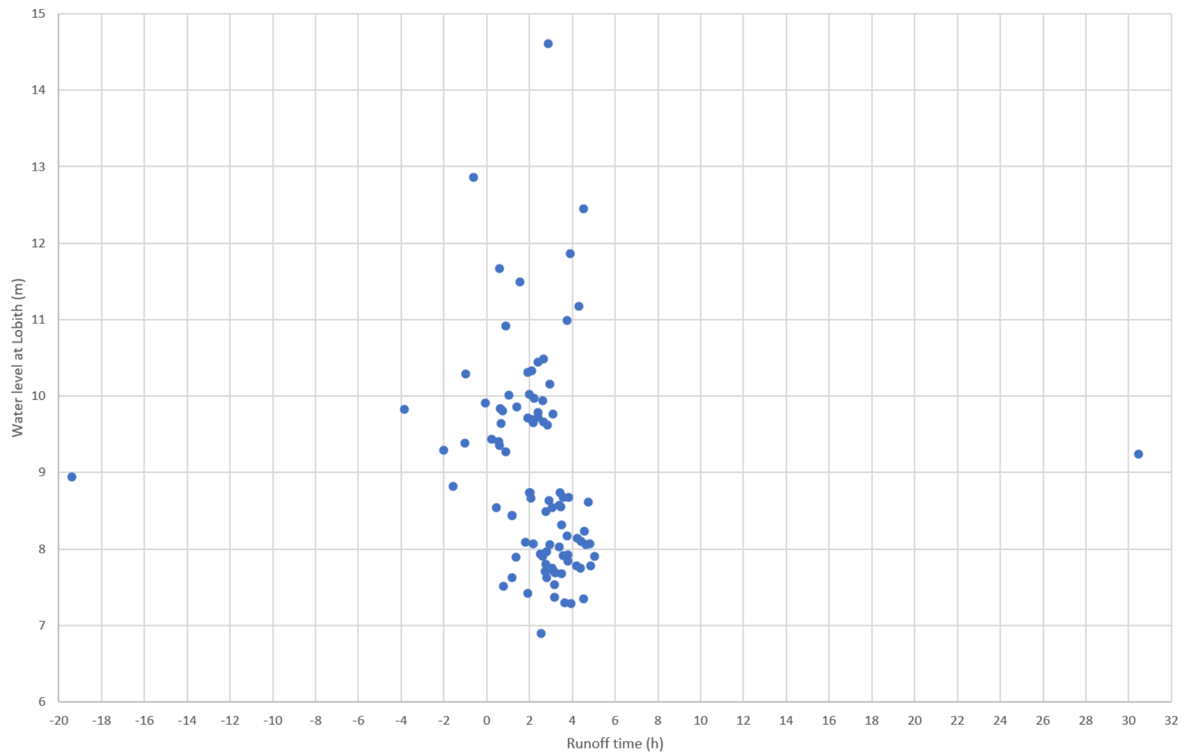


Appendix figure 10 - Lobith and Zaltbommel (peaks, 1985 - 2019)

Lobith – Looveer Huissen

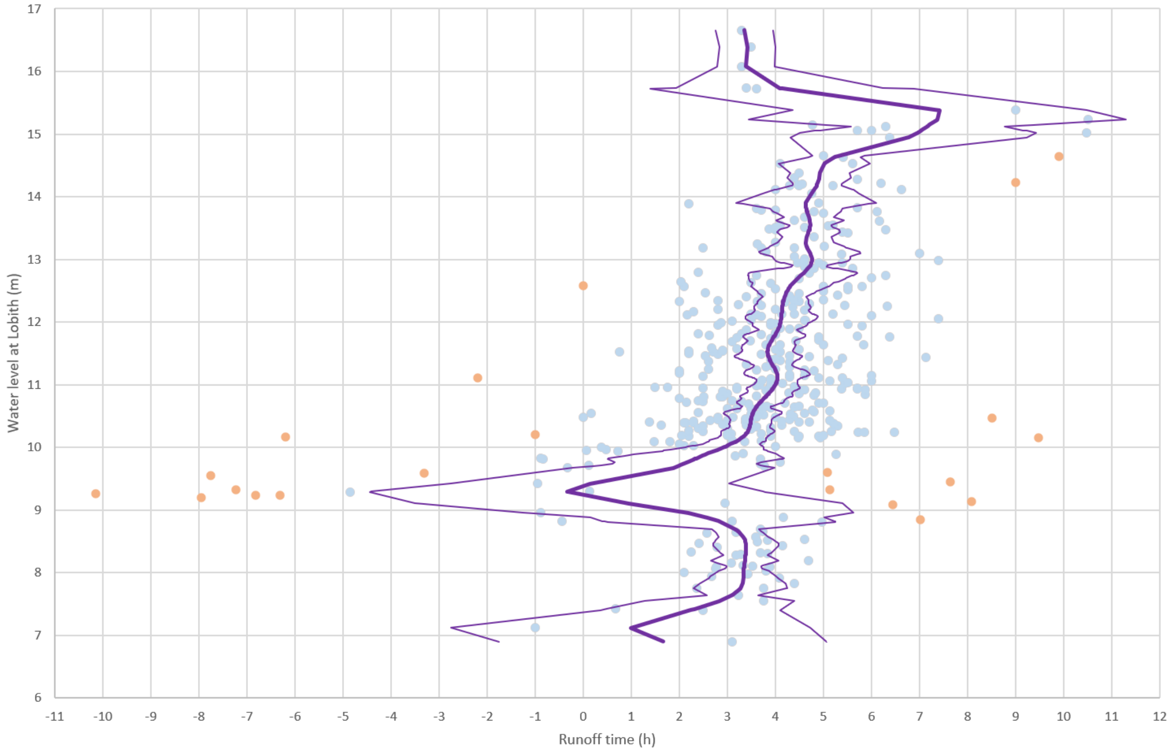


Appendix figure 11 - Lobith and Looveer Huissen (peaks, 2011 - 2018)

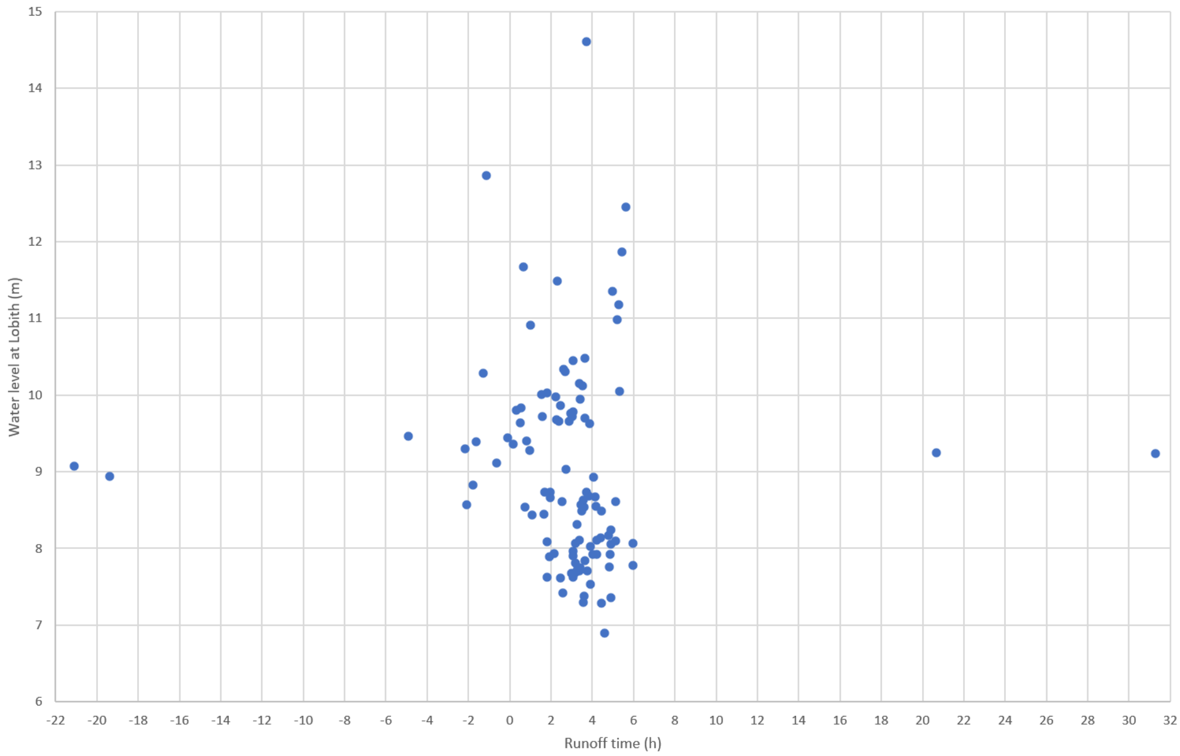


Appendix figure 12 - Lobith and Looveer Huissen (valleys, 2011 - 2019)

Lobith – IJsselkop

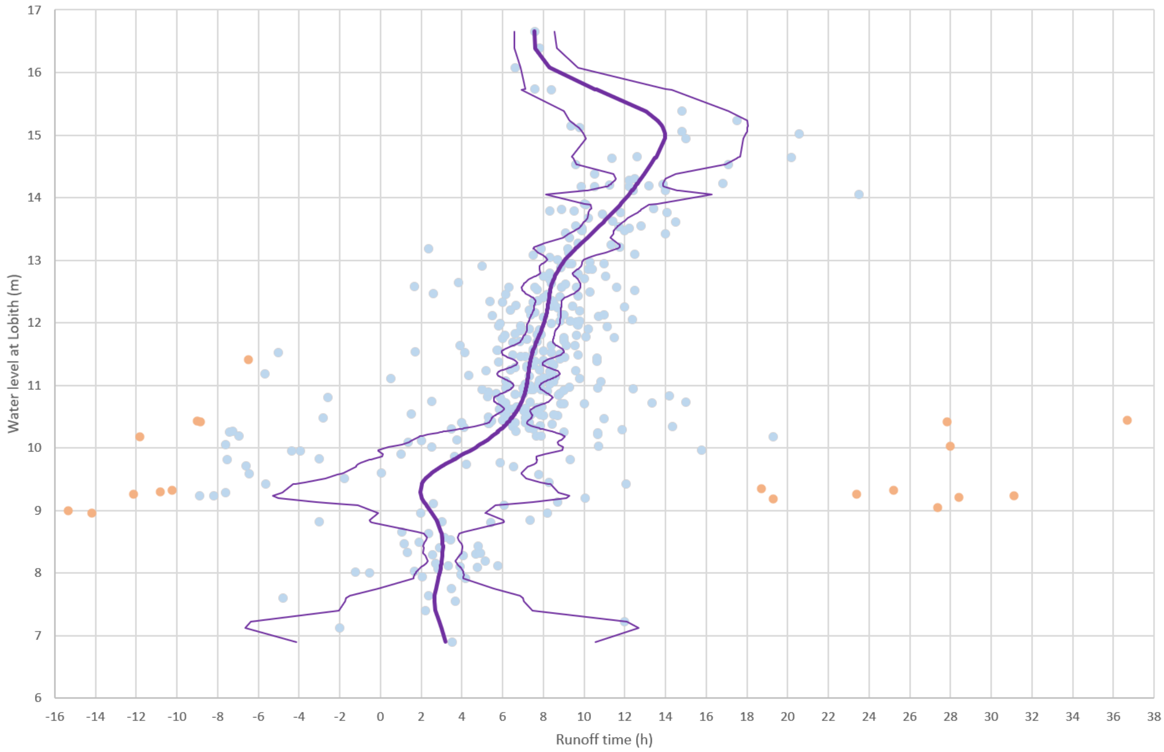


Appendix figure 13 - Lobith and IJsselkop (peaks, 1985 - 2019)

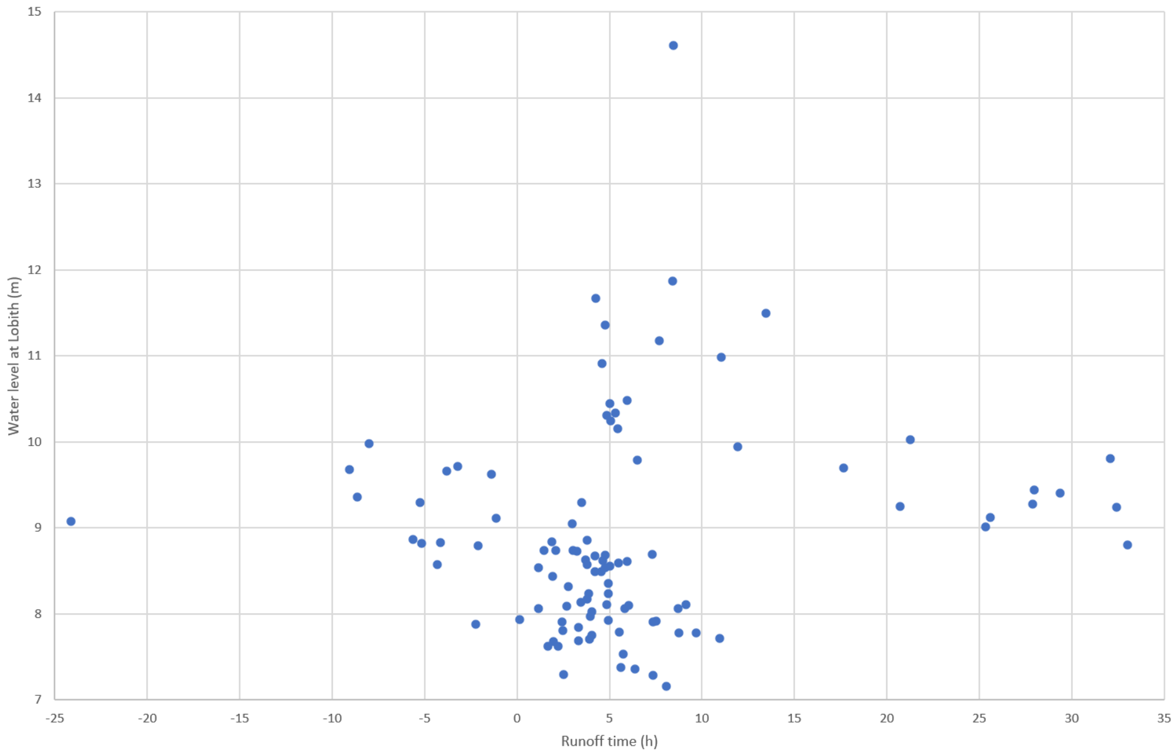


Appendix figure 14 - Lobith and IJsselkop (valleys, 2011 - 2019)

Lobith – Driel boven

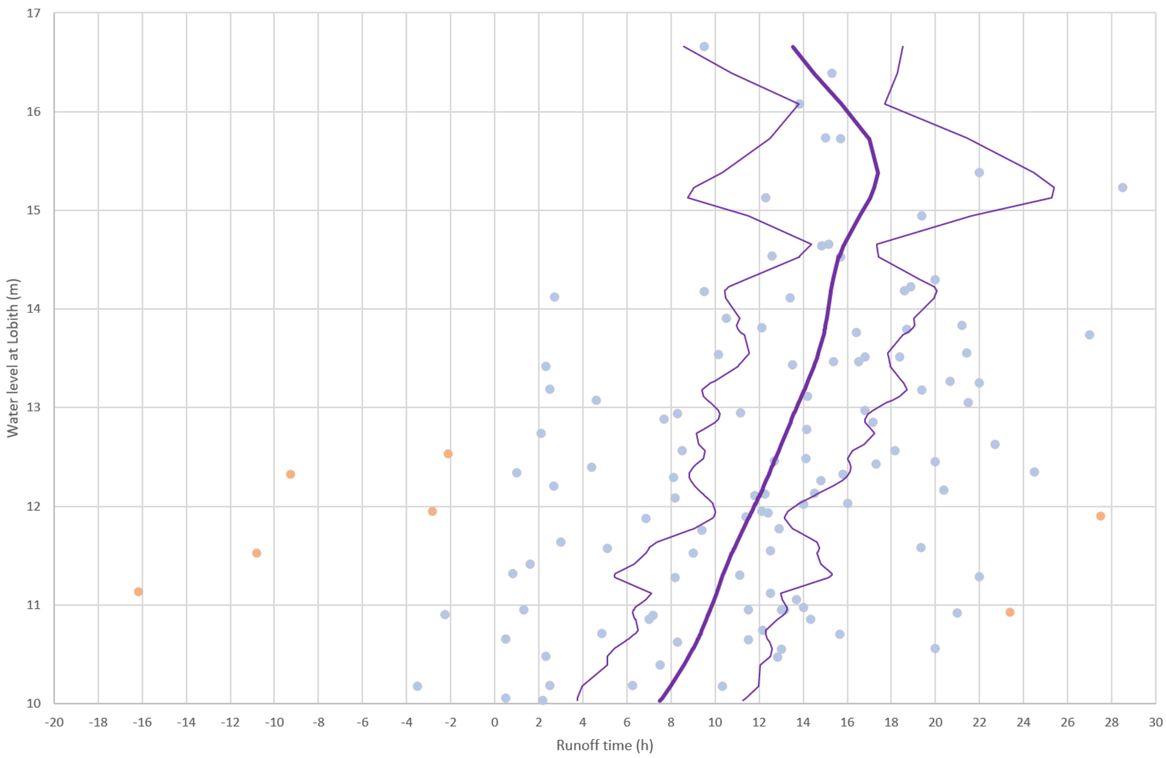


Appendix figure 15 - Lobith and Driel boven (peaks, 1985 - 2019)

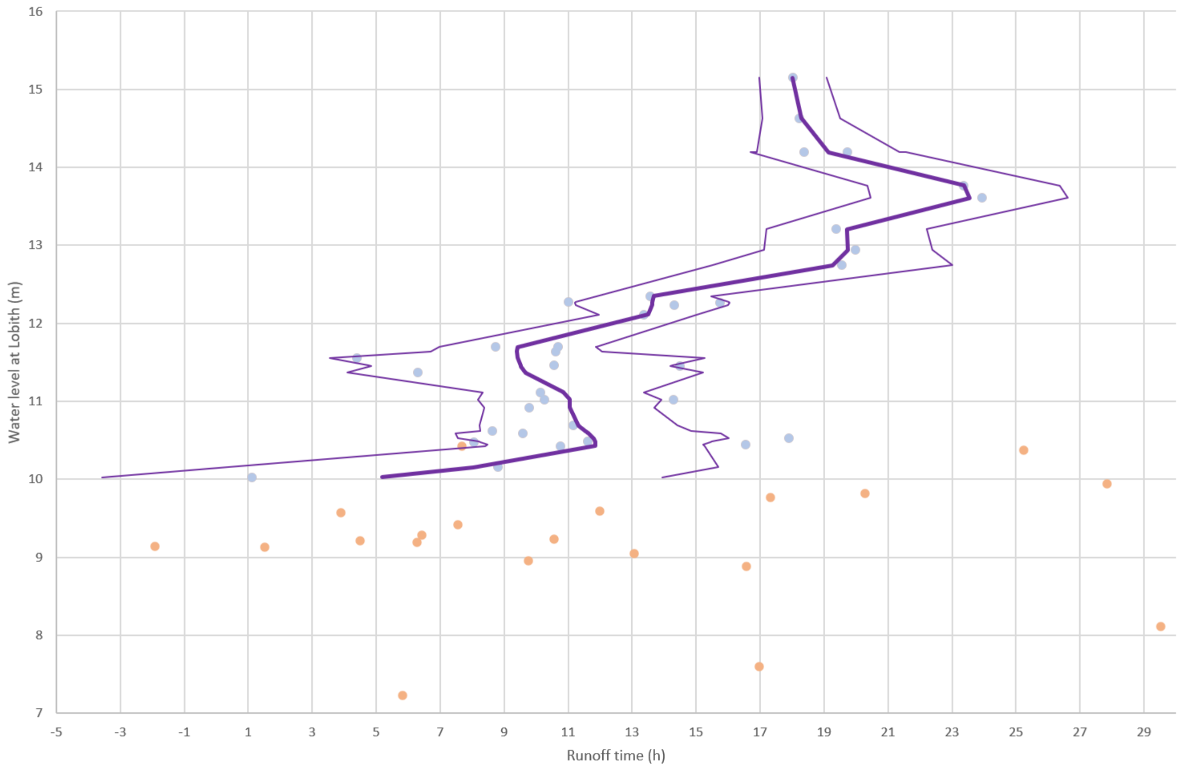


Appendix figure 16 - Driel boven (valleys, 2011 - 2019)

Lobith – Grebbe



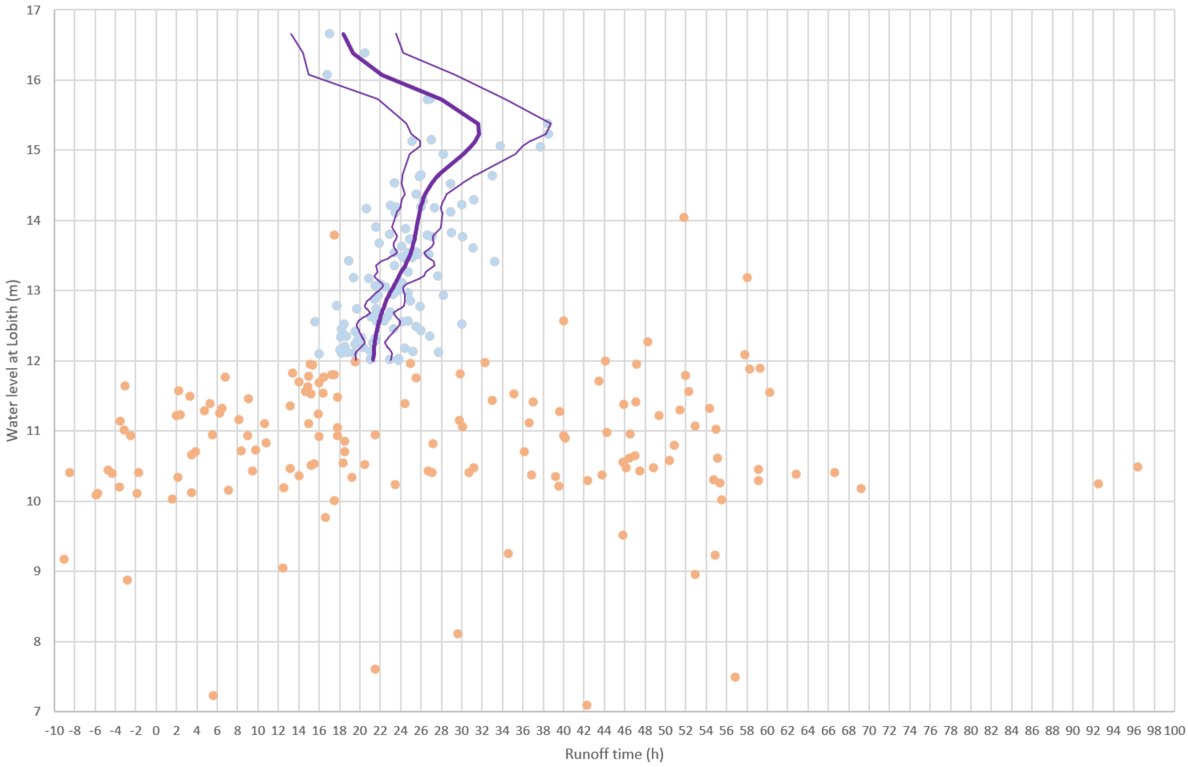
Appendix figure 17 - Lobith and Grebbe (peaks, 1985 - 2009)



Appendix figure 18 - Lobith and Grebbe (peaks, 2011 - 2019)

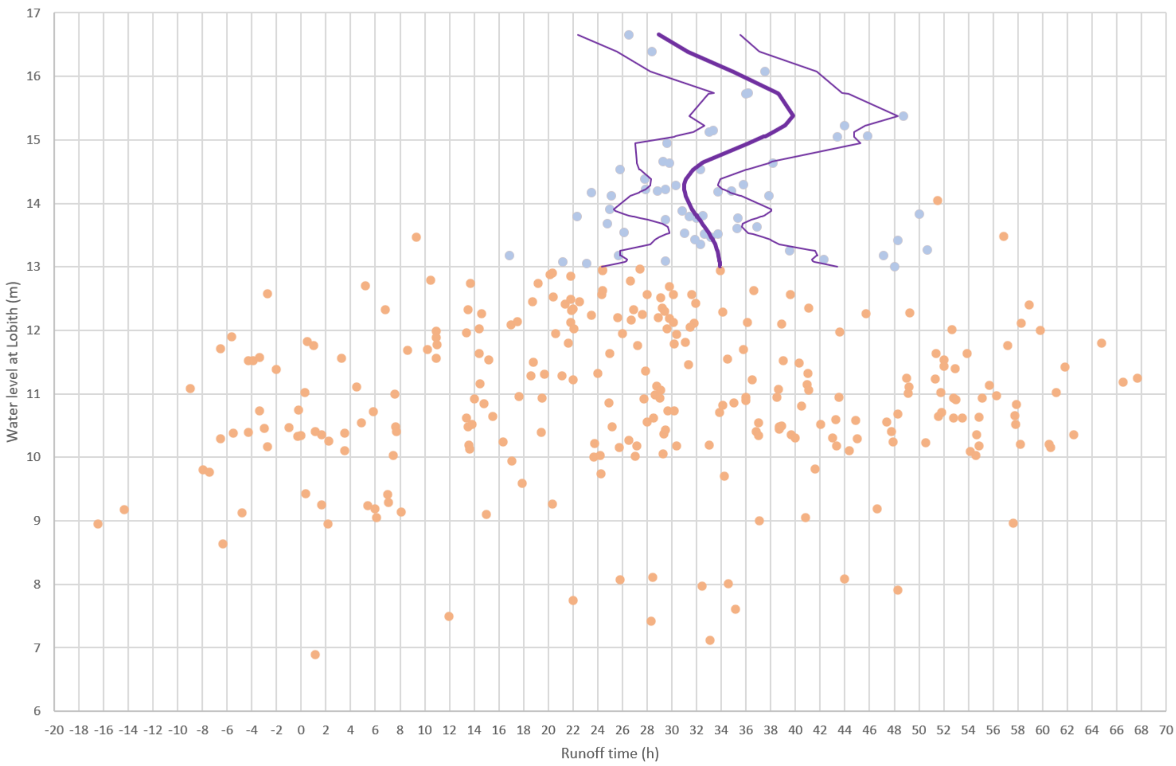
**Between 1985 and the year 2006, the water level measurements were conducted once a day. Hourly values were created for this time period by using interpolation techniques. For this reason it was decided to present the results for the two datasets separately.*

Lobith – Amerongen boven



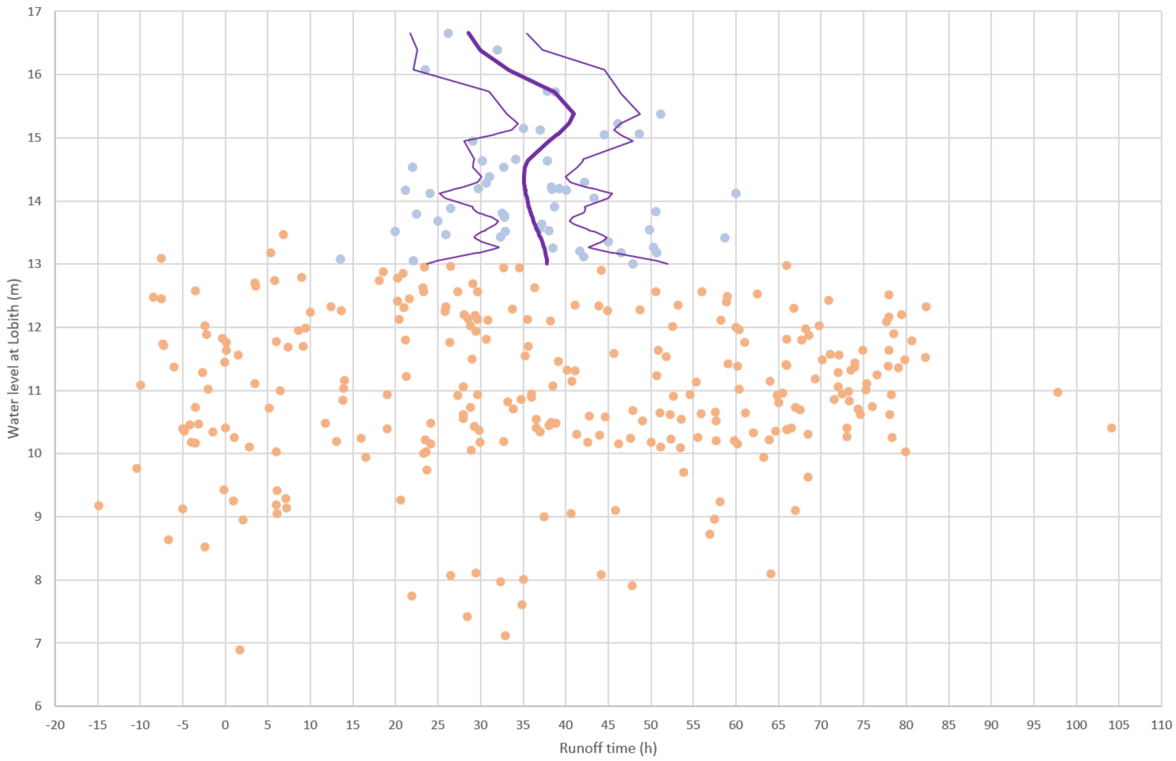
Appendix figure 19 - Lobith and Amerongen boven (peaks, 1985 - 2009)

Lobith – Culemborg



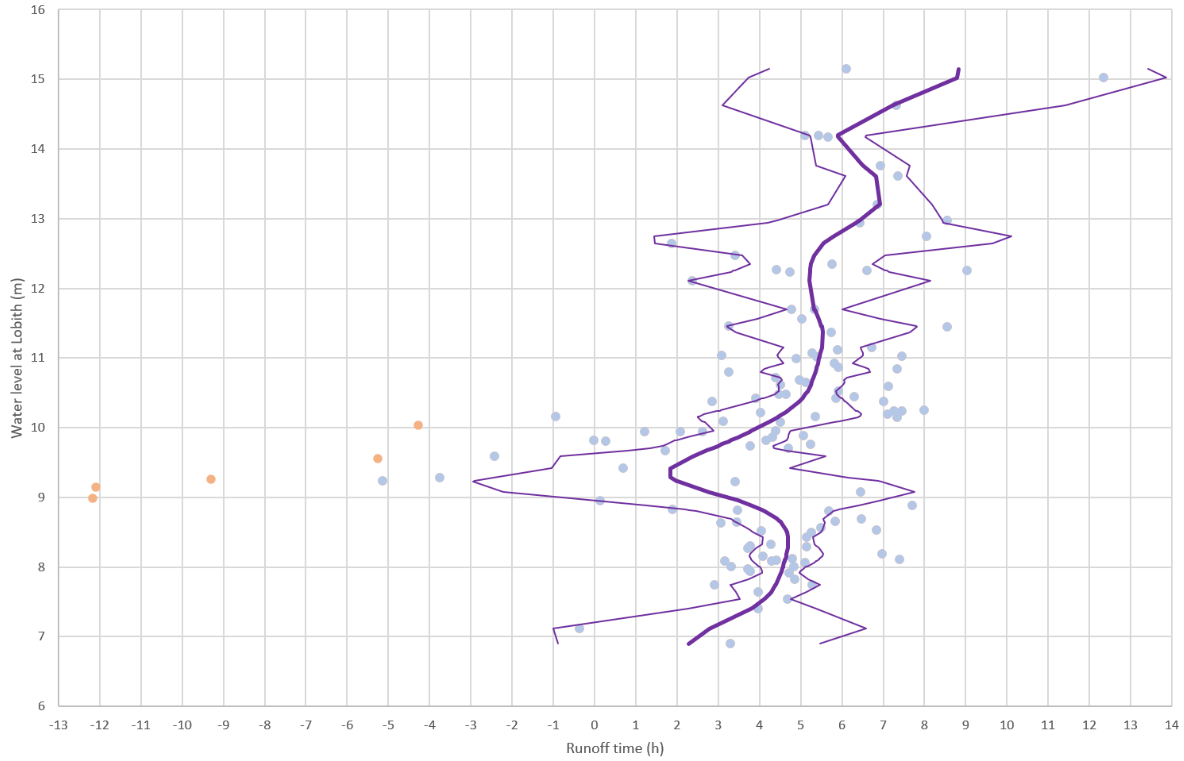
Appendix figure 20 - Lobith and Culemborg (peaks, 1985 - 2009)

Lobith – Hagestein boven

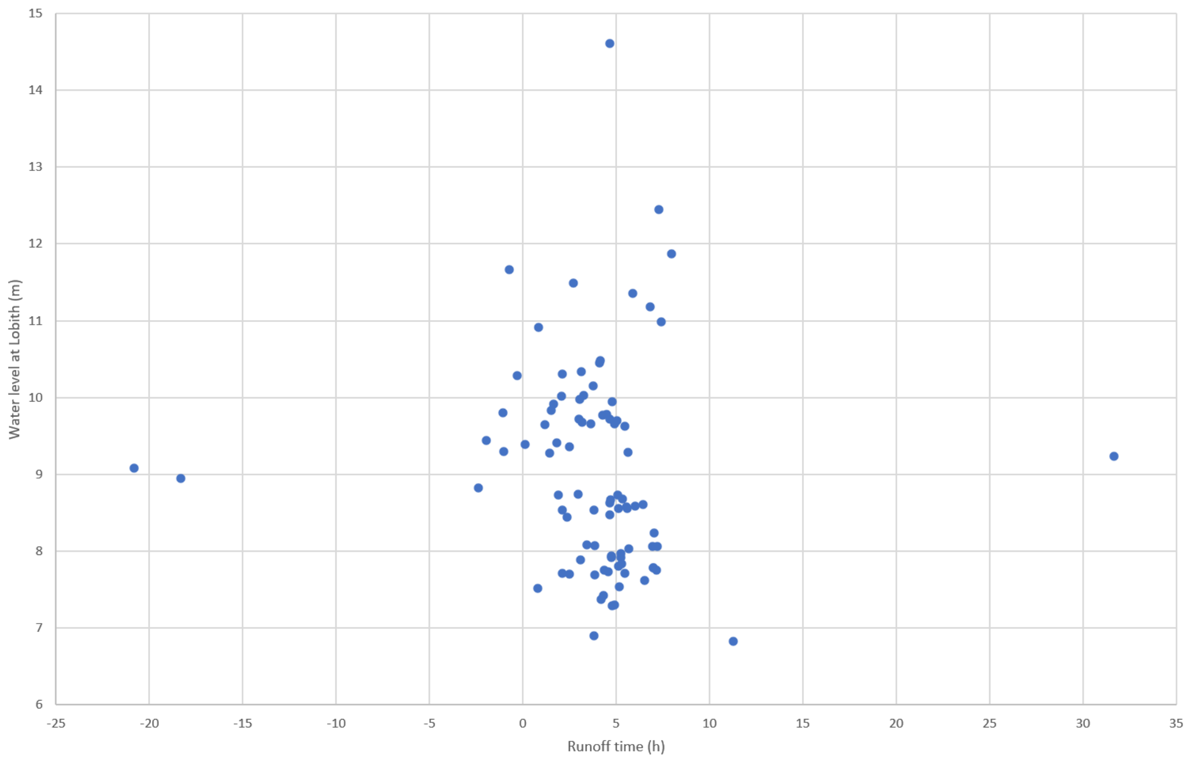


Appendix figure 21 - Lobith and Hagestein boven (peaks, 1985 - 2019)

Lobith – Westervoort

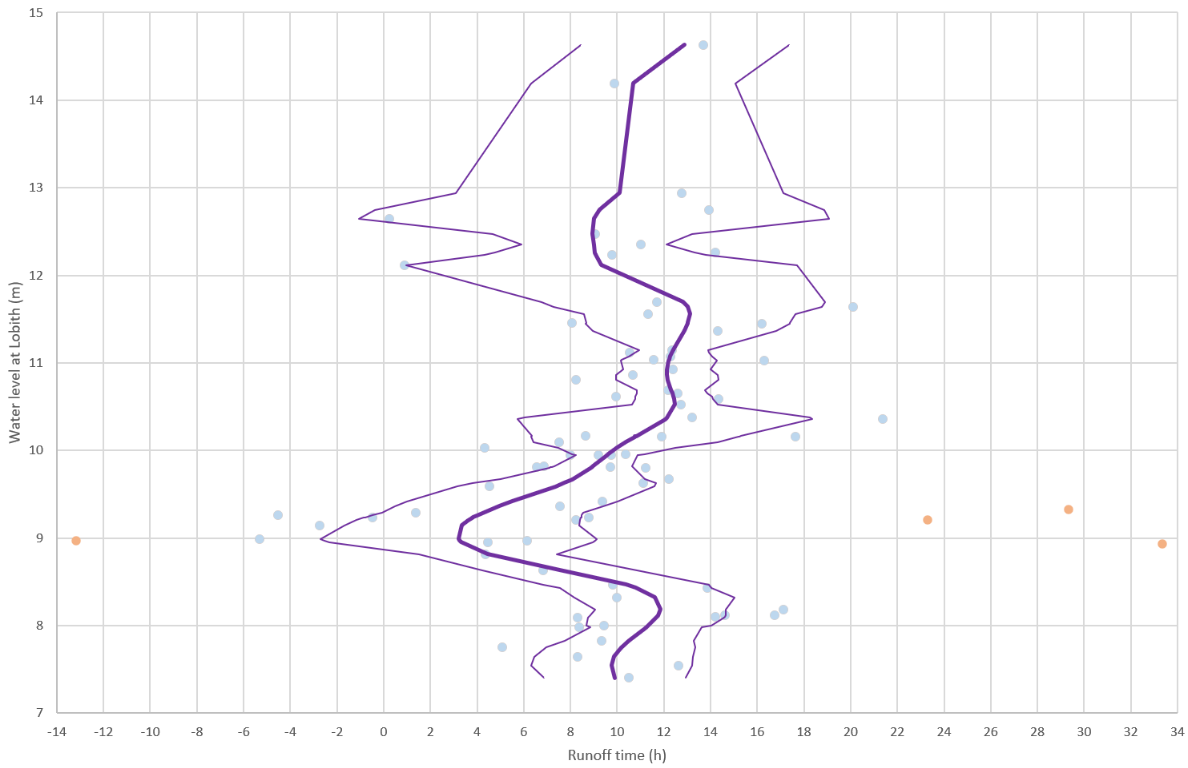


Appendix figure 22 - Lobith and Westervoort (peaks, 2011 - 2019)

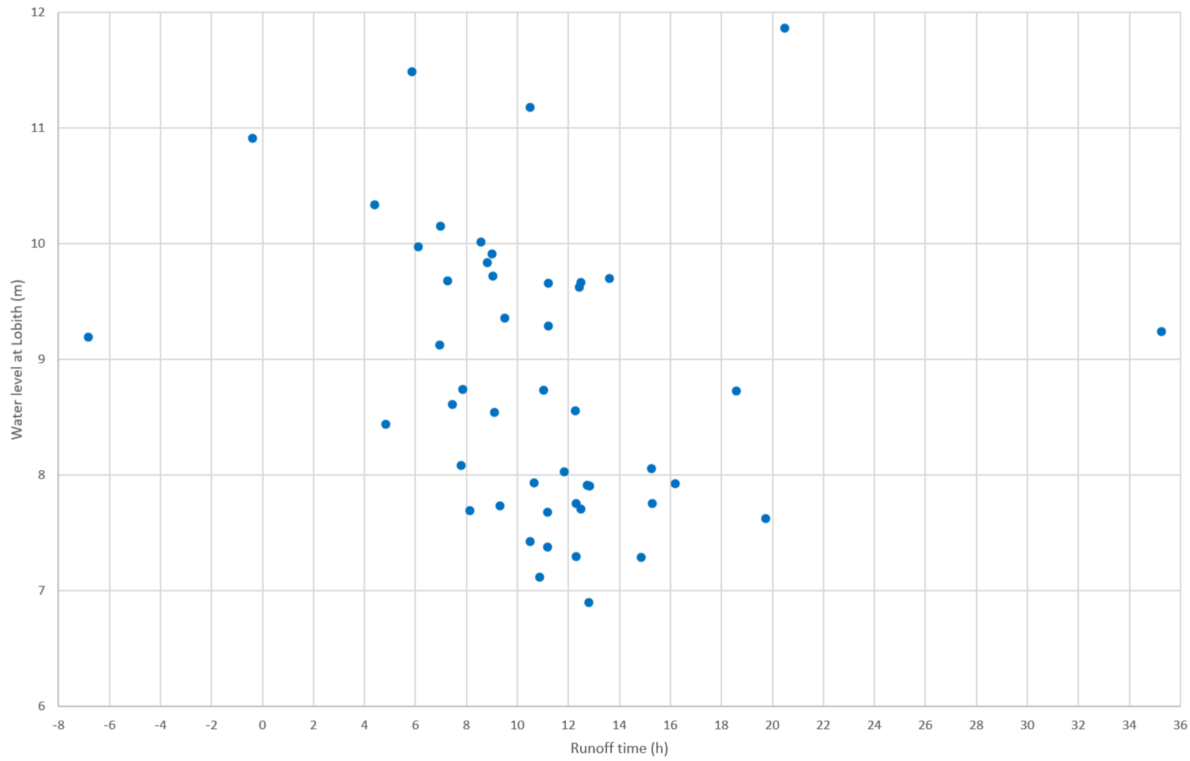


Appendix figure 23 - Lobith and Westervoort (valleys, 2011 - 2019)

Lobith – De Steeg

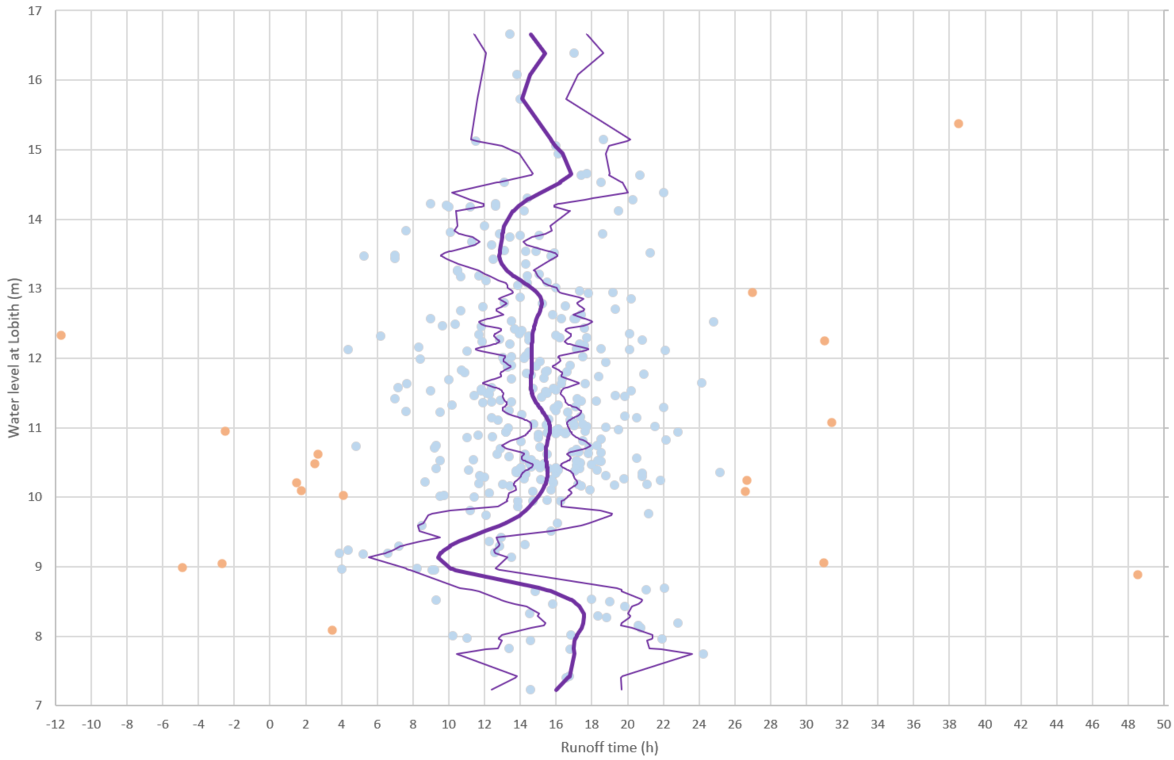


Appendix figure 24 - Lobith and De Steeg (peaks, 2013 - 2018)

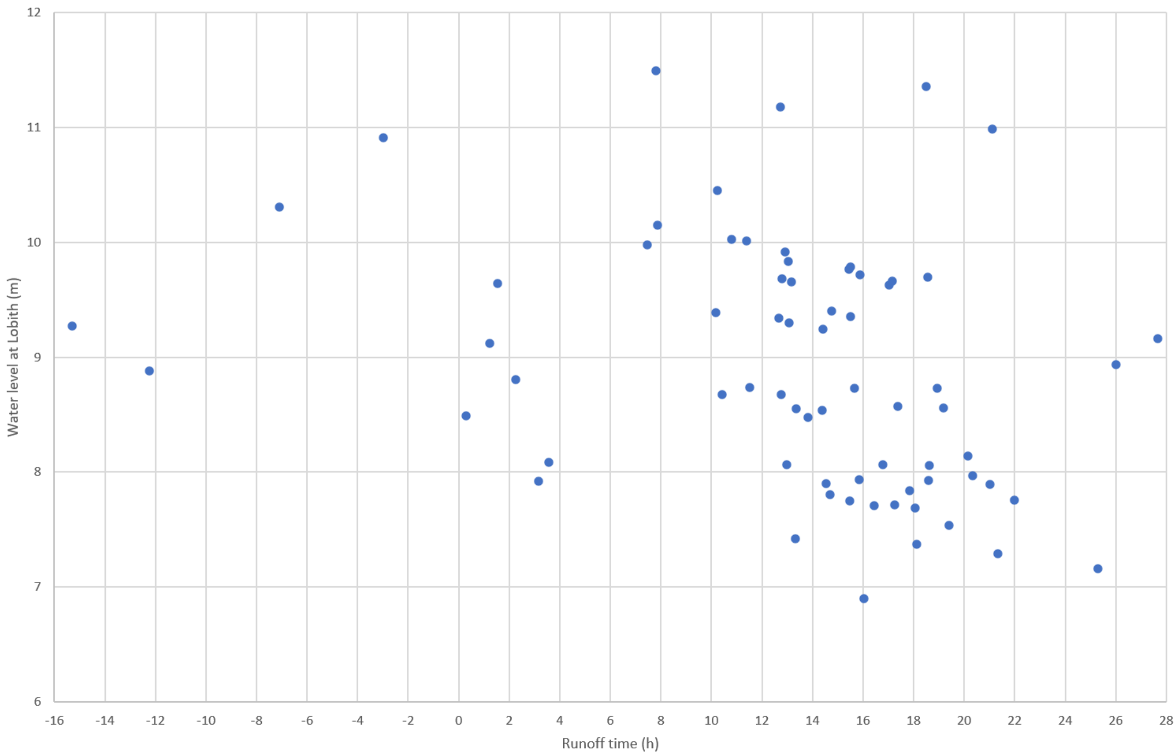


Appendix figure 25 - Lobith and De Steeg (valleys, 2013 - 2018)

Lobith – Doesburg

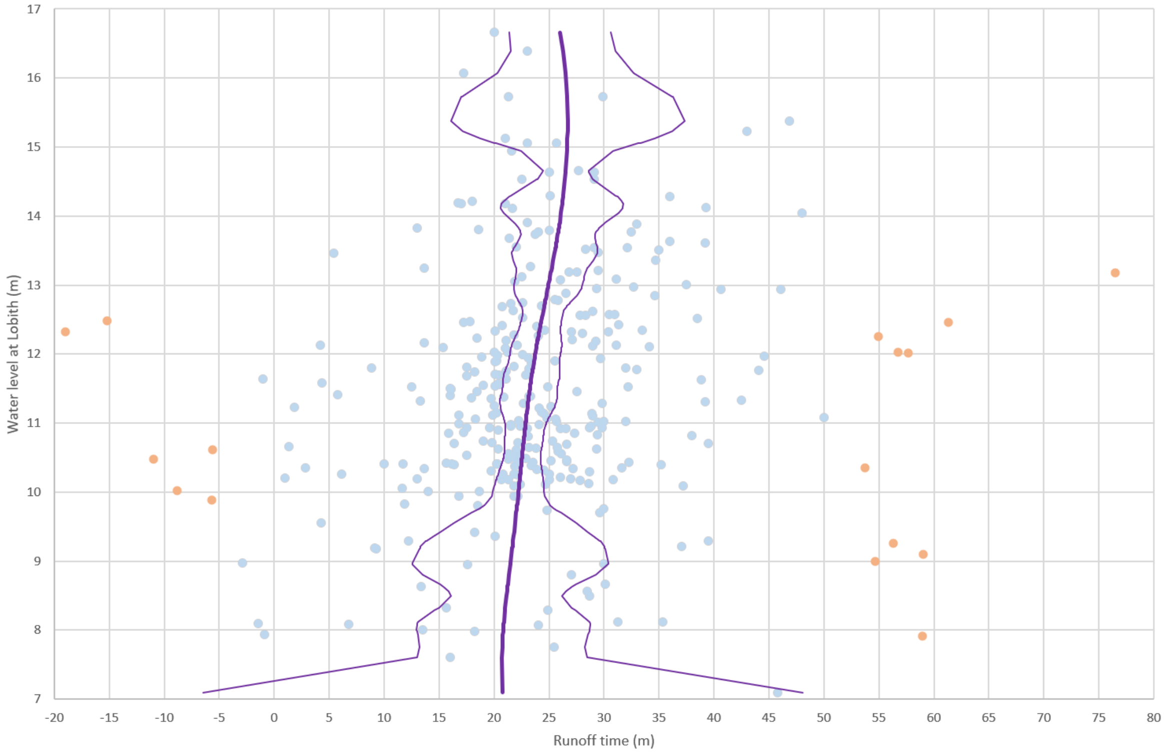


Appendix figure 26 - Runoff time - Lobith and Doesburg (peaks, 1985 - 2019)

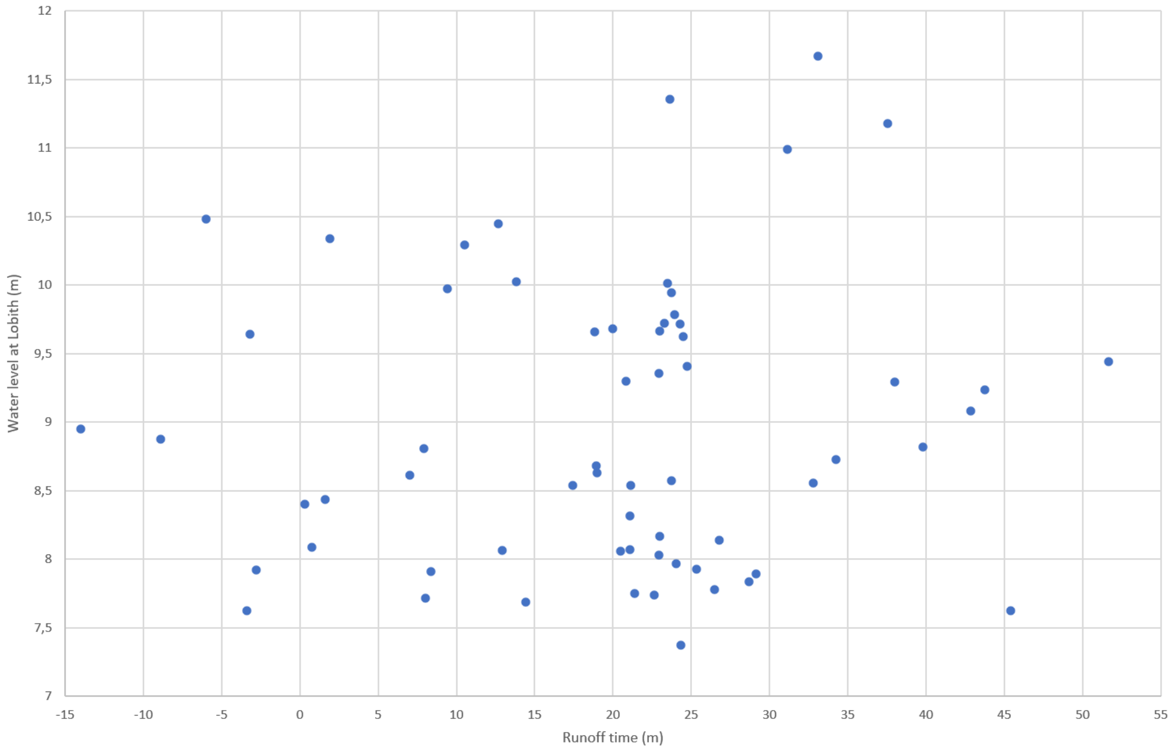


Appendix figure 27 - Runoff time - Lobith and Doesburg (valleys, 2011 - 2019)

Lobith – Zutphen

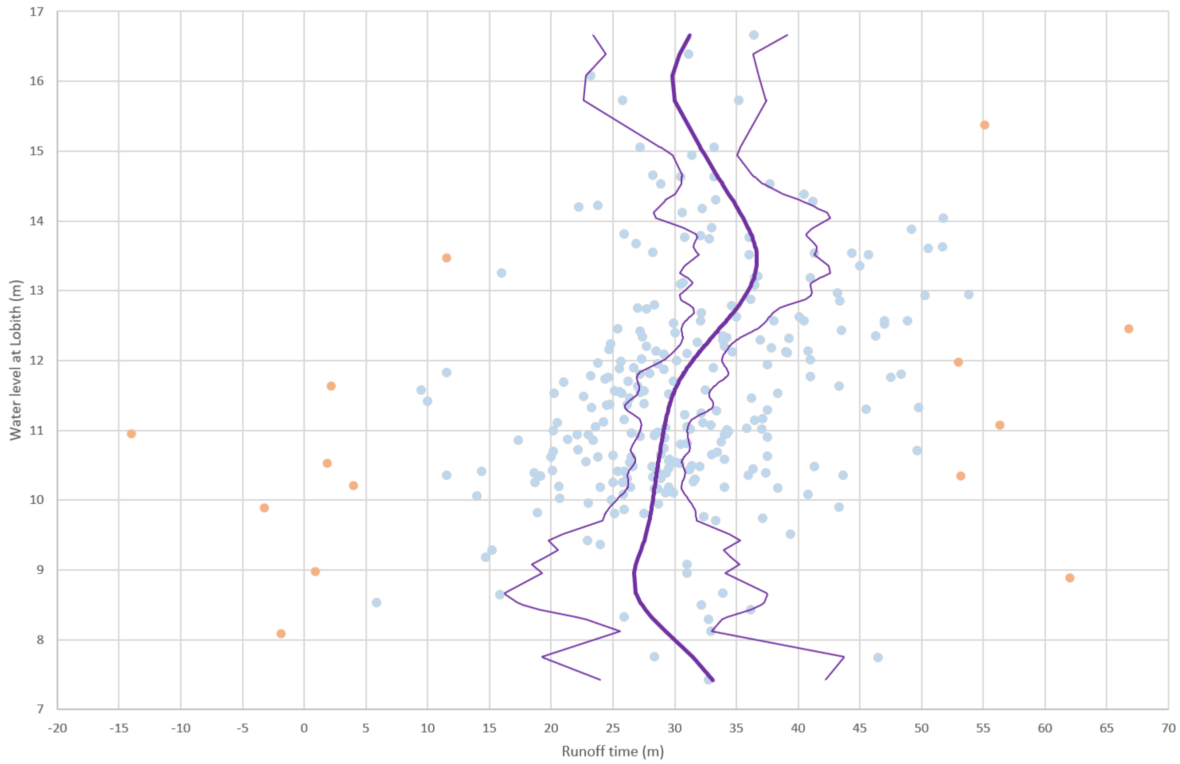


Appendix figure 28 - Lobith and Zutphen (peaks, 1985 - 2019)



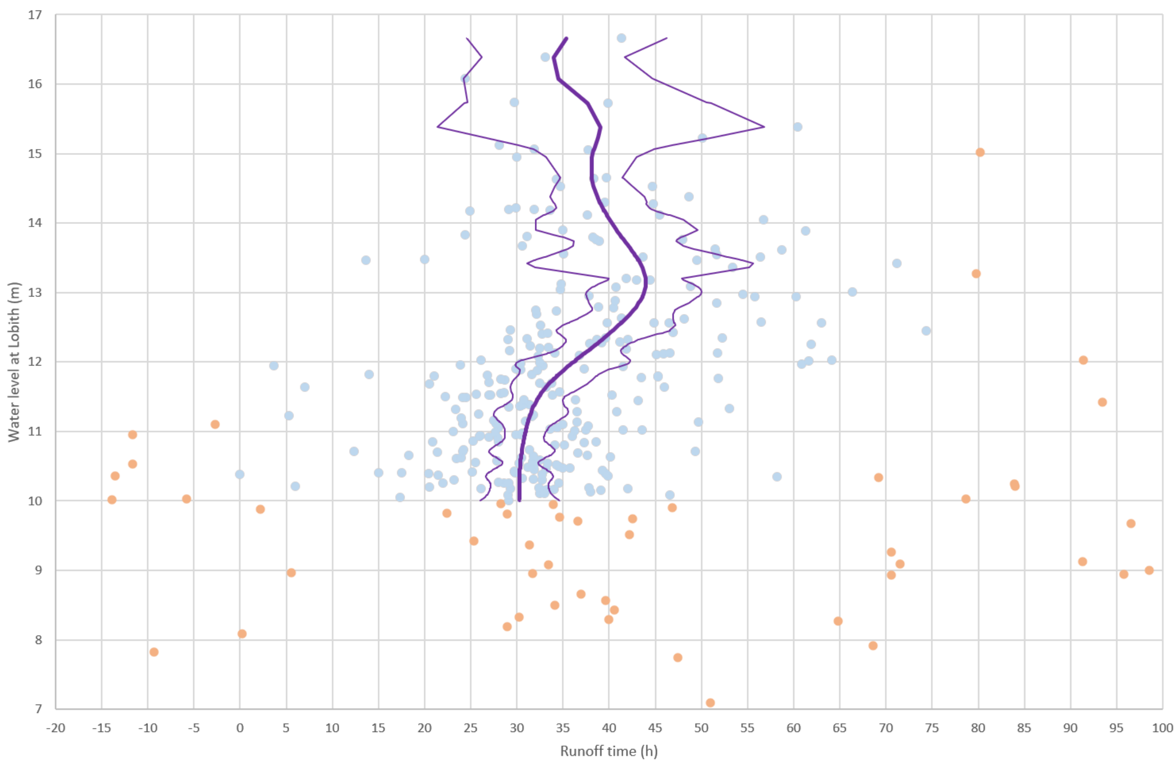
Appendix figure 29 - Lobith and Zutphen (valleys, 2011 - 2019)

Lobith – Deventer



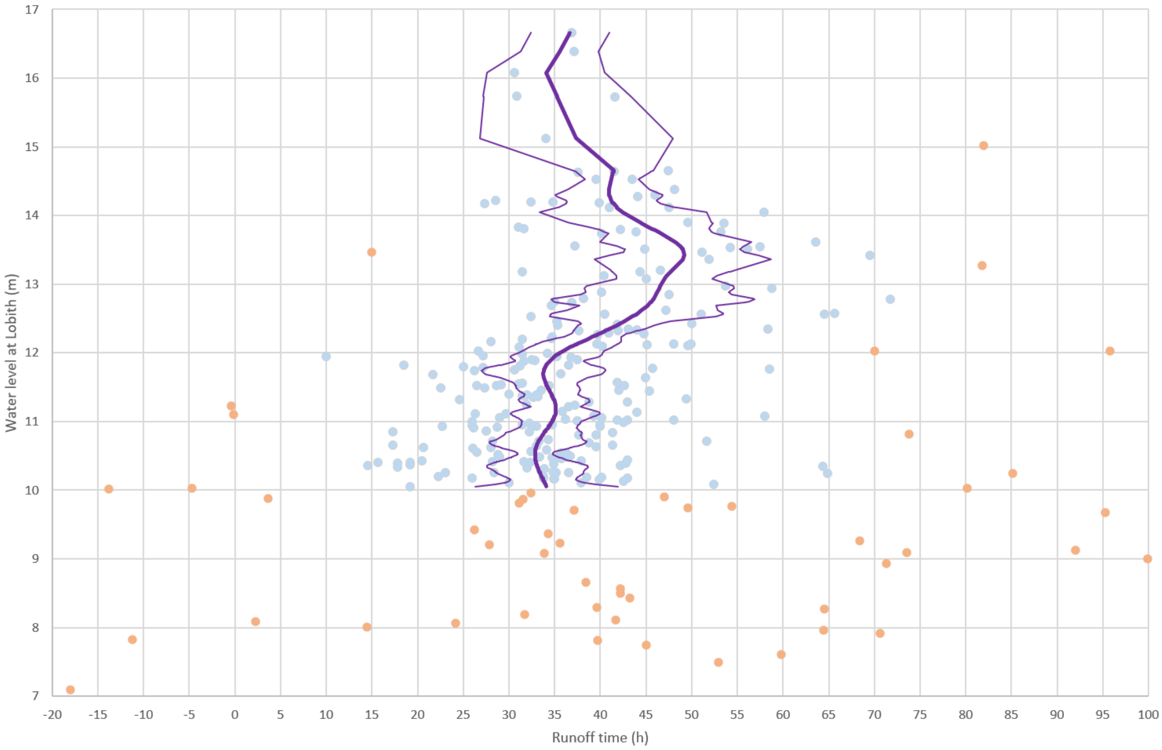
Appendix figure 30 - Lobith and Deventer (peaks, 1985 - 2019)

Lobith – Olst



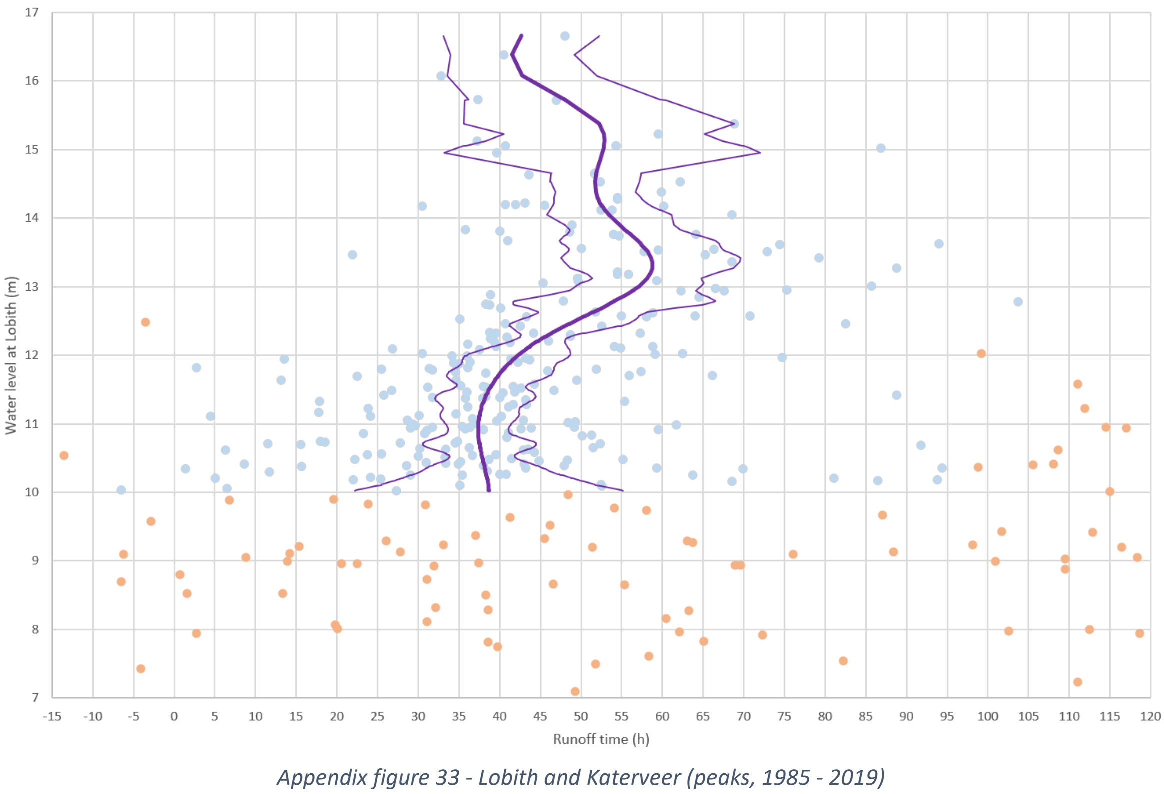
Appendix figure 31 - Lobith and Olst (peaks, 1985 - 2019)

Lobith – Wijhe



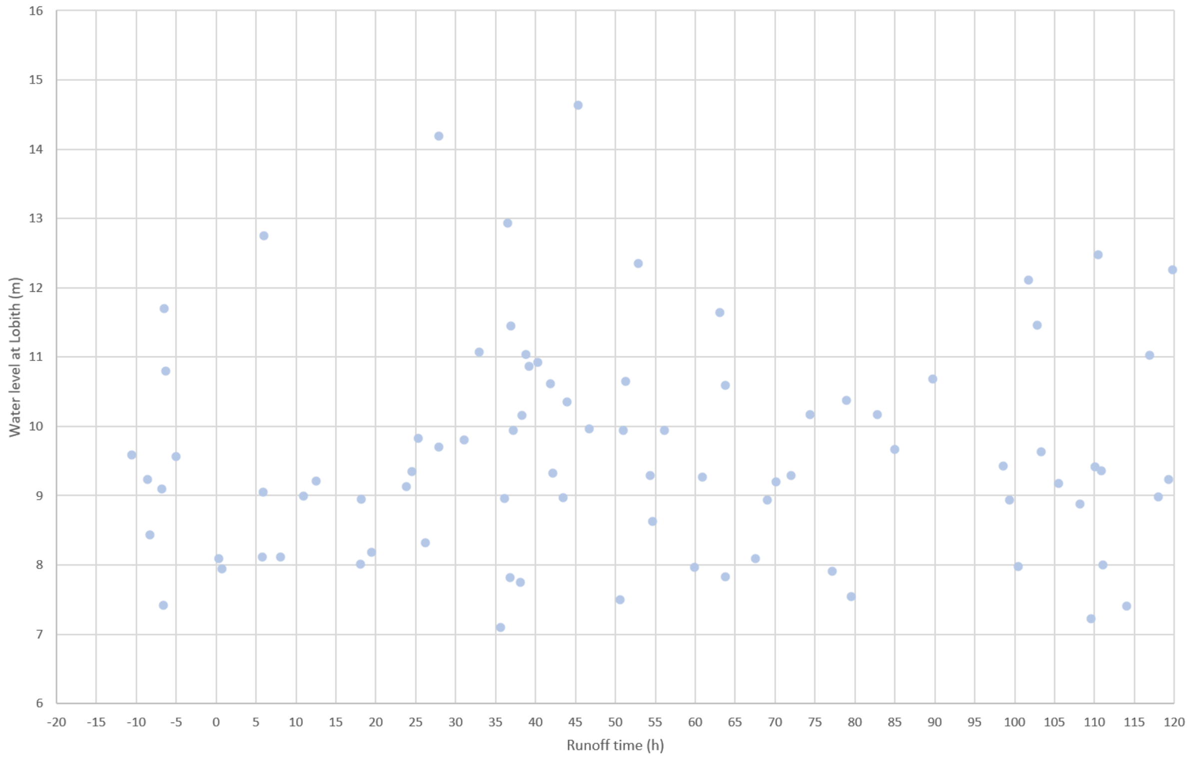
Appendix figure 32 - Lobith and Wijhe (peaks, 1985 - 2019)

Lobith – Katerveer



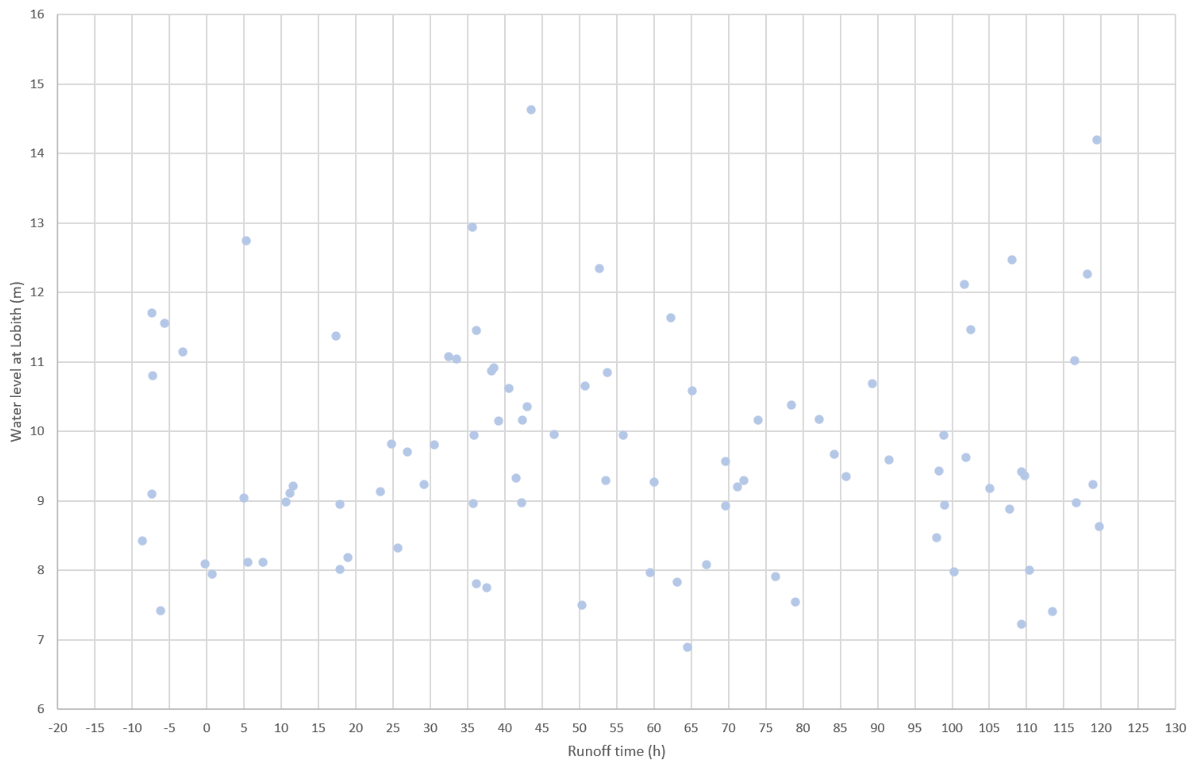
Appendix figure 33 - Lobith and Katerveer (peaks, 1985 - 2019)

Lobith – Kampen



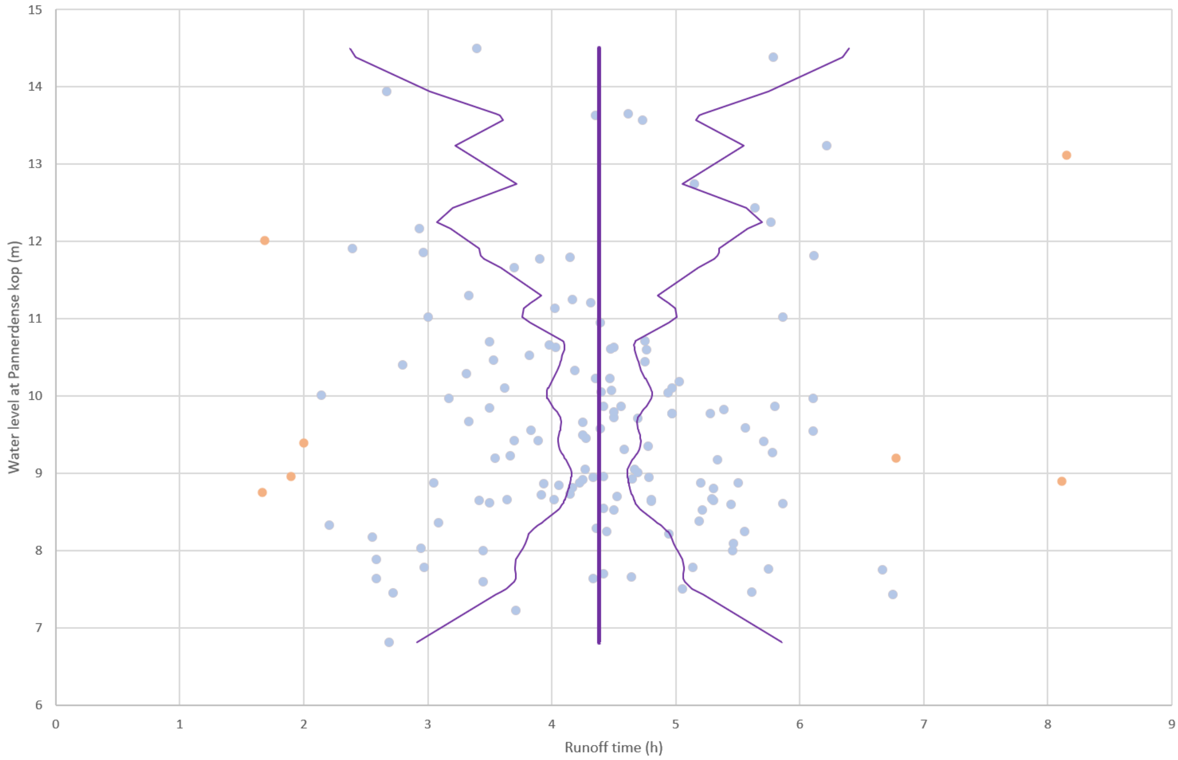
Appendix figure 34 - Lobith and Kampen (peaks, 1985 - 2019)

Lobith – Keteldiep



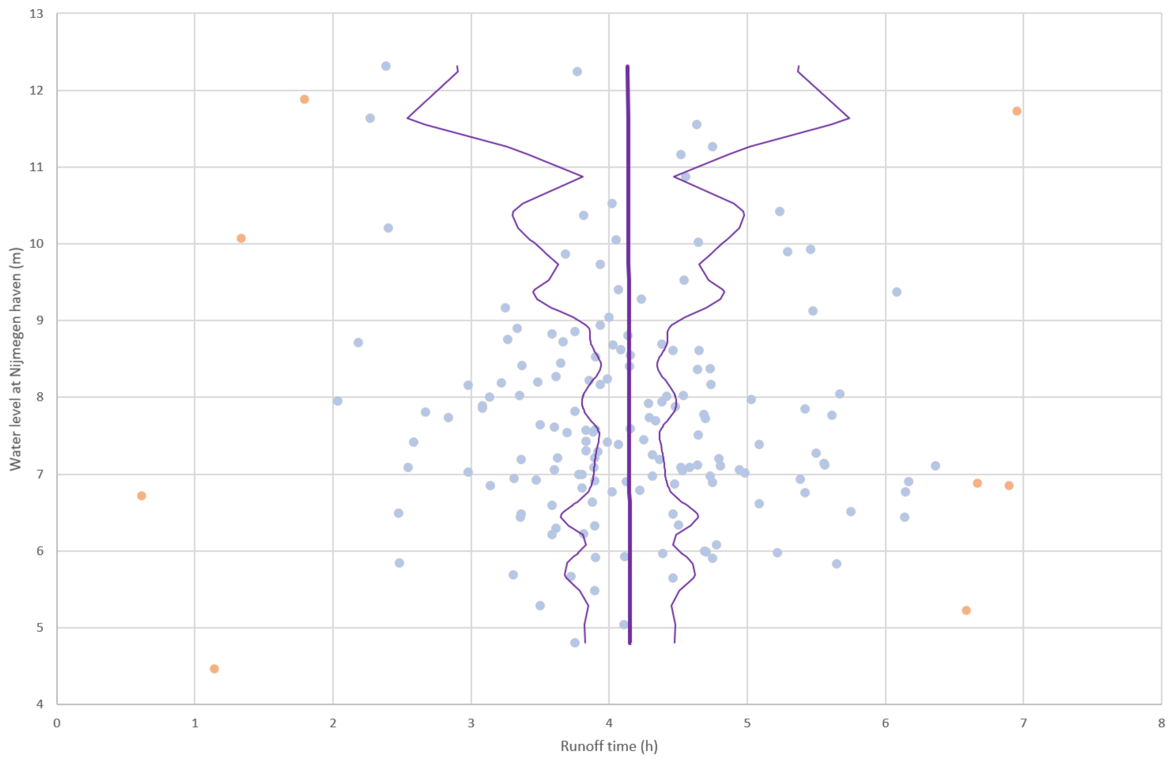
Appendix figure 35 - Lobith and Keteldiep (peaks, 1985 - 2019)

Pannerdense kop – Nijmegen haven



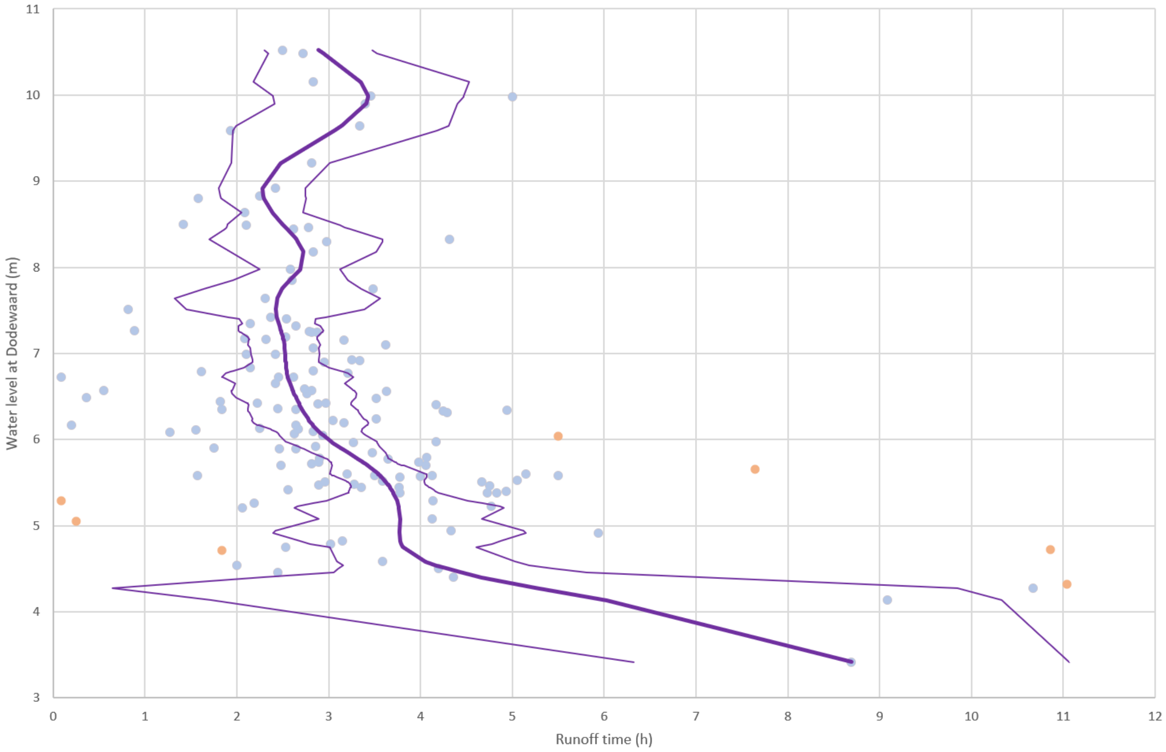
Appendix figure 36 - Pannerdense kop and Nijmegen haven (peaks, 2011 - 2019)

Nijmegen haven – Dodewaard



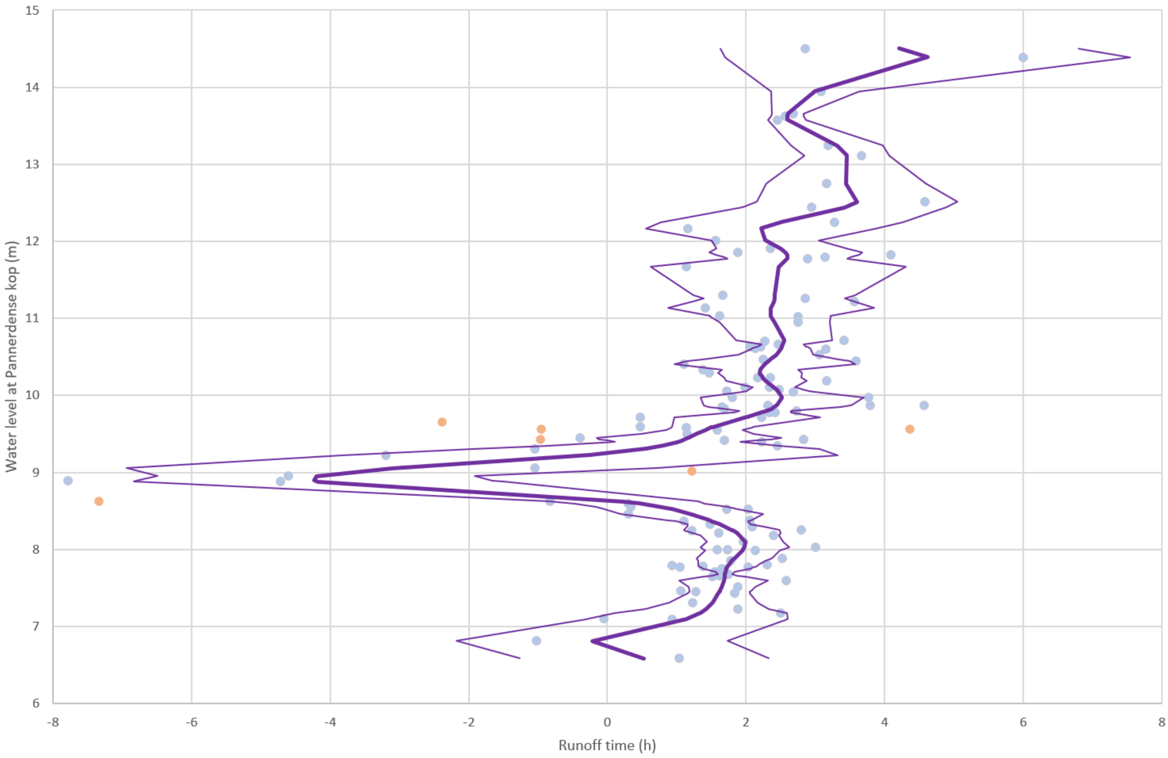
Appendix figure 37 - Nijmegen haven and Dodewaard (peaks, 2011 - 2019)

Dodewaard – Tiel



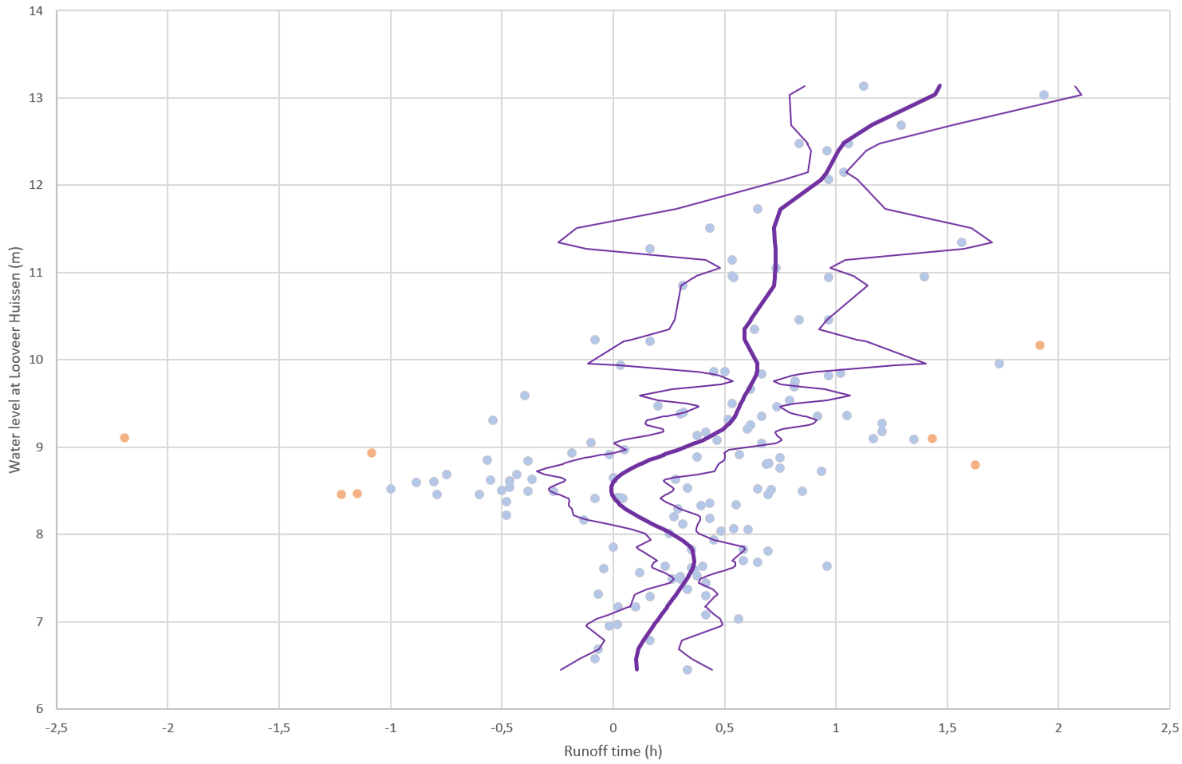
Appendix figure 38 - Dodewaard and Tiel (peaks, 2011 - 2019)

Pannerdense kop – Looveer Huissen



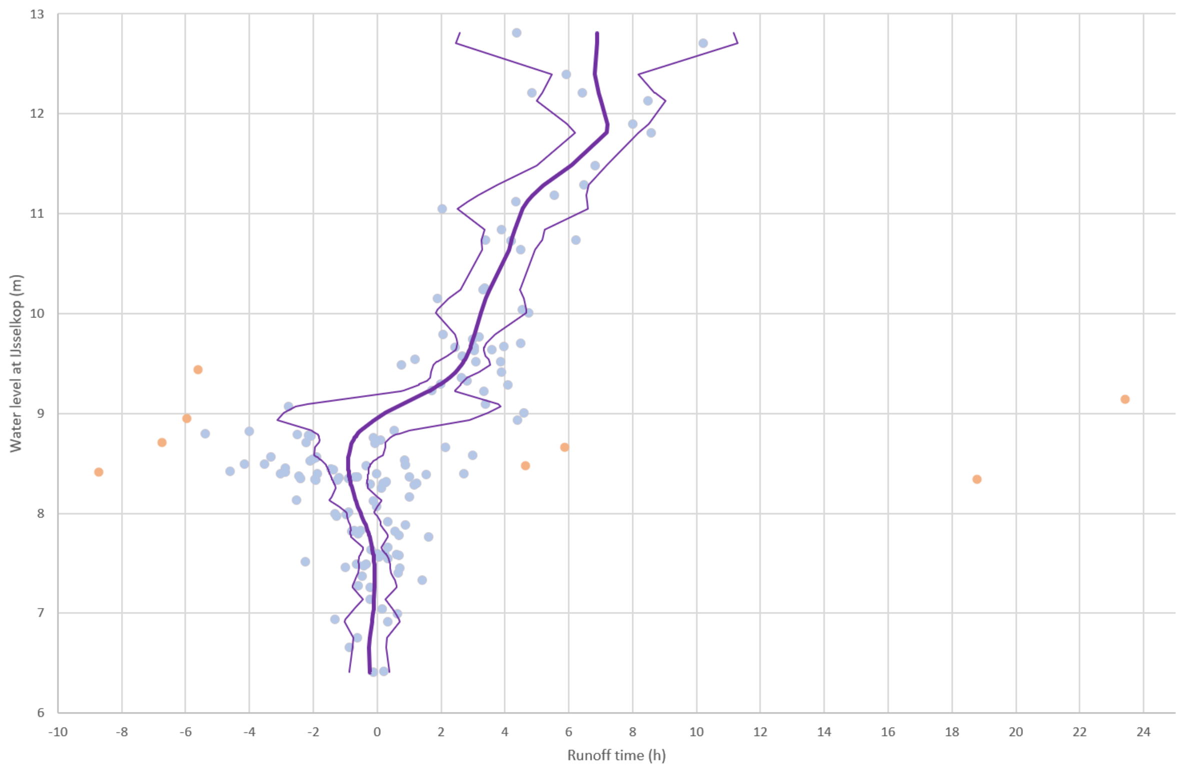
Appendix figure 39 - Pannerdense kop and Looveer Huissen (peaks, 2011 - 2019)

Looveer Huissen – IJsselkop



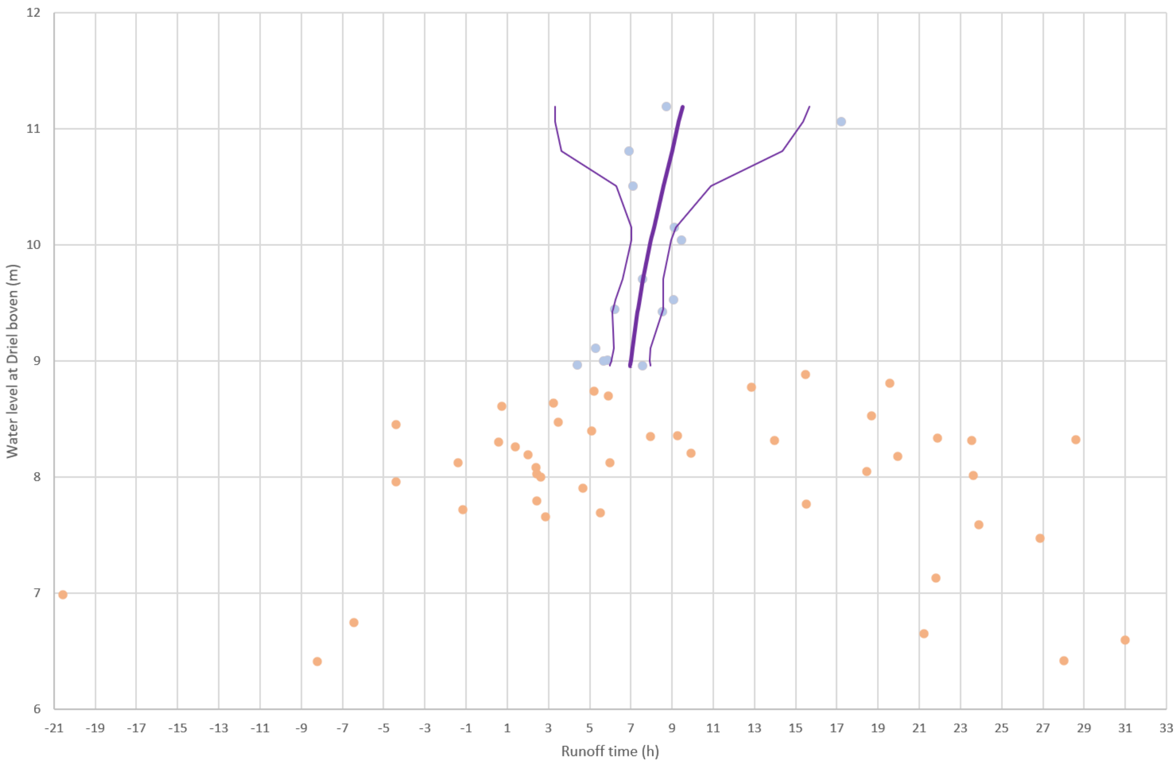
Appendix figure 40 - Looveer Huissen and IJsselkop (peaks, 2011 - 2019)

IJsselkop – Driel boven



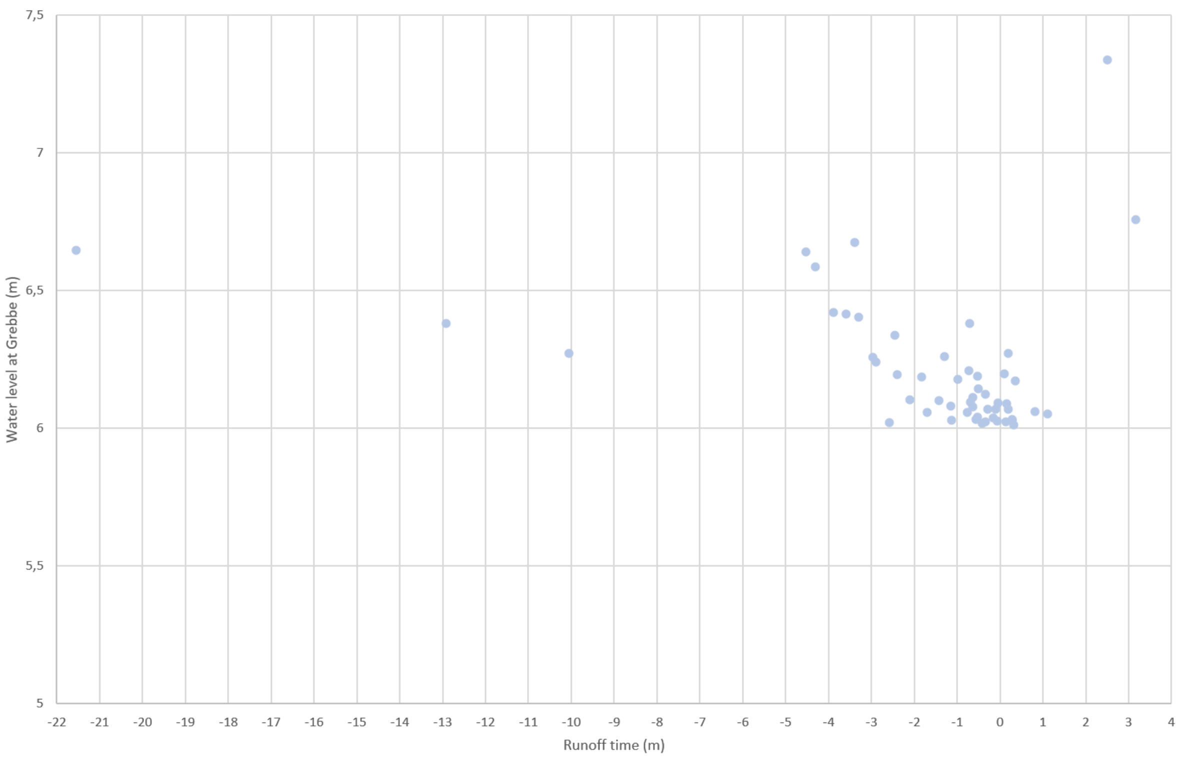
Appendix figure 41 - IJsselkop and Driel boven (peaks, 2011 - 2019)

Driel boven – Grebbe



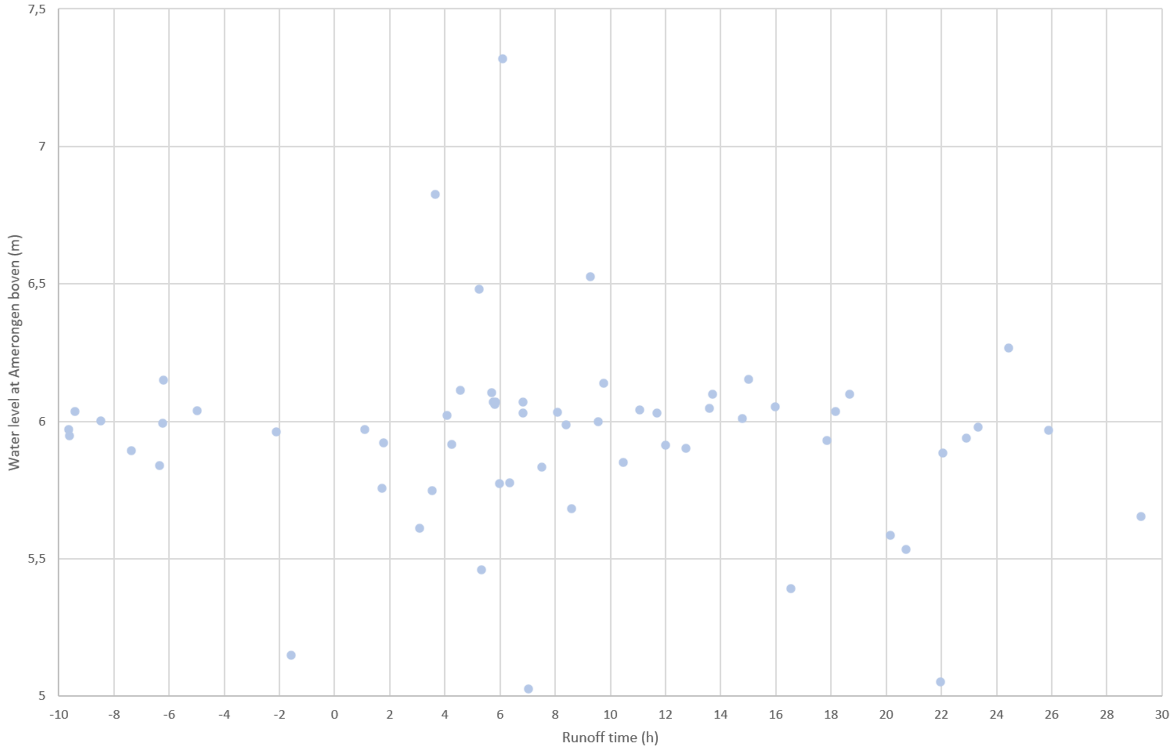
Appendix figure 42 - Driel boven and Grebbe (peaks, 2011 - 2019)

Grebbe – Amerongen boven



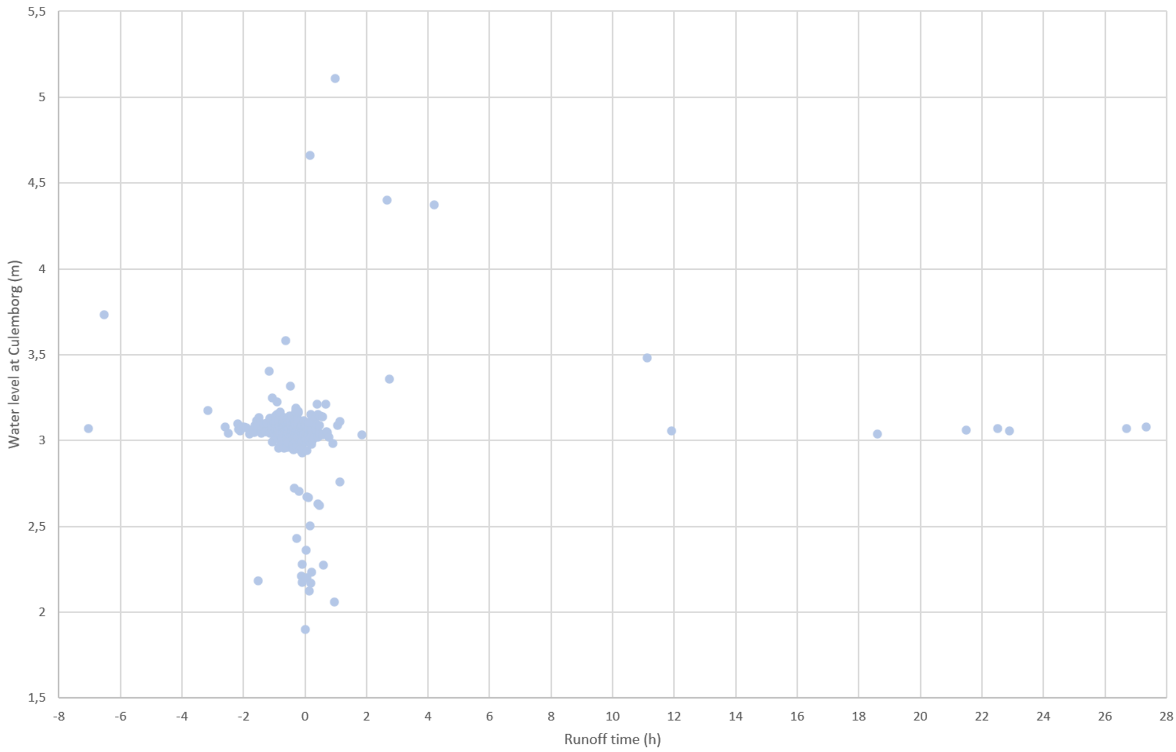
Appendix figure 43 - Grebbe and Amerongen boven (peaks, 2011 - 2019)

Amerongen boven – Culemborg



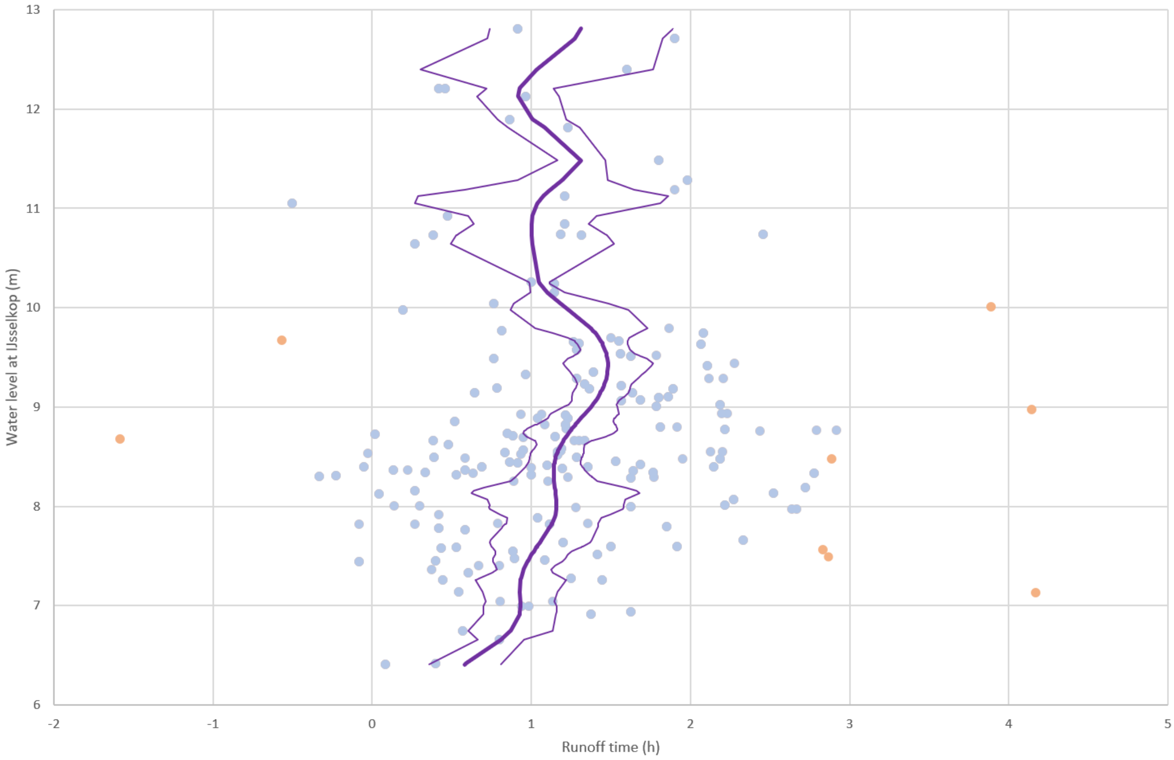
Appendix figure 44 - Amerongen boven and Culemborg (peaks, 2011 - 2019)

Culemborg – Hagestein boven



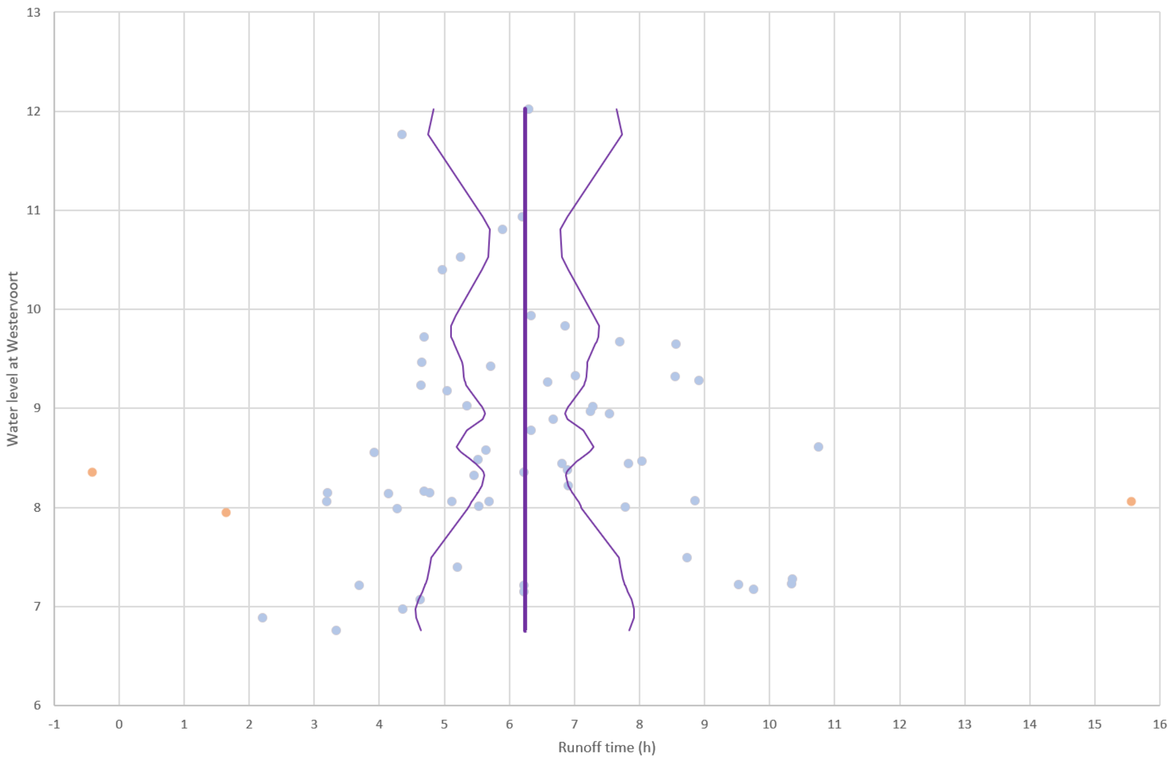
Appendix figure 45 - Culemborg and Hagestein (peaks, 2011 - 2019)

IJsselkop – Westervoort



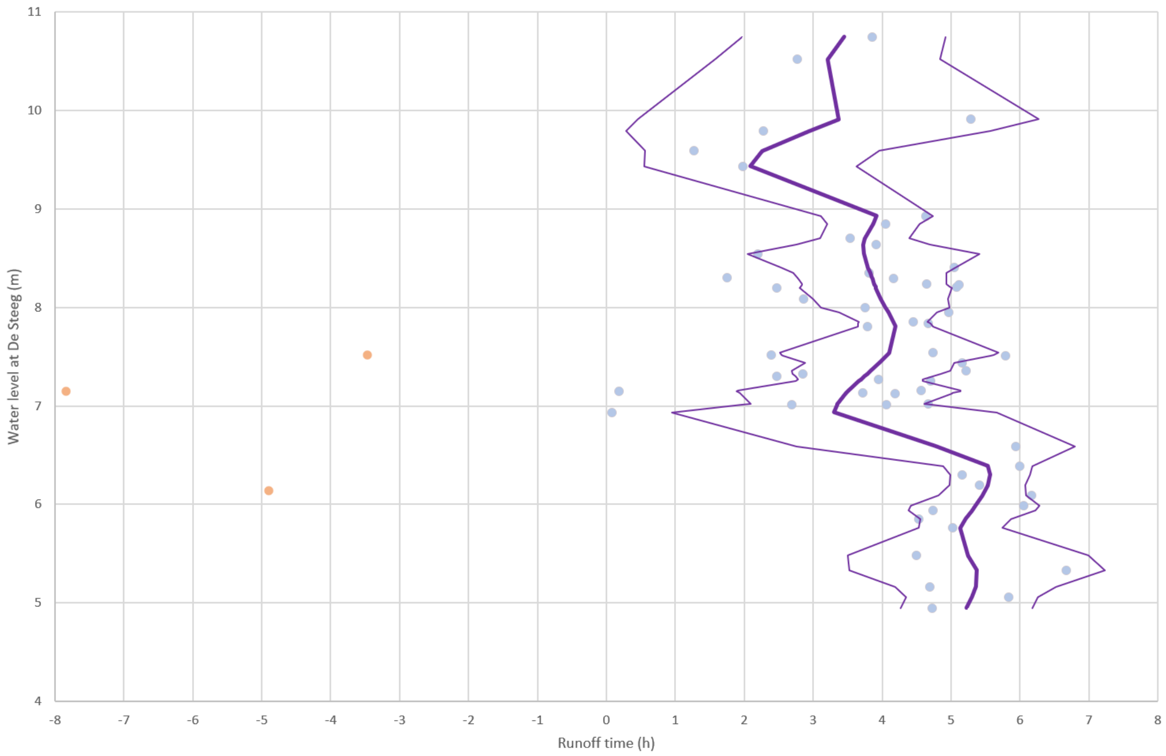
Appendix figure 46 - IJsselkop and Westervoort (peaks, 2011 - 2019)

Westervoort – De Steeg



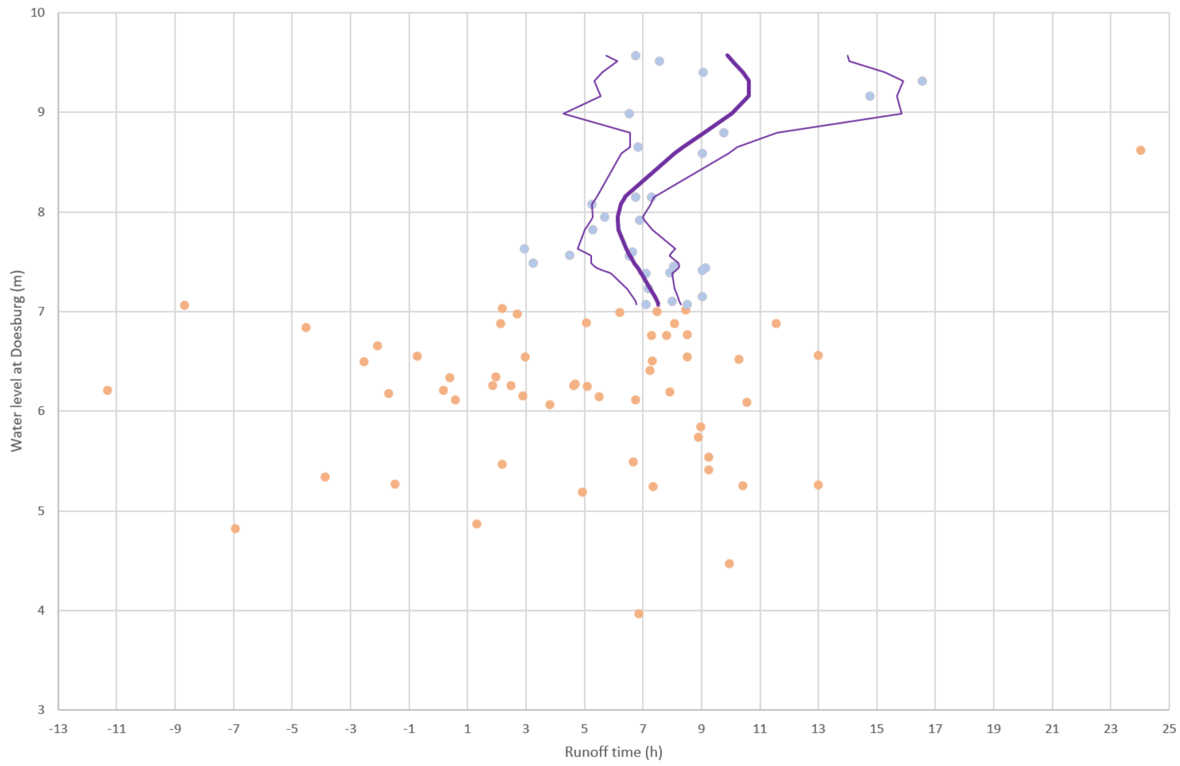
Appendix figure 47 - Westervoort and De Steeg (peaks, 2013 - 2018)

De Steeg – Doesburg



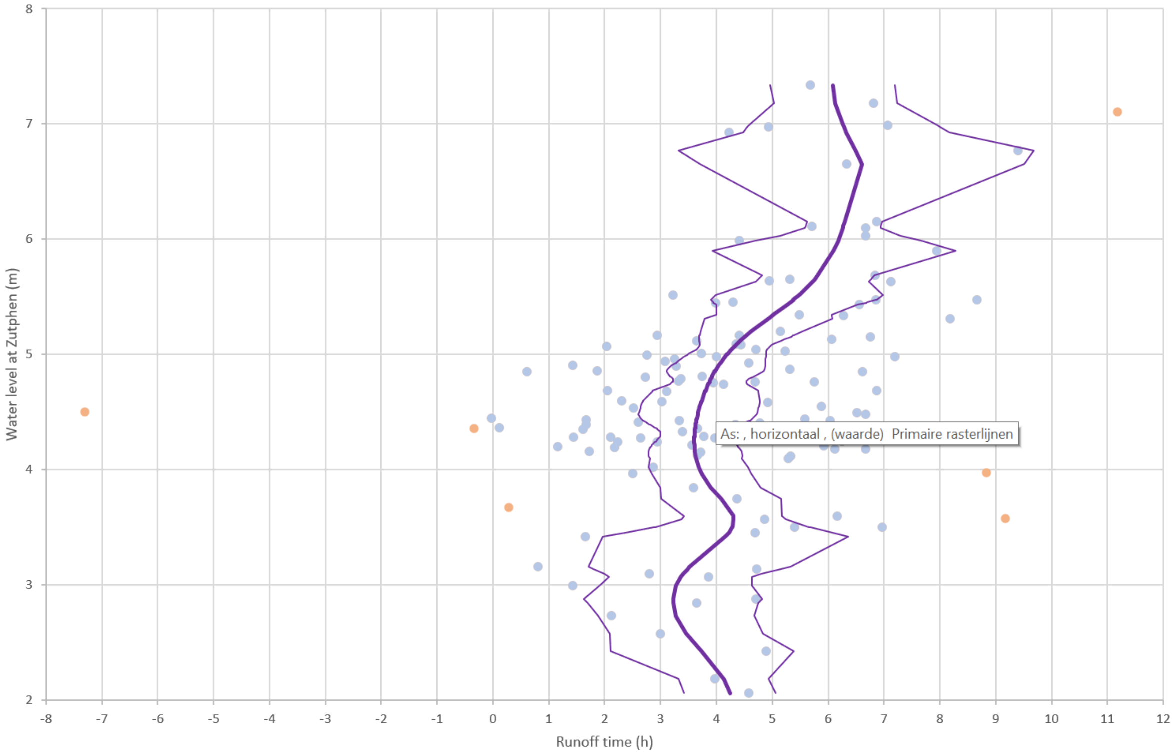
Appendix figure 48 - De Steeg and Doesburg (peaks, 2013 - 2018)

Doesburg – Zutphen



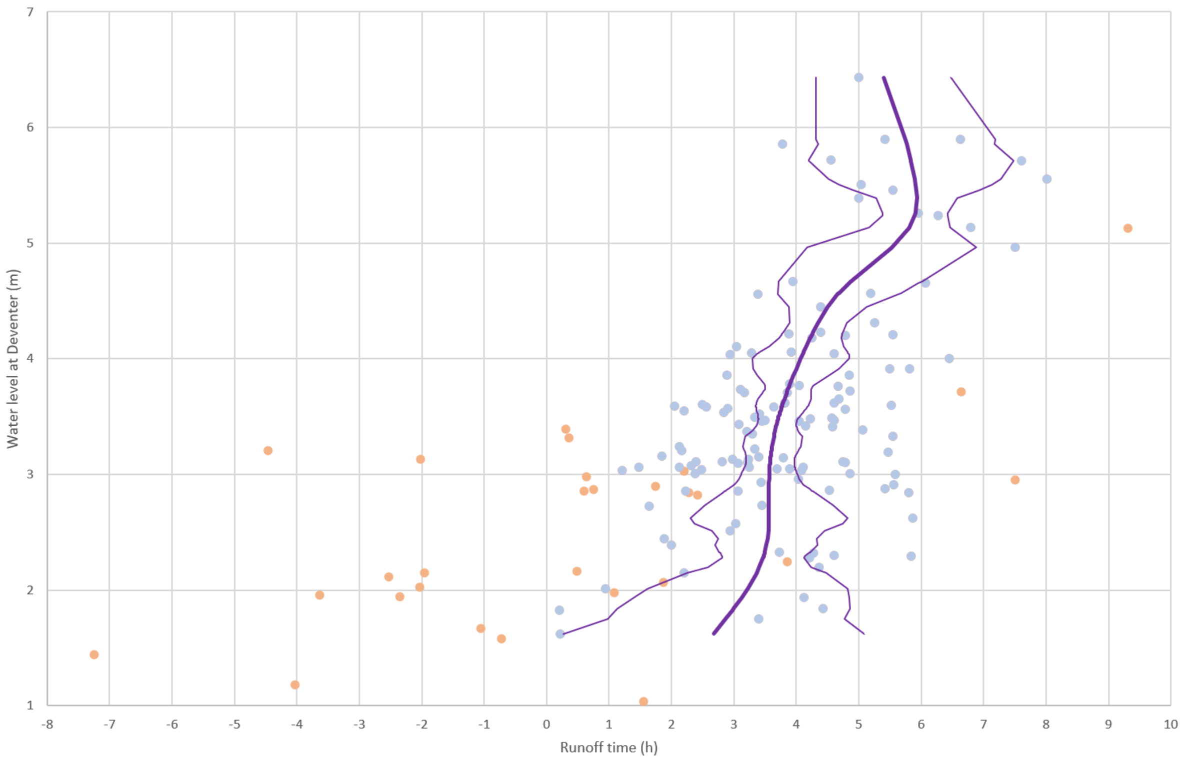
Appendix figure 49 - Doesburg and Zutphen (peaks, 2011 - 2019)

Zutphen – Deventer



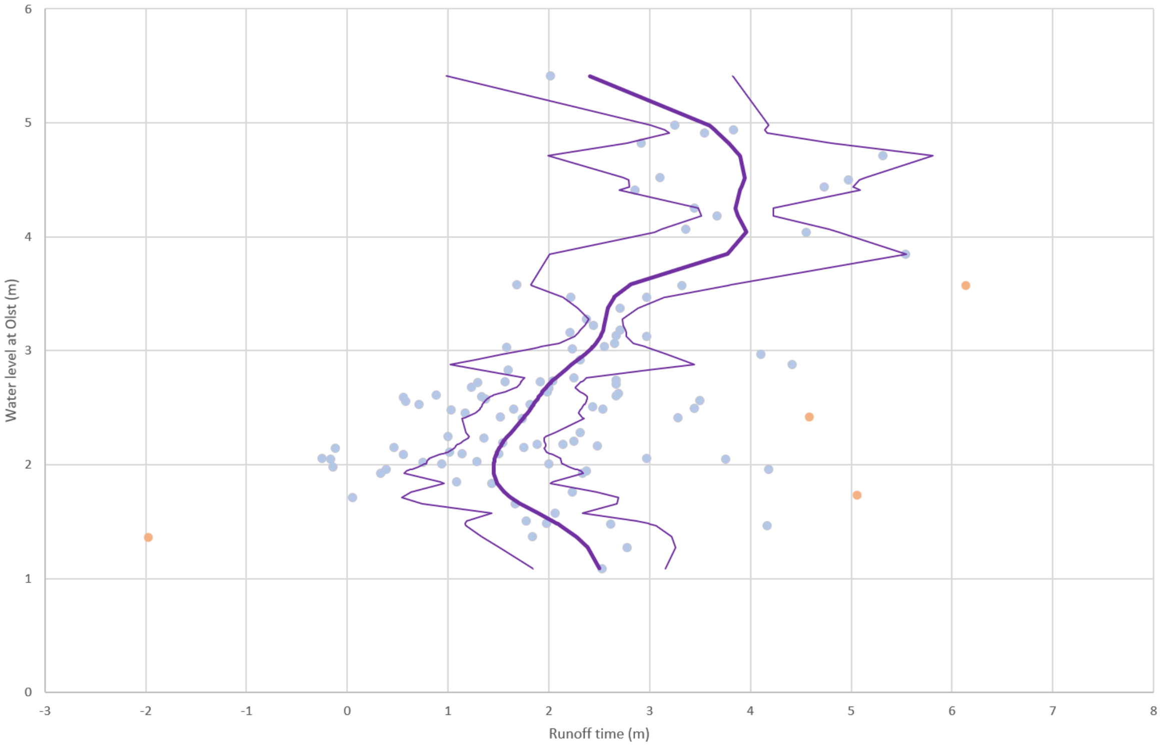
Appendix figure 50 - Zutphen and Deventer (peaks, 2011 - 2019)

Deventer – Olst

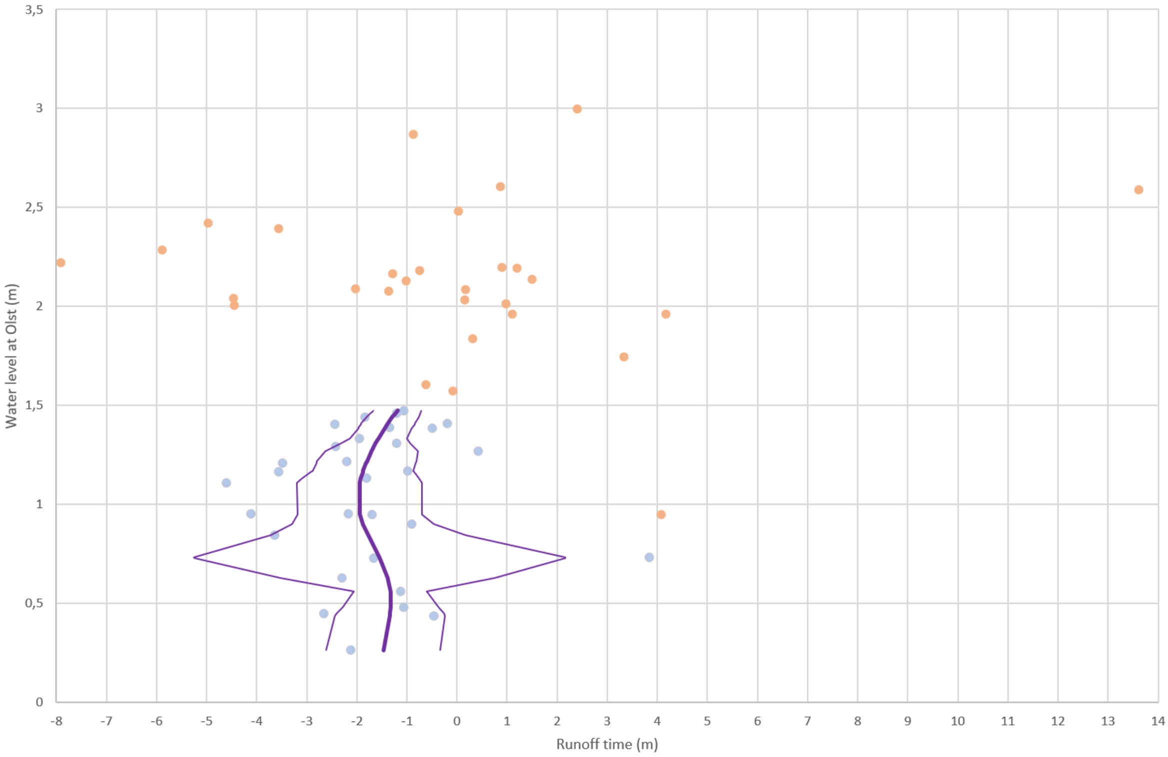


Appendix figure 51 - Deventer and Olst (peaks, 2011 - 2019)

Olst – Wijhe

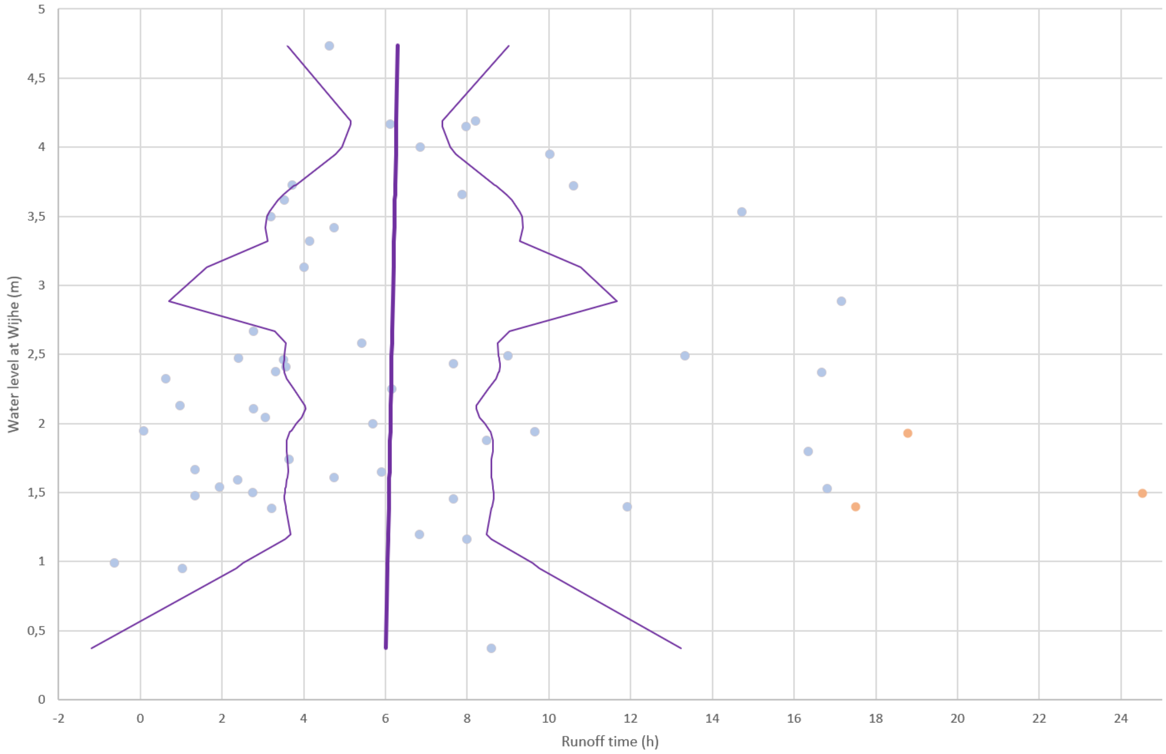


Appendix figure 52 - Olst and Wijhe (peaks, 2011 - 2019, downstream traveling waves)

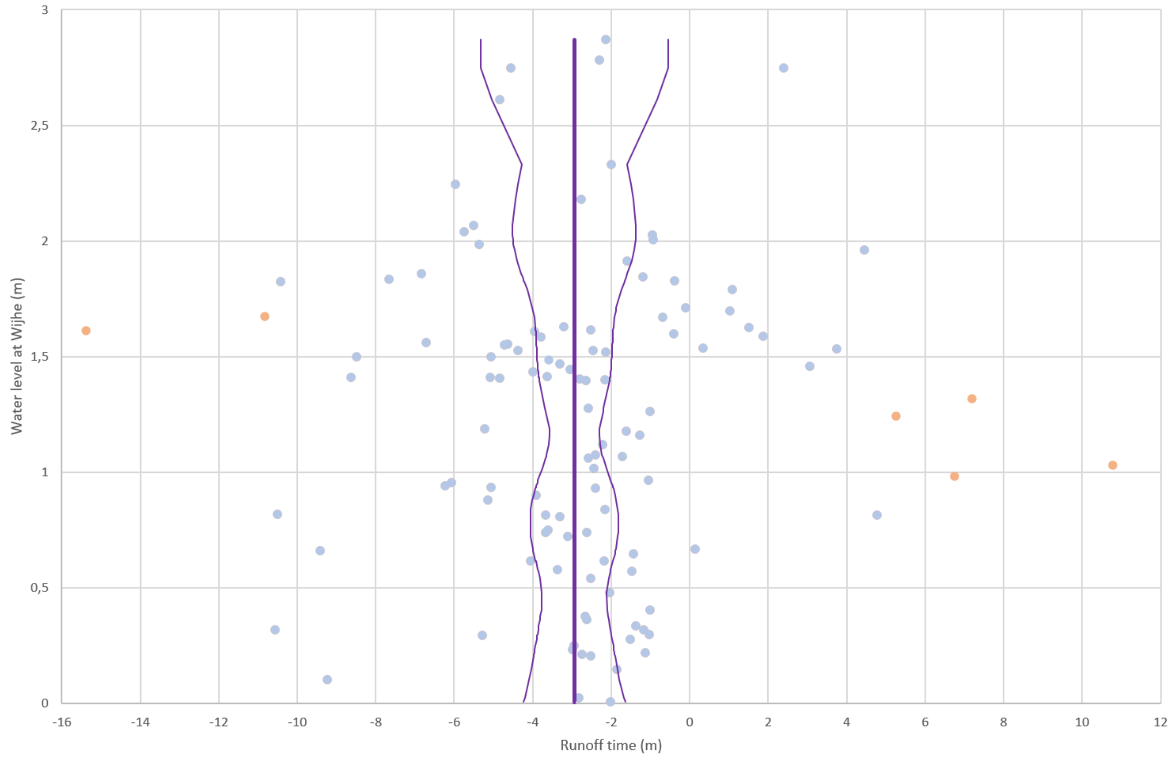


Appendix figure 53 - Olst and Wijhe (peaks, 2011 - 2019, upstream traveling waves)

Wijhe – Katerveer

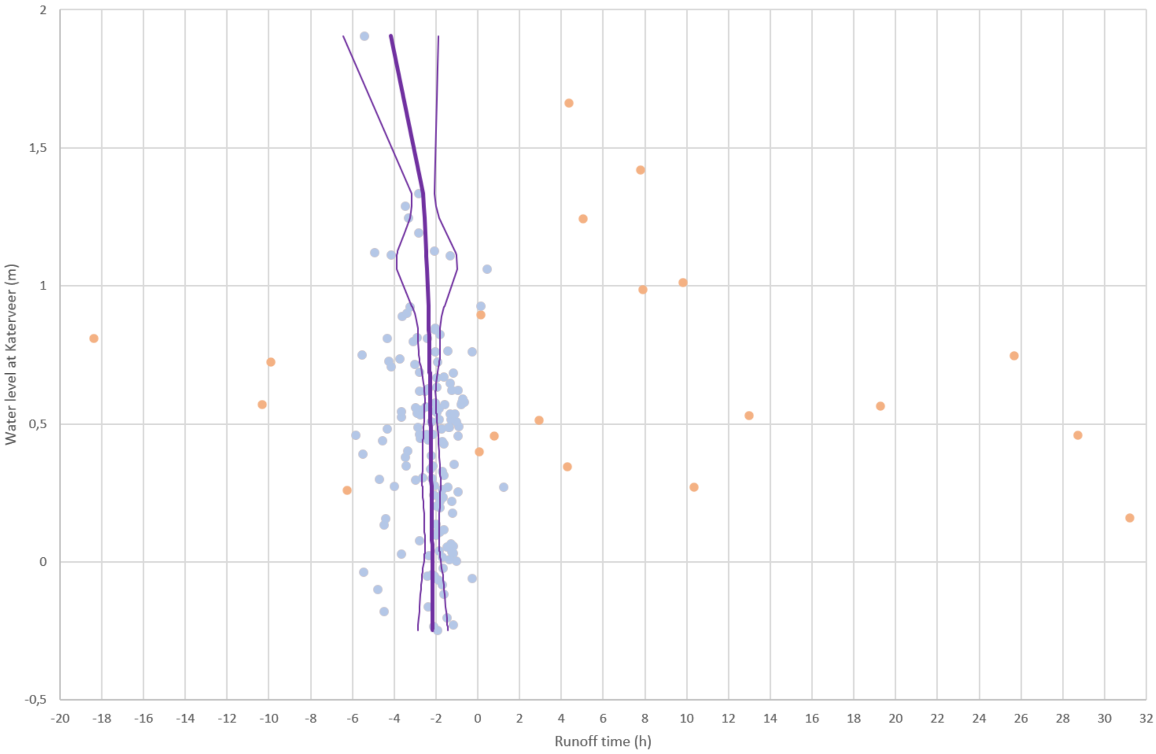


Appendix figure 54 - Wijhe and Katerveer (peaks, 2011 - 2019, Downstream traveling waves)



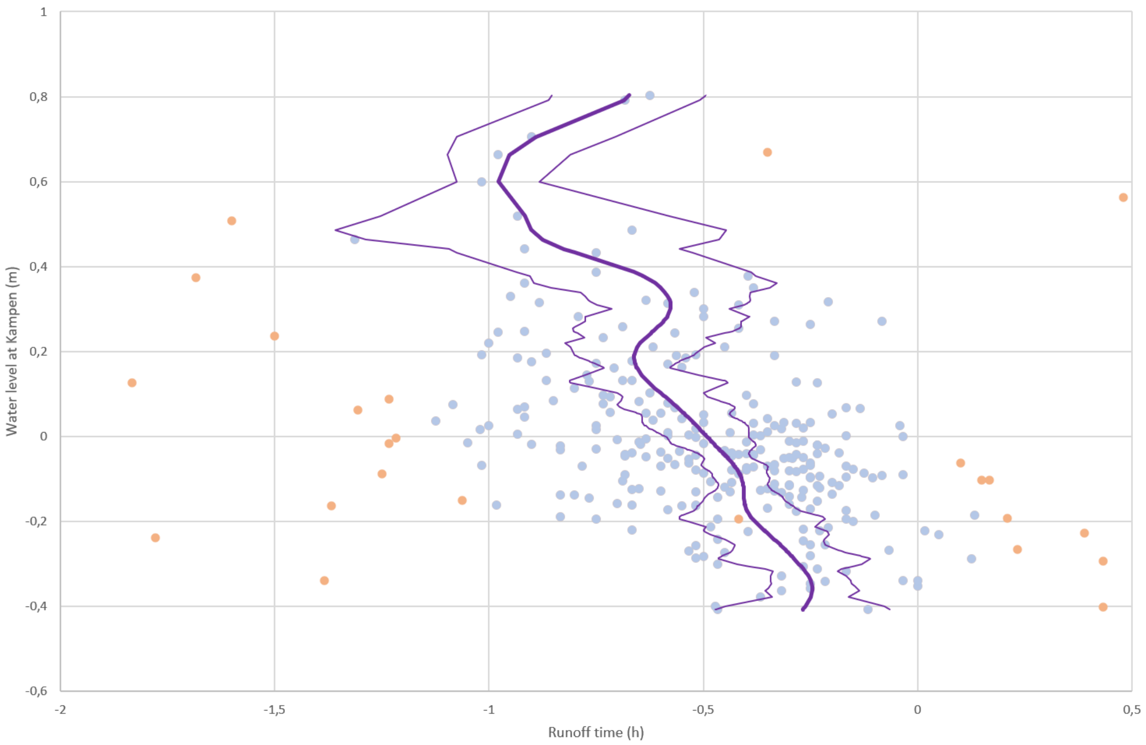
Appendix figure 55 - Wijhe and Katerveer (peaks, 2011 - 2019, upstream traveling waves)

Katerveer – Kampen



Appendix figure 56 - Katerveer and Kampen (peaks, 2011 - 2019, upstream traveling waves)

Kampen - Keteldiep



Appendix figure 57 - Kampen and Keteldiep (peaks, 2011 - 2019, upstream traveling waves)