The influence of vegetation on the hydraulic roughness

Determining the influence of vegetation on the hydraulic roughness and the variability therein in two streams of Waterschap Rijn & IJssel


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Right figure on the cover page is derived from Waterschap Rijn & IJssel (ter Maat 2010)

Preface

This is the final report of my Bachelor thesis for Civil Engineering at the University of Twente. I carried out this assignment at Waterschap Rijn & IJssel in collaboration with Deltares from April 12th 2021 until July 2nd 2021. Due to Covid-19, it was unfortunately not possible to work at the company's office but nevertheless I felt supported and welcome. I would like to thank everybody who helped me to complete this research. A special thanks goes to Koen Berends from Deltares, Gert van den Houten and John Lenssen from Waterschap Rijn & IJssel. Koen helped me locating and solving many of the errors that I encountered while modelling. I would like to thank John for his solid feedback on my report and guidance. Both John and Gert raised critical questions during the process which helped me gaining new insights on scientific reasoning. I would also like to thank Matthijs Gensen for his guidance and helpful feedback on writing this thesis. Without these people, it was impossible to write this thesis.

I hope you will enjoy reading this thesis. If you have any questions, you can contact me through email: l.janssen-1@student.utwente.nl.

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Enschede

Summary

Regional water authorities like Waterschap Rijn & IJssel have the task to regulate water levels but also to improve the water quality, water availability, and biodiversity in and around the surface water. The awareness of the ecological values of watercourses has grown and the regional water authorities now aim for a more natural environment in and around the water. The amount of vegetation plays an important role in this: it adds to habitat variation but it also increases the hydraulic roughness and thus the water level. When the discharge is too high, this can cause flooding. Removing vegetation, also called mowing, can help to reduce this.

Finding the balance between the amount of vegetation removal and flood risk reduction is challenging and requires more knowledge on the development of vegetation over time. Vegetation growth increases the hydraulic roughness of the river bed. The hydraulic roughness is hard to estimate and causes a lot of uncertainty in hydrodynamic models. This thesis is a first step in gaining more insight in the seasonal variation of the hydraulic roughness and the influence of vegetation on the hydraulic roughness. For this research, the hydraulic roughness was calculated for two watercourses in the area of Waterschap Rijn & IJssel: the Baakse Beek and Zwarte Beek. Using a SOBEK model and a Python optimization script, the Manning roughness coefficient was determined for each day of the year from 2013 up until 2020.

Next, the influence of vegetation on the hydraulic roughness was determined for both streams using the Beekruwheidsmodel. Even though the values for the vegetation parameter for the Baakse Beek and Zwarte Beek are relatively low, a seasonal pattern is noticeable. An increase in the vegetation parameter can be observed from April until August for most years. This increase is probably caused by the vegetation that starts growing during this period. For some years, also a sudden drop in the vegetation parameter and Manning coefficient can be seen. The beekruwheidsmodel does not predict this drop based on the discharge which makes it likely that it is caused by human intervention like mowing of the stream.

In this report, an extensive analysis of the results is done including a sensitivity analysis and a comparison to the Leijgraaf, a stream in Noord-Brabant. An earlier study in this stream showed that the Beekruwheidsmodel is capable of modelling the influence of vegetation on the hydraulic roughness. The comparison showed that a possible cause for the low value of vegetation parameter, is the low discharge in the Baakse Beek and Zwarte Beek. This thesis finalizes with the conclusion that for both the Baakse Beek and Zwarte Beek, the vegetation parameter is relatively low and that vegetation thus does not influence the hydraulic roughness much according to the Beekruwheidsmodel. Several suggestions and recommendations are given for further research: continue monitoring the water levels and discharges in the streams and add more measurement locations to streams that have a continuous discharge and a relatively high flow velocity.

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Symbol	Unit	Definition
Q	m^3s^{-1}	Discharge
h	m	Water level
n	$sm^{-1/3}$	Hydraulic roughness coefficient (Manning)
α	(-)	Vegetation parameter
t	day	Time
$\mathbf{i_b}$	m/km	Bed slope
$\mathbf{\alpha_{max}}$	(-)	Maximum value of the vegetation parameter
r	day^{-1}	Growth rate per day
$\mathbf{t_m}$	day	Day in time where growth rate is at its maximum

1. Introduction

1.1 Context

Regional water authorities are governmental organisations and have the task to manage the surface water in a certain area. It is their task to regulate water levels but also improve the water quality, water availability, and biodiversity in and around the surface water. Waterschap Rijn & IJssel (WRIJ) is responsible for managing the water in the east of Gelderland, the south of Overijssel and the south-east of the Veluwe. In total, this includes 200.000 hectare and around 3500 kilometres of streams (Waterschap Rijn & IJssel 2013b), as can also be seen in Figure 2.

The way in which the waterways and streams at WRIJ are managed, is strongly influenced by national and European legislation and policies. Traditionally, flood protection and drainage to facilitate agriculture were most important. However, awareness of the ecological values of watercourses has grown and culminated in regulations like “Wet Natuurbescherming” and the European Water Framework Directive. The latter two demand that water authorities like WRIJ aim for a more natural environment in and around the water. This is also written in the Water Vision 2030 (Waterschap Rijn & IJssel 2013a) of WRIJ where they follow regulations to protect vulnerable populations of endangered and protected species. Preserving vegetation is key, because this contributes to more biodiversity and a better water quality (Penning, Berends and Noorlandt, 2018).

Vegetation plays an important role in the area of regional water authorities. In general, more vegetation increases the hydraulic roughness of the riverbed and thus reduces the flow velocity and increases the water depth. At higher discharges, this may cause flooding. To prevent this, the vegetation in the stream can be removed by mowing. In 2019, a new policy plan for the mowing of streams was established (Waterschap Rijn & IJssel 2019). This policy plan acknowledges, next to managing water levels, the importance of improving the biodiversity in and around the water. This means that for example, in larger streams, only one bank is mown so that vegetation on the other bank is not disturbed throughout that year. The vegetation adds to habitat variation and thus increases the biodiversity. Due to the positive effects of vegetation, it is important to critically look into mowing streams. Mowing too often or removing too much vegetation is undesirable. It is thus important that the mowing of streams is done effectively and only when needed, so that a balance is found between the maximum water level regarding flood safety versus the biodiversity loss, economic expenses and, energy use. Regional water authorities make policy plans with different scenario’s (called maaiprofielen) to describe when and how the different streams are being mown.

1.2 Problem statement

Finding the balance in the amount of vegetation removal and determining the best strategy is challenging and requires more knowledge on the development of vegetation over time (Penning, Berends and Noorlandt, 2018). The management for the streams is not a fixed programme and the regional water authority WRIJ is looking for a different mowing policy (Waterschap Rijn & IJssel 2013a). Some regional water authorities use tools like *‘’ MaaiBOS’’* to determine the mowing policy (Penning, Berends and Noorlandt, 2018). This tool gives a warning signal when the relation between the discharge and water levels in a stream becomes critical. Instead of using *‘’ MaaiBOS’’* , WRIJ mows according to pre-set schedules, in which precise regime is based on the importance and size of the streams (Van Den Eertwegh *et al.*, 2017).

The present mowing schedules are based on rather rough assumptions with respect to (variability in) vegetation based hydraulic roughness. More detailed insight will allow more accurate planning of time and extent of vegetation removal. Besides, the prediction of water levels can improve the understanding of the situation thus make improvements regarding the mowing policy.

The hydraulic roughness is a parameter that describes the roughness of the watercourse. Vegetation growth increases the hydraulic roughness. As a consequence, it decreases flow velocity in the vegetated part of the watercourse and increases in flow velocity in the trajectory without vegetation (Penning, Berends and Gaytan Aguilar, 2020). The hydraulic roughness due to vegetation is hard to estimate and causes a lot of uncertainty in hydrodynamic models (Warmink, Straatsma and Huthoff, 2012). Moreover, roughness parameters are often considered constant throughout the year. This assumption is not realistic if the value of the roughness coefficient is largely determined by the vegetation growth. With a more realistic roughness parameter, that also acknowledges seasonal variation therein, the model will be more accurate and simulate reality better.

The beekruwheidsmodel is Python script that calculates influence of vegetation on the hydraulic roughness based on three vegetation parameters: the growth rate per day, the day of year with maximum growth rate and the maximum vegetation influence (Penning, Berends and Gaytan Aguilar, 2020). Based on those three parameters, the Beekruwheidsmodel estimates the Manning coefficient for each day of the year. The application of the beekruwheidsmodel at the streams of WRIJ can give the regional water authority a better understanding of the influence of vegetation on the hydraulic roughness and the possible consequences of their current mowing policy. This thesis can be seen as a first step in improving mowing policies. To determine the optimal mowing policy, more knowledge about the influence of vegetation on the hydraulic roughness (and thus water levels) is necessary to be known first.

1.3 Research goal and research questions

The goal of this research was to gain insight into the temporal and spatial variation of the influence of vegetation on the hydraulic roughness in streams of the Waterschap Rijn & IJssel. This variability of the influence of vegetation on the hydraulic roughness was determined using the beekruwheidsmodel.

The first step in this assignment was to select streams at the area of WRIJ and determine their characteristics. The following data was gathered for both streams:

1. The characteristics of the selected streams in the year 2021
   a. Types of vegetation that are present in the selected streams
   b. Density of the vegetation in the selected streams
   c. Dimensions of the selected streams
   d. Data of the water levels and discharges

Next, the temporal variation of the hydraulic roughness was estimated for the selected streams:

2. What is the temporal (i.e. within and between years) variation of the roughness coefficient for the selected streams?

The influence of vegetation on the hydraulic roughness was derived from this and the variation thereof:

3. What is the temporal and spatial variation of the influence of vegetation on the hydraulic roughness in the selected streams?
   a. How does the influence of vegetation on the hydraulic roughness change over the year and what differences and similarities of this influence can be found between different years?

With this sub question, the temporal variation in the influence of vegetation on the hydraulic roughness was determined for the individual streams. Secondly, the spatial variability in this influence was determined:

b. What are the differences and similarities between the different streams in the influence of vegetation on the hydraulic roughness?

1.4 General introduction to the methodology

This section serves as summary of the methodology. A more detailed explanation of the used methods can be found at the beginning of each chapter with its corresponding research question.

First, two stream trajectories are selected based on the following criteria: 1) the availability of accurate daily measurements of up- and downstream water levels; 2) availability of accurate daily measurements of discharge; 3) availability of cross sections in a SOBEK model and 4) with sufficient vegetation development.

Secondly, the daily hydraulic roughness (Manning coefficient) was calculated with the aid of SOBEK and a python optimalisation script (see Appendix G) using the water levels, discharge, and cross sections as input values. The Manning coefficient over time is the output value of this SOBEK model and the optimisation script.

In the third step, the measured Manning coefficients were decomposed into the influence of discharge and the influence of vegetation (α). To determine the influence of vegetation on the hydraulic roughness, the Manning coefficient is multiplied by the corresponding discharge. This results in the vegetation parameter α over time, that describes the influence of vegetation on the hydraulic roughness.

Finally, for each trajectory and year, the relevant vegetation growth parameters were estimated: the growth rate per day, the day of year with maximum growth rate and the maximum vegetation influence. Using the Beekruwheidsmodel, the prior distributions for each parameter were determined. Each of the three parameters are set as a normal distribution with a chosen mean and standard deviation. With these parameter distributions, the distribution of the vegetation parameter α and Manning coefficient can be determined. The calculated Manning coefficient from the Beekruwheidsmodel is compared to the measured Manning coefficient as obtained in research question two. The means of the parameter distributions are chosen such that such that all measured data points lie within the confidence interval of 95% of the calculated Manning coefficients. This is done via a trial-and-error process by adapting the means of the three parameters distributions. A schematization of this process is shown in Figure 1.

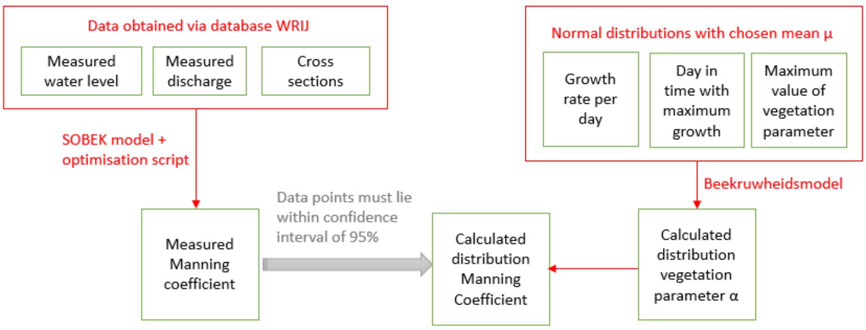

Figure 1 - Schematization of the trial-and-error process for determining the parameter distributions

Finally, these priors were used to estimate the exact values of the growth parameters using the Markov Chain Monte Carlo algorithm.

1.5 Scope

The project concerns a determination of the influence of vegetation on the hydraulic roughness of two streams in the management area of Waterschap Rijn & IJssel. For the beekruwheidsmodel, data is needed as input values. In order to obtain useful results and draw conclusions, the data needs to meet selection criteria. Both the quality and quantity of the available data is a limiting factor for this research.

The total management area of Waterschap Rijn & IJssel can be seen in Figure 2. WRIJ has gathered data for 19 of those streams for 6 years (2015– 2021). The data comes from a measuring network that measures the discharge and water depth of the 19 streams. The summers of 2017, 2018, 2019 and 2020 were very dry and therefore some of the data may be useless for this assignment: some of the streams had no discharge for a long period of the growing season. When the streams were selected, this was an important selection criteria.

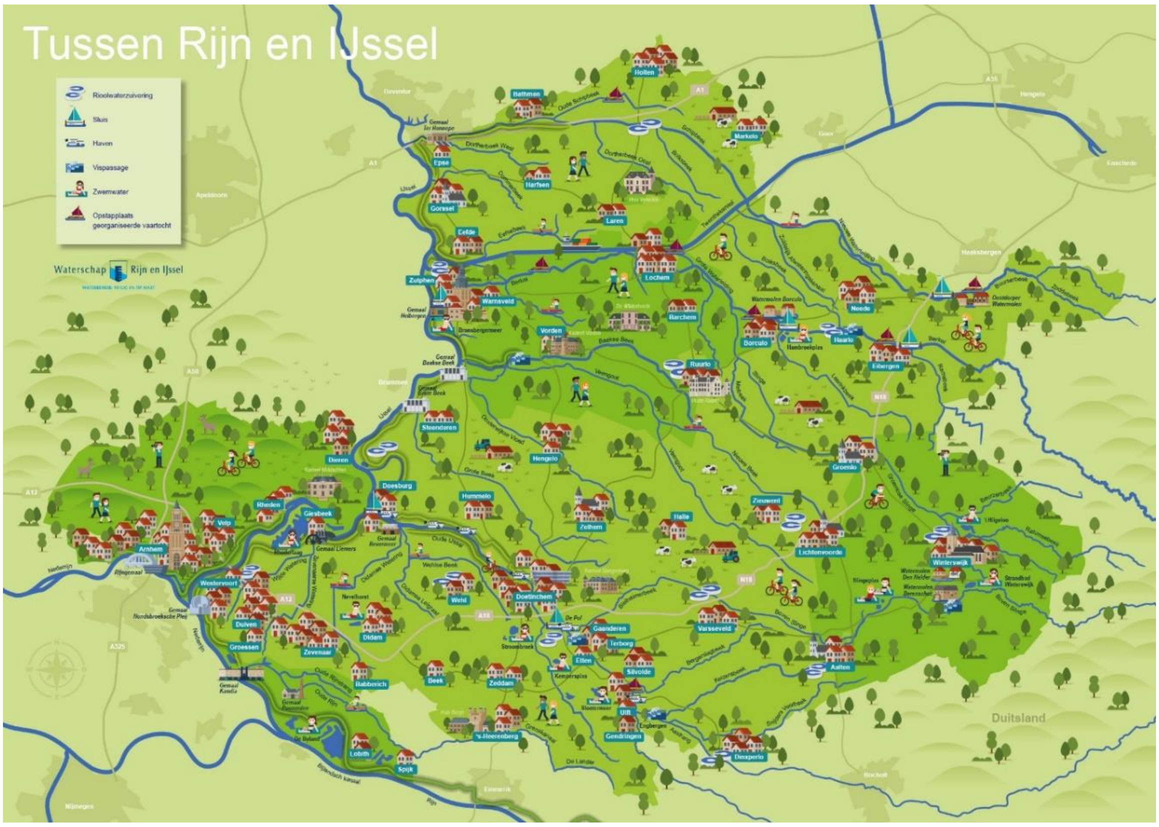

Figure 2 – The Management area of Waterschap Rijn & IJssel (Waterschap Rijn & IJssel, 2013)

For the first step of this thesis, the data was gathered at Waterschap Rijn & IJssel. The thesis started with selecting only one stream, the Baakse Beek, that had sufficient data and a SOBEK model available. The selected stream has a discharge > 0.05 m^3/s and a water depth > 0 m from at least the 1st of January until the 1st of September. Also, the dimensions of the stream (Dutch: profielmeting) were available and already implemented in the SOBEK model. The intention was to also look into 1 to 5 other streams which meet the same criteria but differ in location, average water depth, average discharge and/or different types of vegetation (compared to each other). In the end, the amount of time left available caused that only one other stream, the Zwarte Beek, was selected. Three other trajectories (Visserij, Wijde Wetering and Groenslose Slinge) were researched but the data of those trajectories did not met the selection criteria.

The two trajectories that were selected are: the Baakse Beek from weir Storck Horsterdijk to weir Kunnerij Bokkers and the Zwarte Beek from weir Keizer to weir Van Hal. Both trajectories have an almost continuous measurement record since the 1st of January 2013. The discharge of both trajectories is also larger than 0 m^3/s for a long period of the year, which is a requirement for the Beekruwheidsmodel to work. The third reason for choosing these two trajectories, is that they both do not have tributaries with a significantly large discharge compared to the main trajectory. This makes the discharge measurements more accurate and the SOBEK model simpler. More detailed information about the characteristics of the selected trajectories is given in Section 2.2 and Section 2.3.

2. RQ1: The characteristics of the selected trajectories

2.1 Methodology

The first research question was answered by conducting fieldwork and gathering data at Waterschap Rijn & IJssel. The first step was to select trajectories based on the available data. Waterschap Rijn & IJssel has data available for 19 different trajectories. Those trajectories are part of streams and watercourses and have a measurement point at the starting point and end point of the trajectory. A measurement location can be at a weir (Dutch: stuw) or at a regular measuring point (Dutch: niveaumeting). The discharge of a water course is always measured at a weir. At a weir, the ratio between the water depth and discharge is fixed and therefore the discharge can easily be calculated with a given water depth. For this research, the data of the selected trajectories was obtained via the software WISKI at Waterschap Rijn & IJssel.

2.2 Baakse Beek

The Baakse Beek is a watercourse in the east of Gelderland and belongs to the management area of Waterschap Rijn & Ijssel (Waterschap Rijn & IJssel 2008). The upstream part of the stream is at Lichtenvoorde, while the most downstream part of the stream is at Bronckhorst where it flows into the Gelderse IJssel. The total length of the water course is 35.3 kilometers.

For this research, a trajectory of the stream is selected from weir Storck Horsterdijk (upstream) to weir Kunnerij Bokkers (downstream), see Figure 3. This trajectory of the stream has a measuring point at the upstream and downstream point that provide the data needed for the Beekruwheidsmodel. As can be seen in Table 1 , this trajectory has a length of 3469 meters with its upstream point at a bed level of 16.65 m +NAP and its downstream point at a bed level of 15.65 m +NAP which results in an average bed slope of 0.288 m/km.

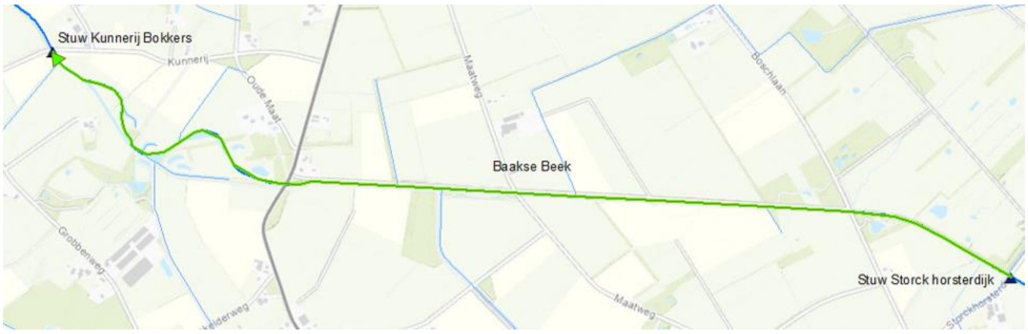

Figure 3 – Trajectory Baakse Beek from weir Storck horsterdijk (upstream) to weir Kunnerij Bokkers (downstream)

Table 1 - Characteristics Baakse Beek

	Baakse Beek
Length	3469 m
Average width	4 m
Bed level upstream	16.65 m
Bed level downstream	15.65 m
Average bed slope	0.288 m/km
Average yearly discharge	0.096 m^3s^{-1}
Average water depth upstream	0.519 m
Average water depth downstream	1.336 m

In Figure 4, the SOBEK model of the selected trajectory of the Baakse Beek can be seen. In this figure, the situation on the 1st of June 2013 is shown. The downstream water level boundary is 16.997m and the upstream discharge boundary is 0.017 m^3/s for that day. The figure shows the side view after running the model with these boundary data.

The jumps in the bed level as can be seen in Figure 4 are caused by the tributaries of the Baakse Beek (see Figure 3). In the SOBEK model, two cross sections are placed close to each other at those inflow points. In reality, no such jump in the bed level will exist since it will erode due to the discharge. However, the jumps in the bed level do not influence the outcome of the model and are therefore not removed.

In Figure 4, two culverts (Dutch: duiker) can be seen at 649.9m from the upstream point and at 3148.1m from the upstream point. Furthermore, the cross sections along the route are shown as the vertical structures. Some of the cross sections are close to each other and are therefore overlapping in the figure. In total, 34 cross sections are located along the trajectory.

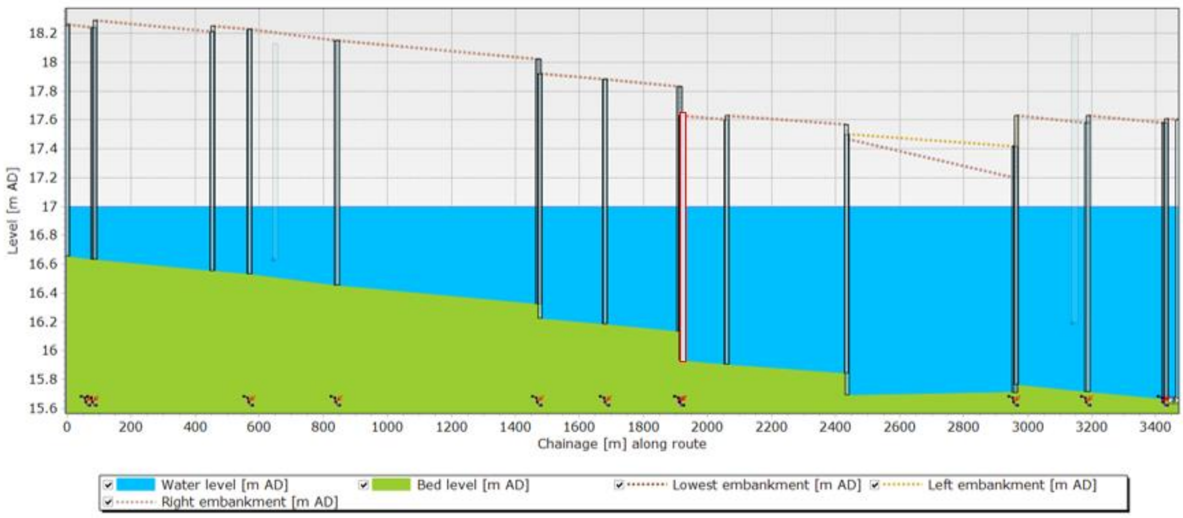

Figure 4 Baakse Beek side view

A cross section of the Baakse Beek at 1919.02 meters downstream from weir Storck Horsterdijk can be seen in Figure 5. This cross section is coloured red in Figure 4. The cross section has the shape of a trapezoid.

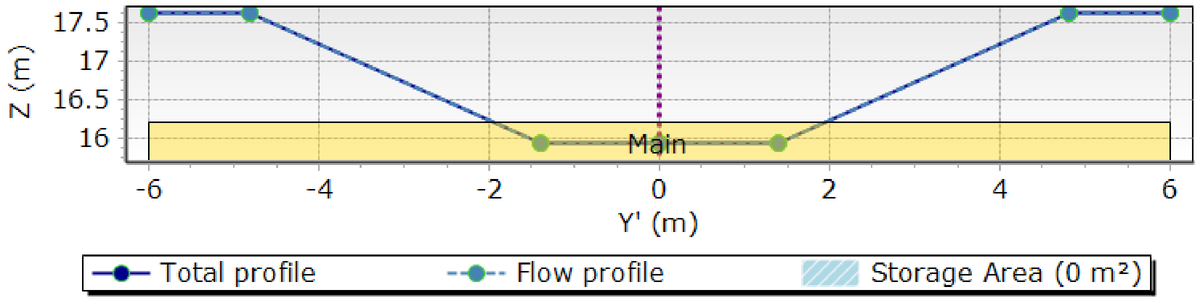

Figure 5 – Baakse Beek cross section at 1919.02 m from upstream measuring point

The following data are available for this trajectory:

- Daily average water levels downstream weir Storck Horsterdijk from 01/01/2013 to 03/05/2021
- Daily average water levels upstream weir Kunnerij Bokkers from 01/01/2013 to 03/05/2021
- Daily average discharge at weir Kunnerij Bokkers from 01/01/2013 to 03/05/2021
- In total 34 cross sections along the trajectory (design profiles)

The average yearly discharge at weir Kunnerij Bokkers is 0.096 m^3/s. As can be seen, there are some smaller tributaries that may occasionally cause extra discharge. However, this discharge is significantly small compared to the discharge in the mainstream Baakse Beek and is therefore neglected. It was assumed that the discharge at weir Storck Horsterdijk is the same as at weir Kunnerij Bokkers.

In Figure 6, the raw data of the Baakse Beek in the year 2016 is shown. The graphs of the years 2013 up until 2020 can be found in Appendix A. The year 2016 is shown here since this year has a continuous discharge larger than 0 m^3s^{-1} for almost the whole year. The blue graph shows the difference in upstream water level and downstream water level (water-surface slope) over time while the red graph shows the discharge over time. Between day 150 and day 250, peaks can be seen in the blue graph while the red graph does not show such high peaks. This increase in water-surface slope could possibly be caused by vegetation.

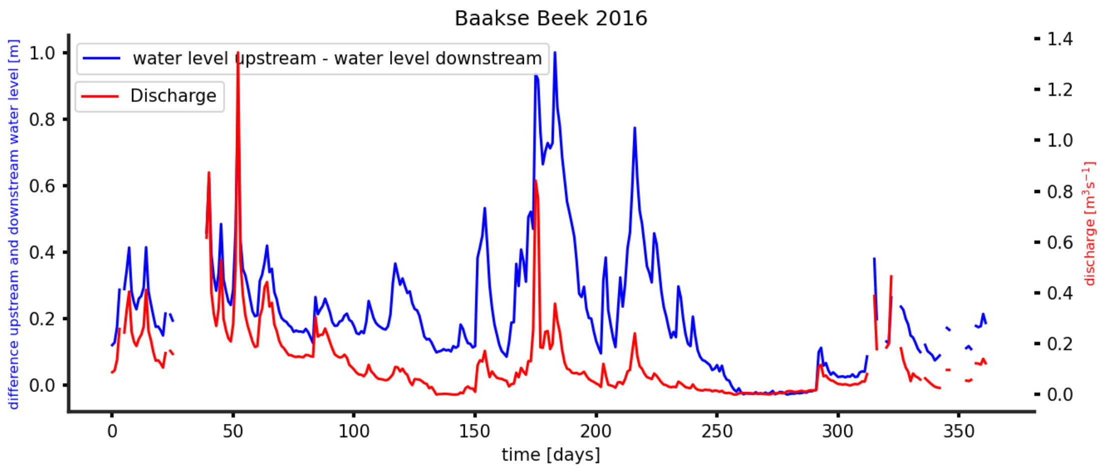

Figure 6 – Raw data Baakse Beek in 2016

For the mowing policy, this trajectory belongs to 'Category 1B' (Waterschap Rijn & IJssel 2020) since 2017. This means that one of the two banks is mown before the 1st of September. After the 1st of September, also the other bank is mown. In that way, at least 25% of the vegetation is still available during the breeding season. There is no data available on mowing in 2016 and before.

2.3 Zwarte Beek

The Zwarte Beek is a stream in the south of Gelderland near Voorst within the management area of Waterschap Rijn & IJssel. For this research, a trajectory of the stream is selected from weir Keizer (upstream) to weir Van Hal (downstream), see Figure 7. At weir Van Hal, this stream flows into the Aa Strang. As can be seen in Table 2, this trajectory has a length of 1324.25 meters with its upstream point at 13.77 m+NAP and its downstream point at 13.63 m+NAP which results in an average bed slope of 0.108 m/km.

Figure 7 – Trajectory Zwarte Beek from weir Keizer (upstream) to weir van Hal (downstream)

Table 2 - Characteristics Zwarte Beek

	Zwarte Beek
Length	1324 m
Average width	3.18 m
Bed level upstream	13.77 m
Bed level downstream	13.63 m
Average bed slope	0.108 m/km
Average yearly discharge	0.180 m^3s^{-1}
Average water depth upstream	0.628 m
Average water depth downstream	0.698 m

In Figure 8, the SOBEK model of the selected trajectory of the Zwarte Beek can be seen. In this figure, the situation on the 1st of June 2013 is shown. The downstream water level boundary is 14.341m and the upstream discharge boundary is 0.07 m^3s^{-1} for that day. The figure shows the side view after running the model with these boundary data. In Figure 8, the cross sections along the route are shown as the vertical structures. Some of the cross sections are close to each other and are therefore overlapping in the figure. In total, 8 cross sections are located along the trajectory.

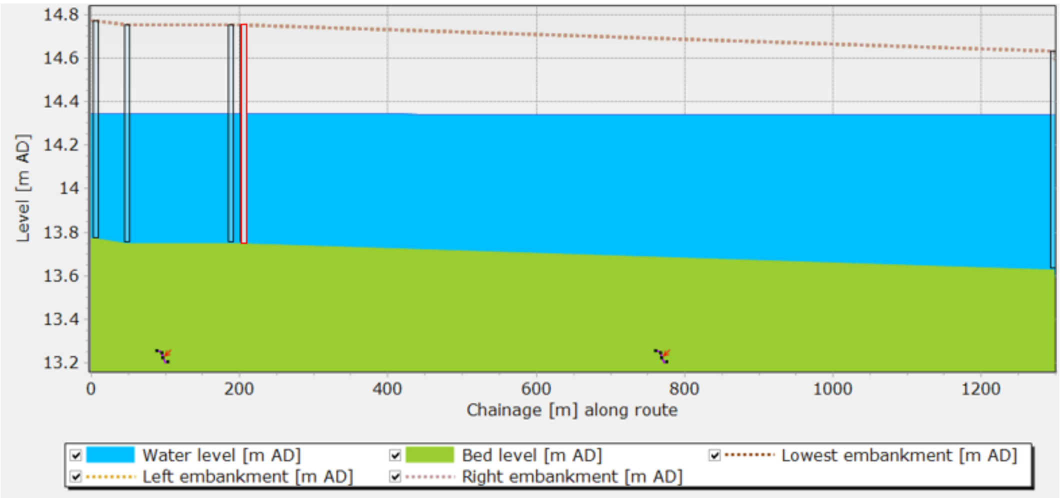

Figure 8 – Zwarte Beek side view

In Figure 9, the cross section of the stream can be seen at 207.37 m downstream from weir Keizer. This cross section is coloured red in Figure 8.

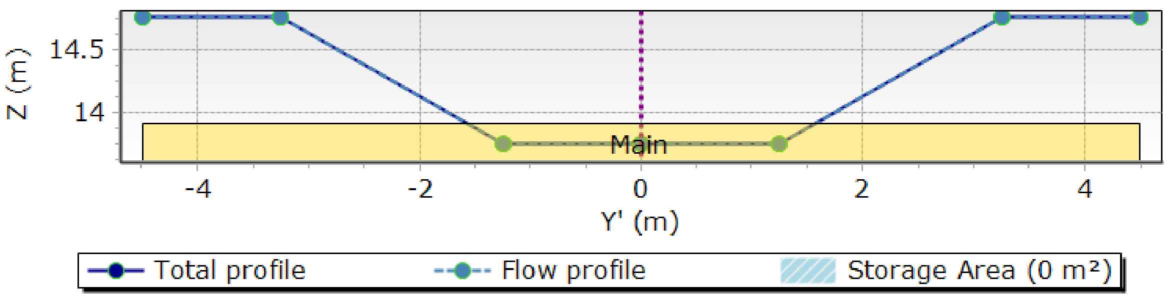

Figure 9 – Zwarte Beek cross section at 191.98 m from upstream point

The following data are available for this trajectory:

- Daily average water levels downstream weir Keizer from 01/01/2013 to 03/05/2021
- Daily average water levels upstream weir Van Hal from 01/01/2013 to 03/05/2021
- Daily average discharge at weir Van Hal from 01/01/2013 to 03/05/2021
- In total 8 cross sections along the trajectory (design profiles)

The average yearly discharge at weir Keizer is 0.18 m^3/s. As can be seen, there is one smaller tributary near weir Keizer that may occasionally cause extra discharge. However, this discharge is substantially small compared to the discharge in the main stream and will therefore be neglected. It is assumed that the discharge at weir Keizer is the same as at weir van Hal.

Figure 10 shows the raw data of the Zwarte Beek in 2015. This year is shown here because there are no missing data points, and the discharge is higher than 0 m^3s^{-1} for most of the year. The graphs of the years 2013 up until 2020 can be found in Appendix A. The blue graph shows the difference in upstream water level and downstream water level over time while the red graph shows the discharge over time. Around day 100 to 150, the discharge is only decreasing while there is a peak in the difference between the upstream and downstream water levels. This increase in water-surface slope could be due to vegetation growth.

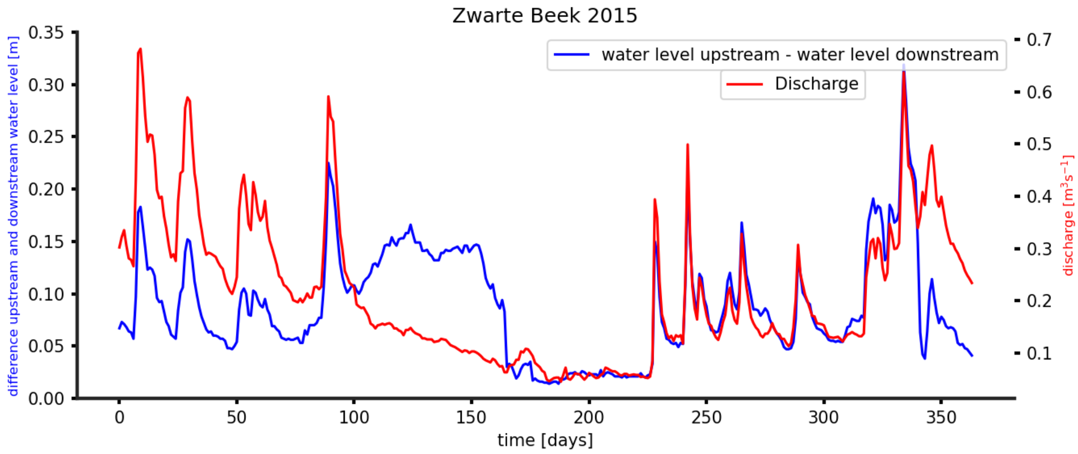

Figure 10 – Raw data Zwarte Beek in 2015

Since 2017, this trajectory belongs to 'Category 1C' for its mowing policy (Waterschap Rijn & IJssel 2020). This means that one of the two banks is mowed before the 15th of July. After the 15th of July, also the other bank is mowed. There is no data available about the mowing policy in 2016 and before.

2.4 Overview selected trajectories

In Table 3, the main characteristics of the two selected trajectories are given.

Table 3 – Overview characteristics trajectories

	Baakse Beek	Zwarte Beek
Length	3469 m	1324 m
Average width	4 m	3.18 m
Average bed slope	0.288 m/km	0.108 m/km
Average yearly discharge	0.096 m^3s^{-1}	0.180 m^3s^{-1}
Average water depth upstream	0.519 m	0.628 m
Average water depth downstream	1.336 m	0.698 m

3. RQ2: The temporal variation of the hydraulic roughness coefficient

3.1 Methodology

The data (discharge and water level over time) that are gathered in the trajectories described above, are implemented in the different SOBEK models for these streams to calculate the hydraulic roughness coefficient. For this research, the Manning coefficient is used to describe the hydraulic roughness. The Manning equation (see Equation 1) can be used to calculate the Manning coefficient. This equation describes the relationship between the discharge and water level, assuming that the flow is both uniform and stationary:

$$Q = \frac{A(d)d^{\frac{1}{6}}}{n}\sqrt{R(d)i_b} \tag{1}$$

Where the discharge Q (m^3s^{-1}), flow area A (m^2), water depth d (m), hydraulic radius R (m) and bed slope i_b (mm^{-1}). This equation is not applicable to the selected trajectories since the water depth is also dependent on the setting of downstream weir and not only on the roughness coefficient, discharge, and cross section. Therefore, a SOBEK model is used to calculate the Manning coefficient corresponding to the measured discharge and water levels.

In this SOBEK model, the measured downstream water level is set as a boundary condition for the downstream node and the measured discharge is set as boundary condition for the upstream node. For both trajectories, the measurement location for the discharge is downstream. As explained in Section 2.2 and Section 2.3, it is assumed that the discharge at the upstream node is the same as at the downstream node. Furthermore, it is assumed that the hydraulic roughness is uniform and thus equal along the whole trajectory.

The hydraulic roughness is derived from the relationship between the water levels and corresponding discharge using an iterative process called inversed modelling with SOBEK 3.7.9. A Python optimisation script (see Appendix G) was used for all different discharges and water levels such that the hydraulic roughness is determined for each day of the year. A schematic version of this process can be seen in Figure 11, where the relationship between the measured discharge and water level correspond to a roughness coefficient of 0.25 $sm^{-1/3}$. The optimisation script calculates the water level based on the measured discharge and a possible roughness coefficient using Equation 1. The values of the parameters A and R can be calculated for the given cross section since the water depth is known and the value of i_b is also given for the trajectory. The calculated water level is compared to the actual measured water level. The roughness coefficient is adapted (increased or decreased in value) based on the calculation result and this process is repeated until the absolute difference between the calculated water level and measured water level is small enough (error is <0.1cm). The value of the hydraulic roughness coefficient that results in a calculated water level close enough to the actual water level, is set as the hydraulic roughness coefficient for that specific discharge.

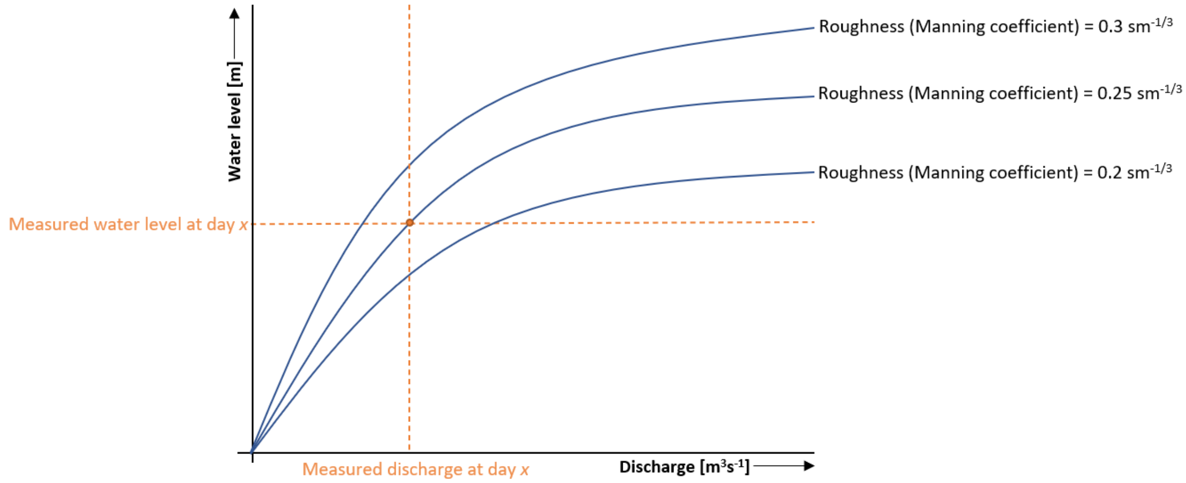

Figure 11 – Possible relationships between discharge and water level to find the corresponding roughness coefficient

As can be seen in Figure 11, each data point consists of a discharge that belongs to a certain Manning Coefficient. Besides plotting the Manning coefficient over time to answer the research question, the Manning coefficient is also plotted against the discharge. This graph can help to create a better understanding of how the roughness coefficient changes in case the discharge increases or decreases. In the resulting figure, a distinction is made between the data points in summer (growing season) and winter (non-growing season). In that way, it is possible to see how the Manning coefficient changes during summer and winter with the same discharge.

3.2 Baakse Beek

In Figure 12, variation in the roughness coefficient (Manning) over time can be seen for the Baakse Beek. Seasonality can be seen in the peaks in the roughness coefficient halfway during the years. Those peaks could be caused by a peak in discharge or by vegetation. For some years, this peak in Manning coefficients is earlier than in other years. Even though some years have a later growing season compared to other years, for all years it holds that the Manning coefficient starts to increase in the 4th month (April). It is possible that this increase is due to vegetation growth, which starts growing around this time as well.

For some days, the roughness coefficient is unrealistically high (Manning coefficient >0.5 $sm^{-1/3}$). In Appendix B, the roughness coefficient and discharge are plotted for each year separately. When the SOBEK model returns a roughness coefficient that is unrealistically high, the corresponding discharge is low or equal to 0 m^3s^{-1}. The roughness coefficients that belong to a discharge of 0 m^3s^{-1}, are not shown in Figure 12 since the SOBEK model is not able to calculate the Manning coefficient in those cases. The roughness coefficients that are unrealistically high, are considered useless for this research and are not taken into account for the analysis of the results. An interesting observation is the fact that the minimum roughness coefficient during the years 2017, 2018, 2019 and 2020 is higher compared to the years before. This can for example be due to a different measuring method of the water levels and discharge, a change in the cross-sectional area, a calibration error in the measurements, or a difference in the mowing policy.

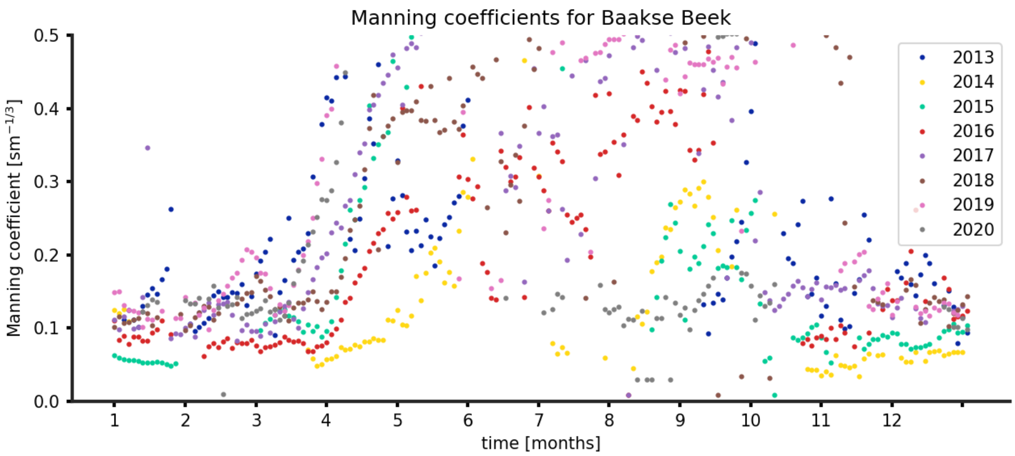

Figure 12 - The temporal variation of the Roughness coefficient of the Baakse Beek

In Figure 13, the relationship between the discharge and roughness coefficient for the Baakse Beek can be seen. A distinction is made between the summer (1st of April until 1st of October) and winter period (1st of October until the 1st of April next year). An inverse relationship can be seen between the discharge and Manning coefficient. If vegetation influences the roughness coefficient significantly, it is expected that a difference can be seen between the data points in the growing season where vegetation is present, and the data points in the non-growing season where there is little to no vegetation present. It is expected that with the same discharge, the data points in summer have a higher corresponding Manning coefficient compared to the data points in winter (so the red data points lie above the blue data points). As can be seen in Figure 13, a clear distinction between the two types of data points can be seen. The data points that belong to a discharge of 0 m^3s^{-1} are not plotted in this figure. First of all, the average discharge during summer is lower compared to winter so the red cluster of data points lies more to the left compared to the blue data points. Secondly, with the same discharge (for example at 0.1 m^3s^{-1}), the red data points lie higher on average compared to the blue data points. It is thus possible that vegetation does influence the roughness coefficient in this trajectory. This hypothesis will be checked at Section 4.2.

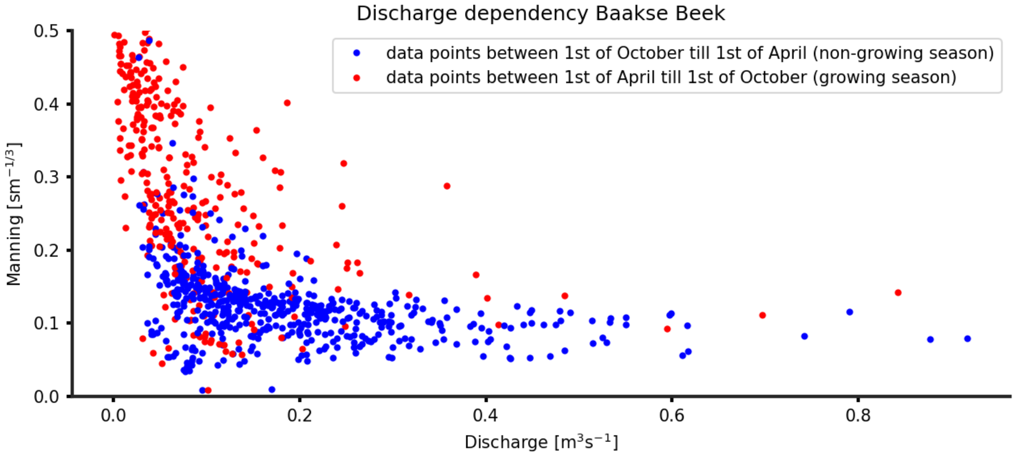

Figure 13 - Relationship between discharge and roughness coefficient Baakse Beek

3.3 Zwarte Beek

In Figure 14, the variation in the roughness coefficient (Manning) over time can be seen for the Zwarte Beek for all different years. The Manning coefficients that belong to a discharge of 0 m^3s^{-1} are not plotted in this figure. As can be seen in the figure, the blue points show peaks halfway during the years. This seasonality in the roughness coefficient can be due to the vegetation. For some years, the peaks in the roughness coefficient are higher than for other years. Especially the years 2013, 2018 and 2020 show high peaks in the roughness coefficient. In the years 2017, and 2019, the Manning coefficient remains low during spring and summer. Furthermore, the minimum roughness coefficient from 2017 onwards is lower than the minimum roughness coefficient in the years before. Different changes can be the cause of this, for example a change in the measuring method for the water levels and discharge, a change in mowing policy (less vegetation is removed), a calibration error in the measurement network, or a change in the cross-sectional area of the trajectory.

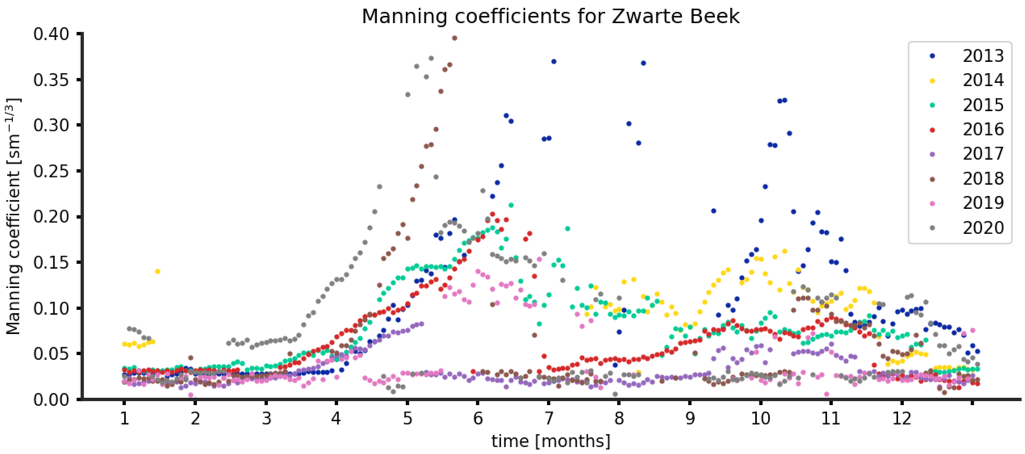

Figure 14 - The temporal variation of the roughness coefficient of the Zwarte Beek

In Figure 15, the relationship between the discharge and roughness coefficient for the Zwarte Beek can be seen. Similarly to the Baakse Beek, also in this graph the data points that belong to a discharge of 0 m^3s^{-1} were removed from the figure. This is because the roughness coefficient cannot be calculated by the SOBEK model in case the discharge is equal to 0 m^3s^{-1} . In Figure 15, a distinction is made between the data points in the growing season (red) and the data points in the non-growing season (blue). An inverse relationship between the discharge and the roughness coefficient can be seen: the lower the discharge, the higher the roughness coefficient. Also, a difference between the summer and winter data points here. Especially with lower discharges (around 0.1 m^3/s), it can be seen that the red data points lie above the blue data points. When vegetation is present (summer), the roughness coefficient is higher than when vegetation is less present (winter) with the same discharge. This suggests that vegetation influences the roughness coefficient.

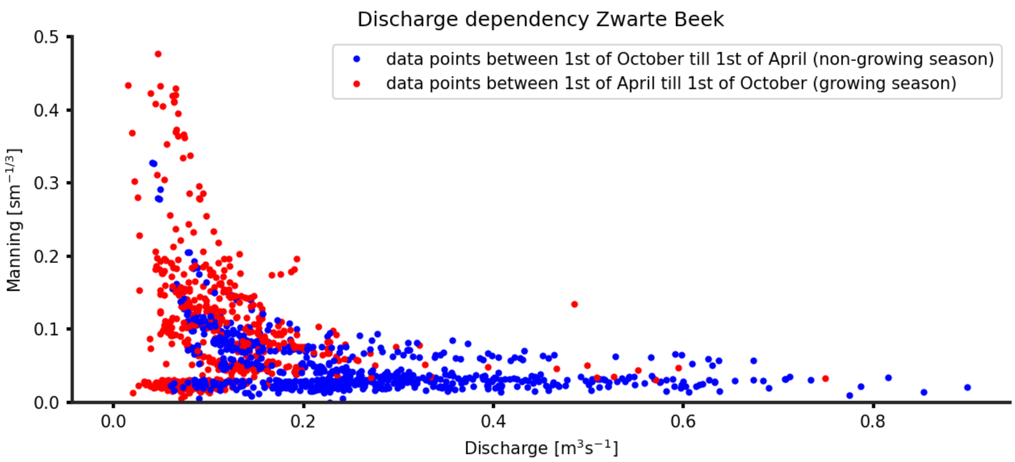

Figure 15 - Relationship between discharge and roughness coefficient Zwarte Beek

4. RQ3: Variation of influence of vegetation on hydraulic roughness

4.1 Methodology

To assess the temporal variation in the influence of vegetation on hydraulic roughness, it is important to distinguish it from the role of discharge. Equation 2 describes how vegetation and discharge influence the hydraulic roughness coefficient (Penning, Berends and Gaytan Aguilar, 2020):

$$n(t) = \frac{\alpha(t)}{Q} + n_b \tag{2}$$

Where n is the Manning coefficient ($sm^{-1/3}$), Q is the discharge (m^3s^{-1}) and n_b ($sm^{-1/3}$) the amount of roughness that is always present in the watercourse, also without any vegetation growth. In this equation, α is the vegetation parameter and it describes the relative contribution of vegetation to hydraulic roughness (effectiveness of the vegetation). The Manning coefficient and vegetation parameter are determined for each time step and are therefore dependent on the time *t* (days). Since the Manning coefficient at each t was found in the previous research step (Section 3.2 and Section 3.3), the measured influence of vegetation on the hydraulic roughness can be calculated using Equation 3:

$$\alpha(t) = Q(n(t) - n_b) \tag{3}$$

For each *t*, i.e. day of the year, the discharge is known via the available data. For the basic roughness n_b that is always present in the system, an assumption was made in order to calculate the vegetation parameter α. The value of the basic roughness coefficient n_b can be assumed as the minimum value of the roughness coefficient as can obtained at RQ 2 in Section 3.2 and Section 3.3. Using the discharge data and the measured Manning coefficients, the measured vegetation parameter was calculated.

Besides deriving the vegetation parameter from the measured Manning coefficient, the vegetation parameter can also be determined using the Beekruwheidsmodel (Penning, Berends and Gaytan Aguilar, 2020). As explained in Section 1.4, the vegetation parameter consists of three parameters: the growth rate, the day in time where the growth rate is at its maximum and the maximum value of the vegetation parameter. This can also be seen in Table 4.

Table 4 – Parameters and their definitions for the Beekruwheidsmodel

Parameter	Unit	Definition
α_{max}	$m^{-1/9}$	Maximum value of the vegetation parameter
r	day^{-1}	Growth rate per day
t_m	day	Day in time where growth rate is at its maximum

Together, these three prior distributions are used to calculate the vegetation parameter α, assuming a logistic growth curve, using Equation 4 (Penning, Berends and Gaytan Aguilar, 2020):

$$\alpha = \frac{\alpha_{max}}{1 + e^{-r(t-t_m)}} \tag{4}$$

where the parameters are described in Table 4 and where *t* is the time in days. Instead of choosing one value of each parameter, each of the three parameters are set as a normal distribution with a chosen mean and standard deviation. The beekruwheidsmodel results in a graph with the measured Manning coefficients as data points and the modelled Manning coefficient as probability distribution. The distribution of the modelled Manning coefficient is calculated by implementing the normal distributions of each parameter in Equation 4. The means of the parameter distributions are chosen such that the measured Manning coefficient obtained at research question 2, lies within the confidence interval of 95% of the calculated Manning coefficient. The boundaries of the confidence intervals are shown by blue coloured planes in the graph. The blue coloured band widths each represent a different confidence interval:

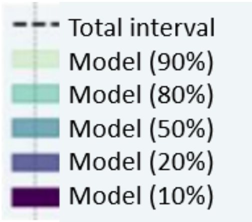

Figure 16 - Confidence interval Beekruwheidsmodel (prior)

This means that for example, the probability that the actual Manning coefficient calculated by the Beekruwheidsmodel, lies in the navy-blue interval, is 10%. The goal is to choose the means of the parameter distributions in such a way that the measured Manning coefficients lie within the total interval. For the prior distribution, this is done manually via trial and error but with the Markov Chain Monte Carlo algorithm, this process of determining the values of the parameters is optimised.

When the measured Manning coefficient suddenly drops while the beekruwheidsmodel does not expect a drop in the Manning coefficient, it might be the case that human intervention took place. For example, mowing the watercourse could lead to a lower Manning coefficient which is not expected by the model. This moment in time of human intervention needs to be implemented manually in the model. In this way, different sections were created, and each section has two boundaries of either a new year (1st of January) or a moment where mowing took place. The parameter distributions were calculated separately for each section.

4.2 Baakse Beek

In this section, first the vegetation parameter is calculated for the Baakse Beek. Secondly, the Beekruwheidsmodel is applied to determine the influence of vegetation on the hydraulic roughness using the prior distributions for the vegetation parameters.

Vegetation parameter Baakse Beek

In Figure 17, the influence of vegetation on the hydraulic roughness coefficient over time can be seen for the Baakse Beek. For this calculation, a basic roughness n_b of 0.02 $sm^{-1/3}$ is assumed because the Manning coefficient for this trajectory is always higher than 0.02 $sm^{-1/3}$ (see Figure 12 and Figure 13), also in winter when no vegetation is present. The data points that have a corresponding discharge of 0 m^3s^{-1} are not shown in this figure.

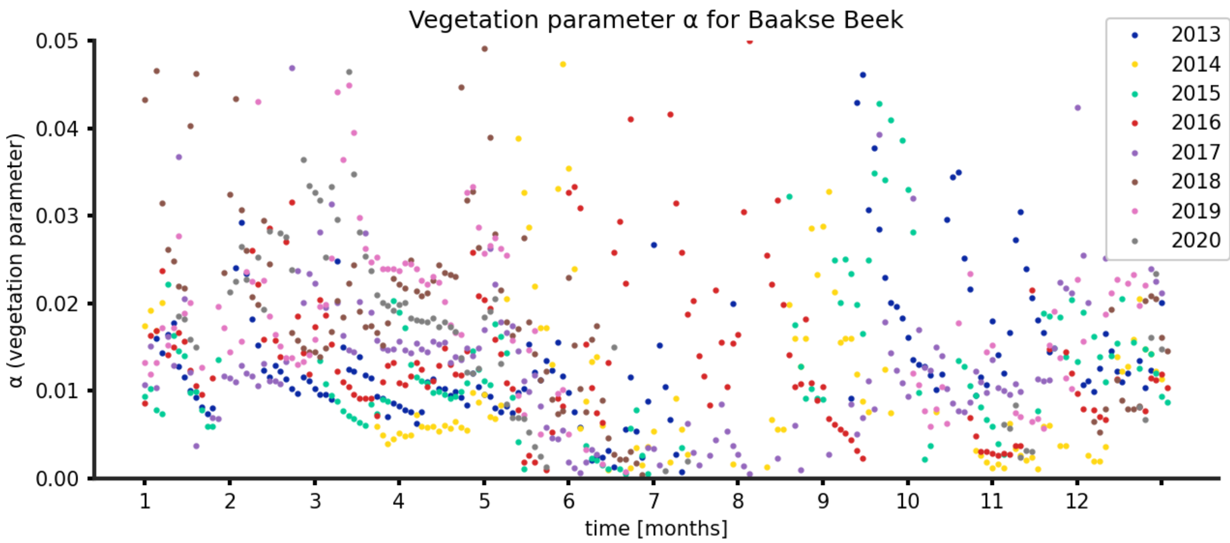

Figure 17 - Influence of vegetation on hydraulic roughness Baakse Beek for all years

Figure 17 shows all years (2013 up until 2020) together, but the separate years can be found in Appendix C. During the first 4 to 5 months, the values of the vegetation parameter lie relatively close to each other while in summer, there is way more spreading. In the years 2018, 2019 and 2020, the discharge was low in summer which results in a low vegetation parameter during summer. During the summers of 2013 till 2016, an increase in the vegetation parameter can be seen from April onwards.

The graph of the year 2016 separately can be seen in Figure 18. During the year 2016, there was a continuous discharge > 0 m^3s^{-1} during summer and therefore the influence of vegetation on the hydraulic roughness can be analysed. Here, a sign of vegetation growth might be visible since the vegetation parameter is increasing during the growing season. Two peaks can be seen around July and August where the vegetation influences the hydraulic roughness more compared to the rest of the year. Halfway July, also a drop in the vegetation parameter can be seen which can be caused by human intervention. During spring, fall and winter, no clear vegetation growth can be observed in the graph.

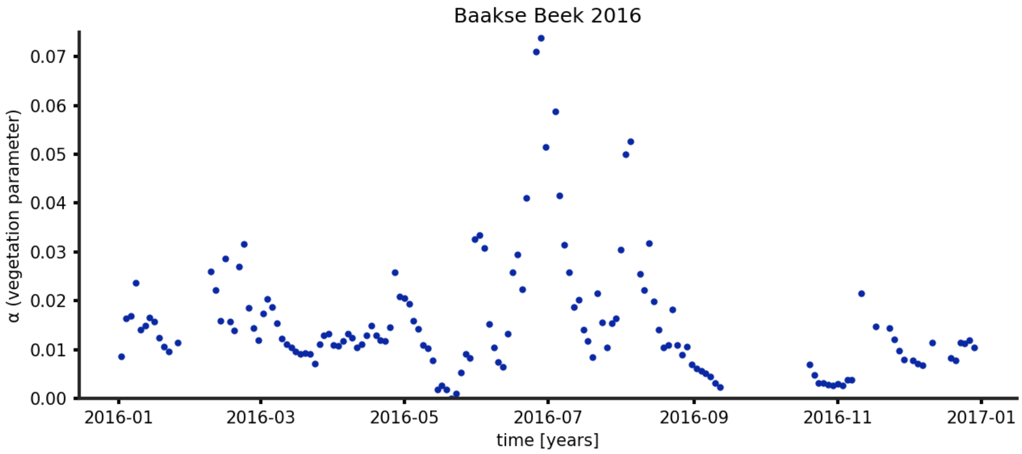

Figure 18 - The vegetation parameter α for Baakse Beek in 2016

Beekruwheidsmodel Baakse Beek

The next step is applying the Beekruwheidsmodel to model the vegetation parameter instead of calculating it from the data, as explained in Section 4.1. The means of the prior distributions for the parameters that give results that fit the data for the Baakse Beek are shown Table 5. The prior parameter distributions differ for each year because the course of the growing season also differs per year (for example the temperature).

During the trial-and-error process of finding the prior distributions, it was found that different combinations of the parameters give results that match the data. For example, increasing the day at which maximum vegetation growth occurs (t_m) and decreasing the growth rate (r) at the same time gives results that also fit the data.

Table 5 - Parameters (prior) distributions Baakse Beek

Parameter	Mean value 2013	Mean value 2014	Mean value 2015	Mean value 2016
α_{max}	0.06	0.02	0.04	0.04
r	0.03	0.03	0.06	0.02
n_b	0.08	0.04	0.06	0.06
t_m	160	120	150	160

For the year 2013, the influence of vegetation on the roughness coefficient over time using the Beekruwheidsmodel and the parameters as described in Table 5 can be seen in Figure 19. The top graph shows the measured Manning coefficients (obtained via the data) as red dots. The different blue coloured planes show the different intervals of the modelled Manning coefficient distribution as explained in Section 4.1. The bottom graph shows the discharge over time in blue.

Around day 115 and day 250, the measured Manning coefficient suddenly drops. This is probably due to human intervention like mowing. Therefore, three different sections are created here by splitting the time series at those two days. After day 160, the model predicts higher Manning coefficients than the measurements, but adding a different section in the time series did not solve this issue. During the period from day 150 and day 200, the discharge was too low to calculate a realistic value for the Manning coefficient. After day 300, the measured Manning coefficient is also lower than the model expects, but there is no sudden drop. It is possible that this is for example due to mortality of the aboveground vegetation or a measurement error.

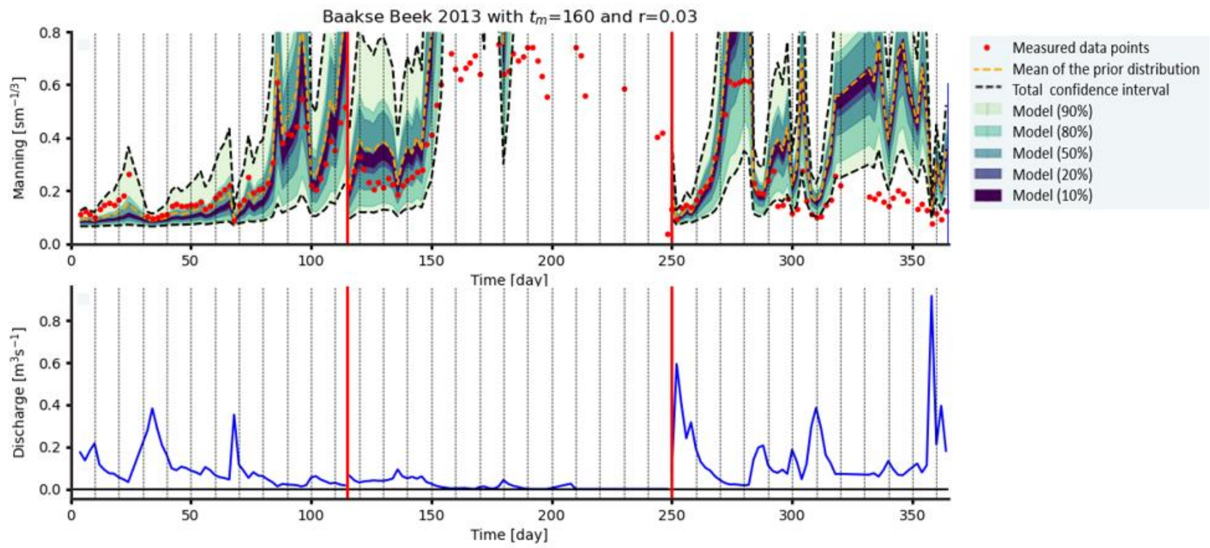

Figure 19 - Beekruwheidsmodel for Baakse Beek 2013 (prior)

For the Baakse Beek, different sets of prior parameter distributions both lead to graphs where the measured Manning coefficient lie within the confidence interval. In Figure 20, the Beekruwheidsmodel is again applied on the data of the Baakse Beek in 2013 but with different normal distributions as prior parameters. Now the day of the maximum growth is 140 instead of 160 and the growth rate is 0.06 instead of 0.03. This graph shows that different values of the parameters give a result that also matches the data. Also here the model predicts higher Manning coefficients than the measurements after day 160, but adding a different section in the time series did not solve this issue.

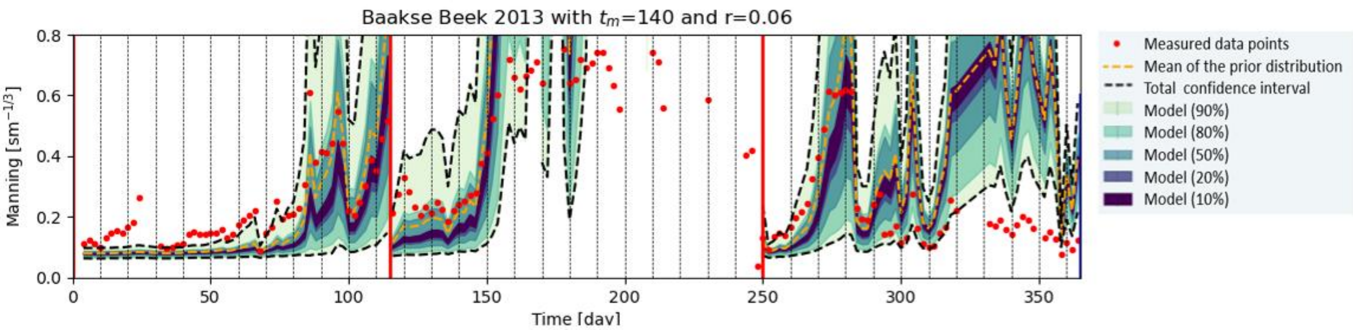

Figure 20 - Beekruwheidsmodel Baakse Beek 2013 but with different parameter distributions

In Figure 19 and Figure 20 , it can be seen that in the beginning of January and around day 170, the Beekruwheidsmodel does not give matching results with different prior parameter distributions but in general, the shape of the models is corresponding. This shows that multiple combinations of the parameters give the same results for the vegetation parameter α. The consequences of this are discussed in Section 5.2.

In Figure 21, results of the Beekruwheidsmodel can be seen for the year 2014 for the Baakse Beek. The red dots again show the measured Manning coefficient while the blue planes represent the confidence intervals for the modelled Manning coefficient. For this graph, the input values for the means of the parameter distributions are used as described in Table 5. Also for this year, multiple other combinations of values would have given the same output of the model.

Between day 10 and day 80, no data is available so the vegetation parameter cannot be calculated for those days. Between day 140 and 190, the discharge was too low to calculate a realistic value for the Manning coefficient. Therefore, this part of the calculation is not considered when analysing the results. At day 145, 190 and 300, the time series is split into different sections since those are the boundaries of the periods that give unreliable results due to low discharge. In general, the Manning coefficients in the year 2014 are significantly smaller than the Manning coefficients in 2013. It might be the case that vegetation did not influence the hydraulic roughness that much in the year 2014 or it could be due to a measurement error.

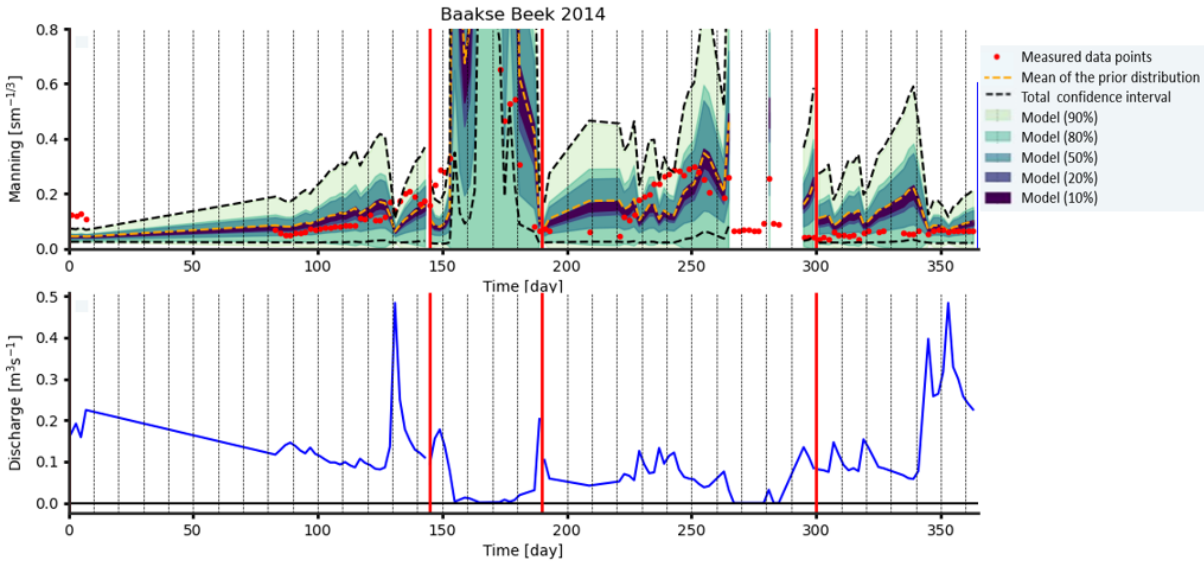

Figure 21 - Beekruwheidsmodel Baakse Beek 2014 (prior)

For 2015, the influence of vegetation on the roughness coefficient over time by the Beekruwheidsmodel can be seen in Figure 22. For the year 2015, there is a large period between day 140 and day 230 where little data is available. The data that is available, shows a discharge close to 0 m^3s^{-1} which causes the Manning coefficient to be infinitely large. This makes it difficult for the Beekruwheidsmodel to estimate the vegetation growth during this period. This can also be seen in the graph, where the model does not fit the data at this moment during the growing season.

Besides the period between day 140 and 230, figure 22 does show signs of vegetation growth around day 100. Also after day 220, the Beekruwheidsmodel matches the measured data. From day 300 onwards, the model expects higher Manning coefficients than the measurements show. This is not a sudden drop in measurements, but a more structural difference. This could for example be caused by mortality of the aboveground vegetation which is not part of the Beekruwheidsmodel.

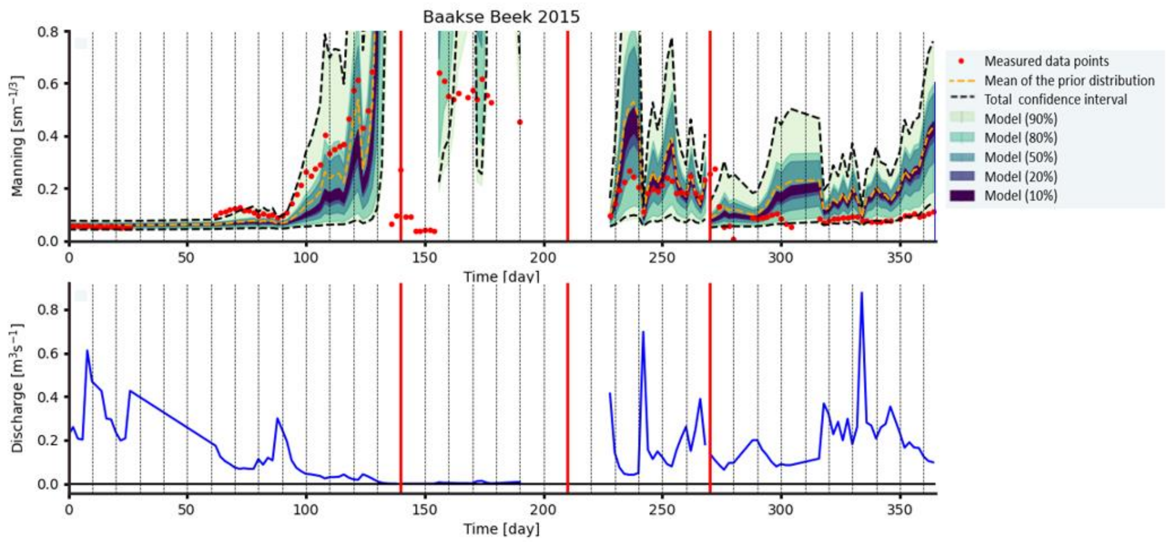

Figure 22 - Beekruwheidsmodel Baakse Beek 2015 (prior)

The results of the Beekruwheidsmodel for the Baakse Beek in 2016 can be seen in Figure 23. The input values as described in Table 5 are used to get this result, but again other combinations of parameters would have given the same results. During summer, the model does not fit the data perfectly even with the relatively high discharge. The measured data points in red do mostly lie within the 99% confidence interval, but the trend of the Beekruwheidsmodel is not followed. Adapting the prior parameter distributions did not solve this issue. This issue could be caused by an error in the measurements.

There is no data available for the period between day 250 and day 290. Therefore, this part of the model is not plotted correctly. For the period between day 300 and day 365, the model does not fit the data either. This is probably caused by mortality of the vegetation which is not modelled in the Beekruwheidsmodel.

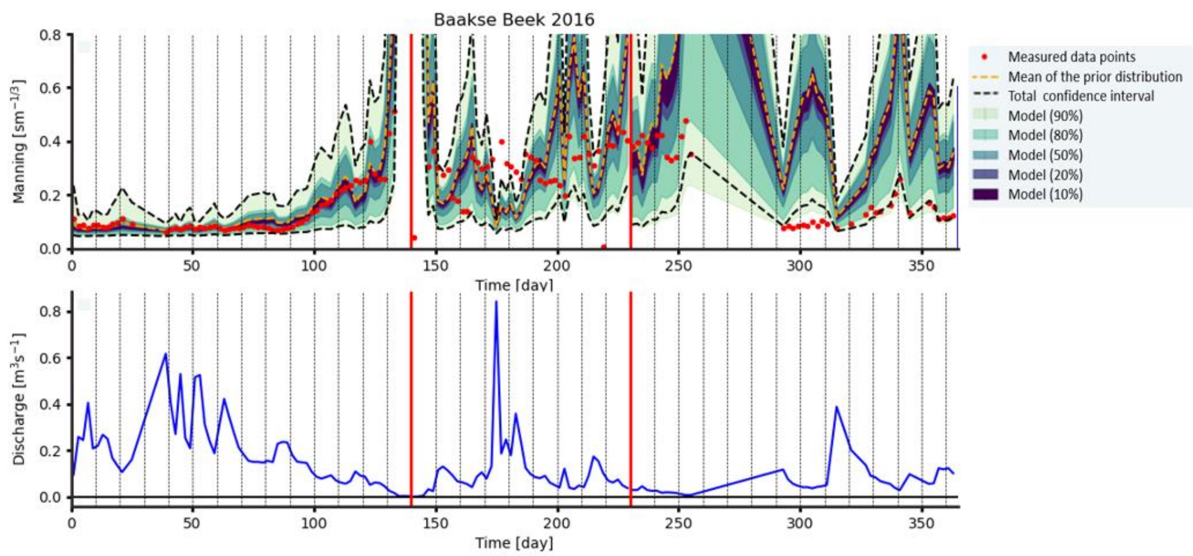

Figure 23 - Beekruwheidsmodel Baakse Beek 2016 (prior)

For the years 2017 up until 2020, the discharge in the Baakse Beek was equal to $0 m^3 s^{-1}$ for a large part of the spring and summer. This makes it impossible to calculate the Manning coefficients. For other days during spring and summer, the discharge was very low which resulted in unrealistically high values for the Manning coefficient. This can also be seen in the figures in Appendix C, where the vegetation parameter becomes 0 during the spring and summers of those years. It is not possible to determine the influence of vegetation on the hydraulic roughness during those periods. Therefore, those years are not analysed via the Beekruwheidsmodel.

4.3 Zwarte Beek

In this section, first the vegetation parameter is calculated for the Zwarte Beek. Secondly, the Beekruwheidsmodel is applied to determine the influence of vegetation on the hydraulic roughness using the prior distributions for the vegetation parameters.

Vegetation Parameter Zwarte Beek

Figure 24 shows the influence of vegetation on the hydraulic roughness for the Zwarte Beek in the years 2013 till 2020. Again, the years 2017 until 2021 have a discharge of $0 m^3 s^{-1}$ during the late springs and summers and therefore no trend in the influence of vegetation on the hydraulic roughness can be observed in the data for these years. The low discharges cause the vegetation parameter to be zero and therefore this data is considered useless for this research. During the year 2014, the measurement network was broken and therefore no data is available during both spring and summer. For all other years, an increase in the value of the vegetation parameter can be seen from April onwards. This increase could be caused by the vegetation that starts growing during this period. For the years 2013-2016, a clear trend can be seen during spring and early summer, where the vegetation parameter is increasing. Also in August and September, drops in the vegetation parameter can be observed which could be caused by mowing. During fall, there is a lot of variation in the values of the vegetation parameter while there is not so much variation in January and February.

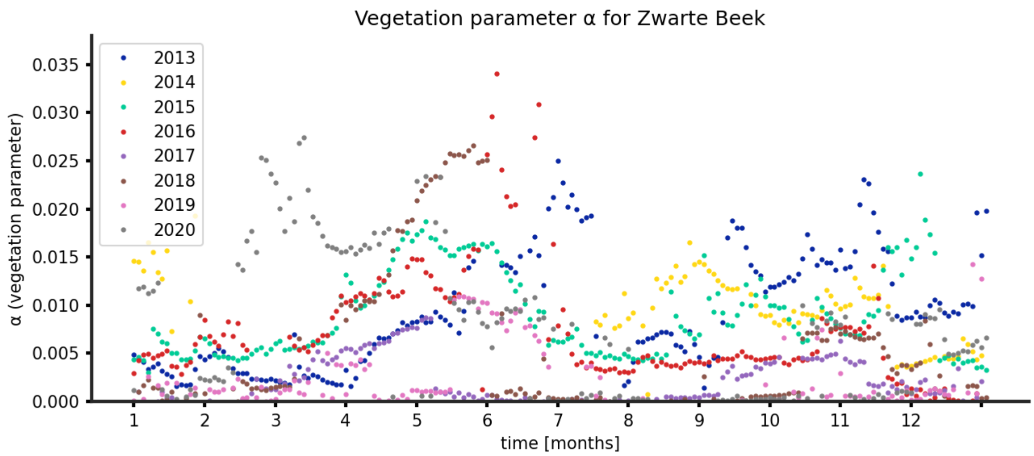

Figure 24 - Influence of vegetation on hydraulic roughness Zwarte Beek for all years

Figure 25 shows the vegetation parameter over time in the year 2015 for the Zwarte Beek. This year is plotted separately since a sign of vegetation growth can be seen here. The results of the other years are plotted separately as well and can be found in the figures in Appendix C. For 2015, a clear trend in the influence of vegetation on the hydraulic roughness can be seen in the spring with its peak in the beginning of June. The decrease in the value of the vegetation parameter from June onwards can be caused by human intervention but this graph shows a more gradual decline instead of a sudden drop.

In the end of August and September, an increase in the value of the vegetation parameter can again be noticed. It is possible that the vegetation is growing back again after mowing and that that is the reason why the vegetation parameter is increasing. In December, the value of the vegetation parameter is higher than expected. This might possibly be caused by an error in the measurement network.

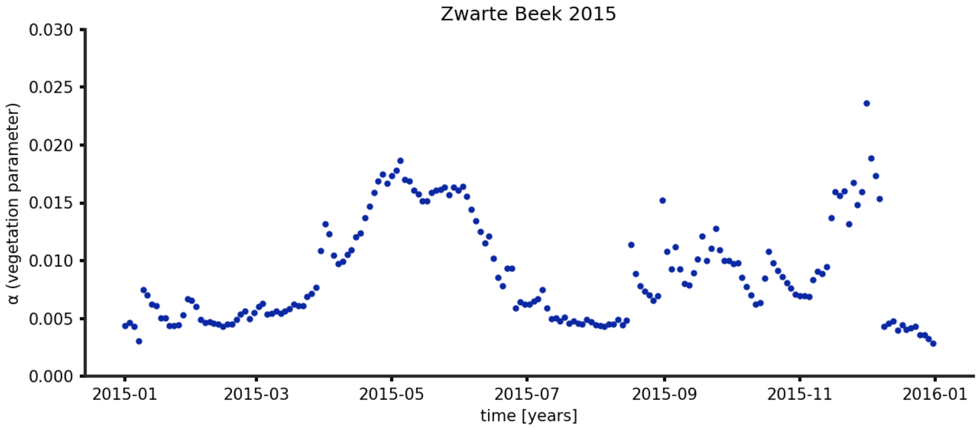

Figure 25 - The vegetation parameter α for Zwarte Beek in 2015

Beekruwheidsmodel Zwarte Beek

The next step in this process, was applying the Beekruwheidsmodel on the Zwarte Beek. This results in modelled distributions for the vegetation parameter instead of calculated values. This method is described in Section 4.1. The prior-parameter distributions that are obtained for the Zwarte Beek trajectory can be found in Table 6. These distributions differ per year since also the growing season differs per year. Just like for the Baakse Beek, also for this trajectory, multiple combinations of prior distributions give the same results. The year 2014 is skipped in this analysis since there is no data available during spring and summer of this year. The years 2017 up until 2020 are also skipped since the discharge is 0 m^3s^{-1} for most part of the year causing the Manning coefficient to be infinitely large. A possible combination of parameters for the years 2013, 2015 and 2016 can be found below:

Table 6 - Parameters (prior) distributions Zwarte Beek

Parameter	Mean value 2013	Mean value 2015	Mean value 2016
α_{max}	0.10	0.02	0.02
r	0.05	0.015	0.05
n_b	0.03	0.03	0.03
t_m	190	190	150

Figure 26 shows the results of the Beekruwheidsmodel for the Zwarte Beek in the year 2013. As input parameters, the values as described in Table 6 are used. The red dots in the top graph show the measured Manning coefficients as obtained from research question 2 in Section 3.2. The blue coloured band widths each represent a confidence interval of the normal distribution of the modelled Manning coefficient. The blue line in the bottom graph shows the discharge over time.

At day 180, the Manning coefficient decreases with a sudden drop that is not expected by the model. This decrease in hydraulic roughness is most likely caused by human intervention. Therefore, the time series is split in to two different sections here, as described in the method in Section 4.1.

Until day 195, the model fits the data correctly. After this day, the discharge drops to 0 m^3s^{-1} which causes an infinitely large value for the Manning coefficient. From day 250 onwards, the model fits the data again. The last 50 days of the year, the model is predicting a higher Manning coefficient than the measured roughness. Adding an extra section here did not solve the issue. This misfit in data could be caused by mortality of the aboveground vegetation, which is not covered in the Beekruwheidsmodel.

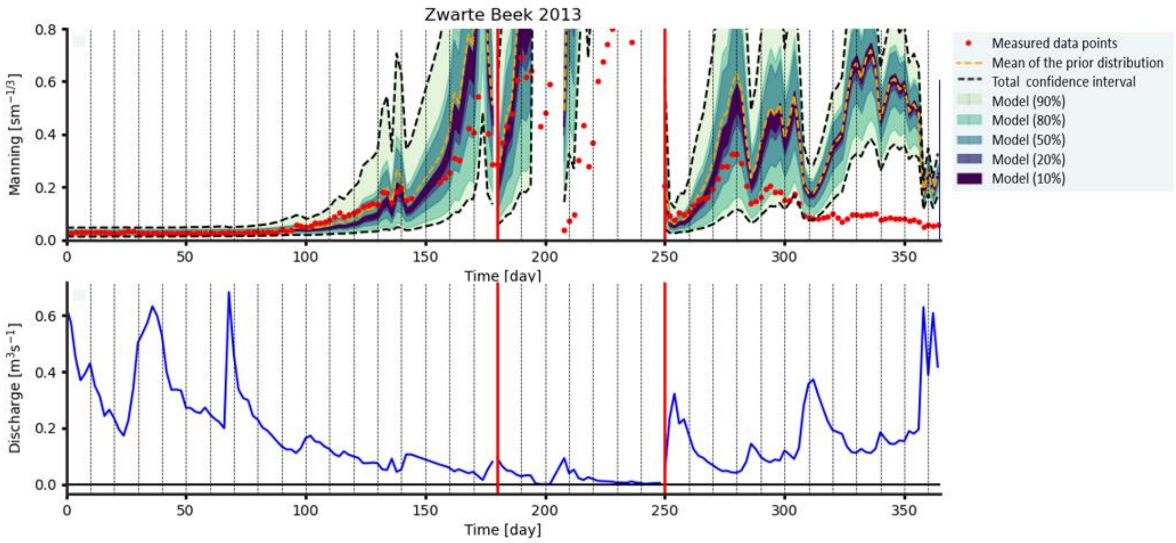

Figure 26 - Beekruwheidsmodel Zwarte Beek 2013 (prior)

In figure 27, the results of the beekruwheidsmodel for the Zwarte Beek in 2015 can be seen. The input values for the normally distributed parameters are used as described in Table 6. In the year 2015, the discharge was continuously larger than 0 m^3s^{-1} all year long. This could be the reason why the Beekruwheidsmodel fits the measured data points so well. The Manning coefficient is relatively low but does not show unrealistic values. A small drop in the Manning coefficient can be seen around day 160, so therefore the time series is split here. The drop is relatively low, so it is questionable whether this is due to mowing. If mowing took place, the effect on the Manning coefficient was not that much since the there is only a small decrease.

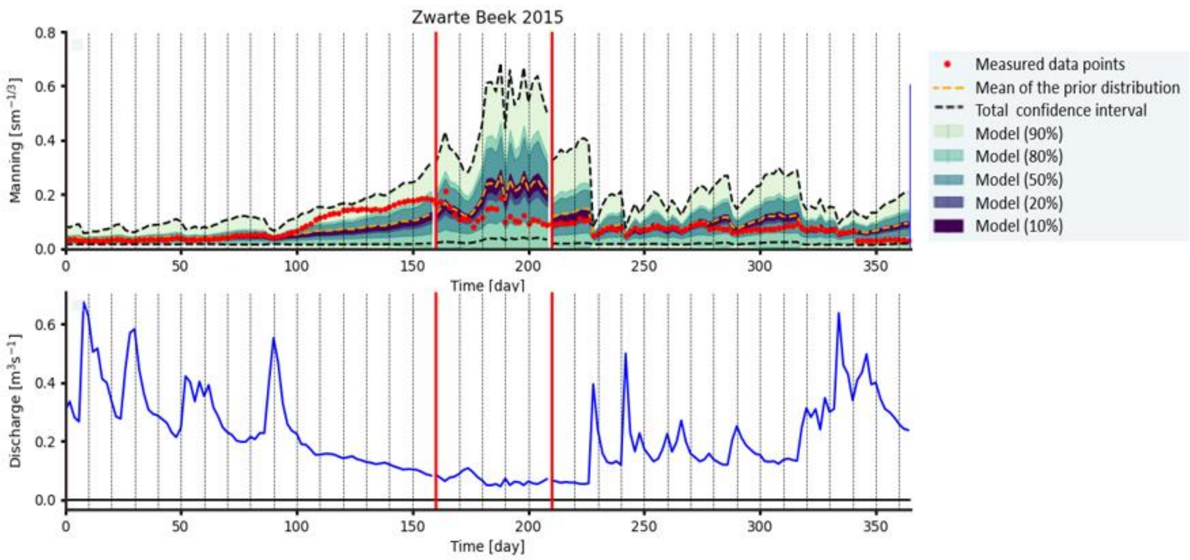

Figure 27 - Beekruwheidsmodel Zwarte Beek 2015 (prior)

In Figure 28, the beekruwheidsmodel for the Zwarte Beek in 2016 can be seen. Although the Manning coefficient is relatively low, the model does predict the trend in the Manning coefficient correctly: all the measured data points are fitting the boundaries of probability distribution of the model. For this year, the discharge during summer was high. This could be the reason why the model is working correctly for this year and this case. At day 175, a sudden drop in the Manning Coefficient can be observed. It is possible that this drop is caused by mowing and therefore the time series is split here.

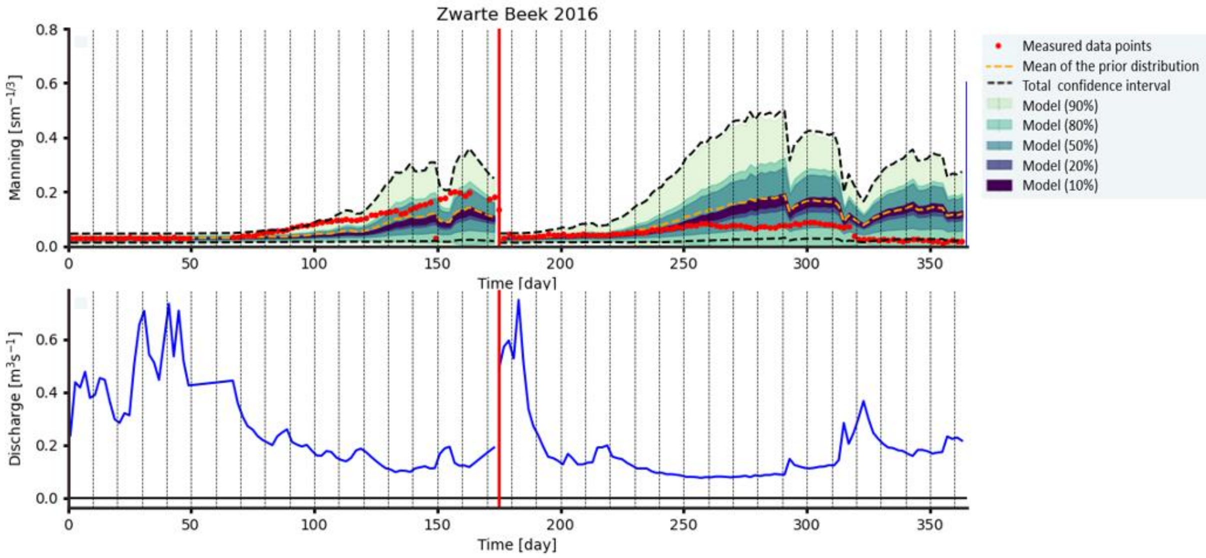

Figure 28 - Beekruwheidsmodel Zwarte Beek 2016 (prior)

5. Discussion

In this section, the results of the Beekruwheidsmodel are analysed and discussed. First, a general analysis of the results on the Manning coefficient and vegetation parameter was done for both watercourses. The value of the vegetation parameter is low for both streams and possible reasons for this are discussed. Multiple hypothesis are checked and discussed in this section. First, the Markov Chain Monte Carlo algorithm to determine the exact values of the three vegetation parameters, is discussed. The beekruwheidsmodel was previously successfully applied to the Leijgraaf. A comparison is made between the Baakse Beek, Zwarte Beek and Leijgraaf to find out the differences in characteristics that might cause the low value of the vegetation parameter. Next, a sensitivity analysis is done for the vegetation parameter on different values of the discharge and the Manning Coefficient. Also the uncertainty in measurements is taken into account to find out if that could cause the low values and little spreading of the vegetation parameter. The last hypothesis that is checked in this section, is that the variation in the vegetation parameter is so low, that a constant value for the vegetation parameter would give more accurate results.

5.1 General discussion of the results

Figure 29 shows the Manning coefficient over time for both the Baakse Beek (blue dots) and Zwarte Beek (green dots) in the same figure. It can clearly be seen that the Manning coefficient for the Baakse Beek is significantly larger compared to the Zwarte Beek. For both streams, the Manning coefficient increases halfway during the years and possibly some seasonality can be seen.

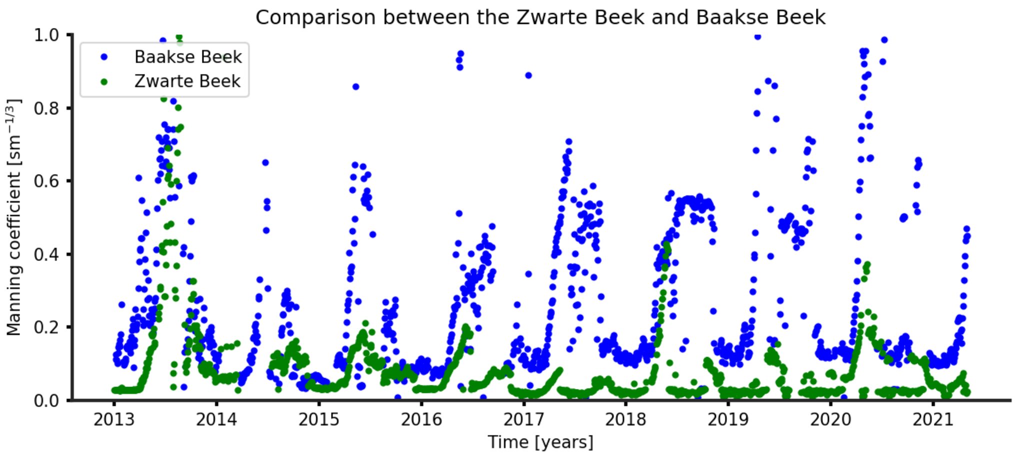

Figure 29 - Manning coefficient over time (all years) for both Baakse Beek and Zwarte Beek

For determining the Manning coefficients, the optimalisation script assumes that the spreading of the vegetation is uniform. This means that along the complete trajectory, the spreading of the vegetation is equal. It is questionable if this assumption can be made in case of the Baakse Beek and Zwarte Beek. Especially in case of the Baakse Beek, the trajectory is long (3469 m) and the environment changes along the route. Some parts of the trajectory are mostly in the shadow due to the trees next to the watercourse. The assumption of uniform spreading of the vegetation between two measurement locations needs to be made to calculate the Manning coefficient. More accurate results could be obtained if more measurement locations are added such that the complete trajectory between two measurement locations is uniform in its vegetation (types and spreading).

Another assumption that is done for determining the Manning coefficients, is the assumption that the discharge measured at the downstream location, is the same as the discharge at the upstream location. For the Zwarte Beek, this assumption will mostly be correct since there is only one small branche in the selected trajectory. For the Baakse Beek, there are a couple of branches but those have a small discharge compared to the main water course. Adding extra measurement locations after larger branches can help with better assuming what the discharge is at the upstream location. This will make the calculation of the Manning coefficient more accurate.

Something that stands out in Figure 29, is the minimum Manning coefficient for the Zwarte Beek and Baakse Beek after 2017. For the Baakse Beek, the minimum values for the Manning coefficient increase after 2017: from around 0.1 $sm^{-1/3}$ to around 0.15 $sm^{-1/3}$. This can also be seen in the raw data (see Appendix A), where the water-surface slope on average increases after the year 2017. This difference could be explained by a change in the measurement system (e.g. change in set-up or a calibration error).

For the Zwarte Beek, there is also a change in lower Manning coefficients after 2017. The average value of the Manning coefficient lies around 0.1 $sm^{-1/3}$ before 2017 and around 0.05 $sm^{-1/3}$ after 2017 (see Appendix A for the years individually). This can also be seen in figure 29, where the lowest green dots after 2017 lie lower compared to before 2017.

A possible cause for the drop in the lower Manning coefficients is in the SOBEK model and its optimisation script. In Figure 30, the residual after the optimisation algorithm is plotted for the Zwarte Beek. The blue dots represent the remaining error in centimetres after the iterations and when the Manning coefficient is determined. As explained in Section 3.1, the optimisation script determines the Manning coefficient by comparing the measured upstream water level with the calculated upstream water level. If a value of the Manning coefficient returns a calculated upstream water level that is close enough (error <0.1 cm) to the measured upstream water level, this value of the Manning coefficient is set as the hydraulic roughness for that specific day. The residual or remaining error is the difference between the measured upstream water level and calculated water level. In other words: the smaller the residual, the more accurate the value of the Manning coefficient.

Figure 30 shows the remaining error for the Zwarte Beek from 2013 to 2021 in blue dots. Note that the remaining errors are not plotted for the days when the discharge is 0 m^3s^{-1}. For the years 2014-2016, the optimalisation process runs smoothly. The value of the remaining error is smaller than 0.1 cm for almost all days. In the year 2013, the error is a bit larger (around 2cm) but still acceptable. For the years 2017-2021 however, the remaining error is significantly large: more than 5 centimetres and for some days even more than 15 centimetres. There is a sudden jump in the remaining error on the 8th of May 2017. Before this day, the remaining error is around 0.02 cm for a very long period. On the 8th of May, the remaining error jumps to 6.67 cm centimetres and remains high after this day.

To find the cause of the large remaining error, the raw data is also plotted in Figure 30 by plotting the water-surface slope. Here a possible correlation can be seen: the graph of the difference between the upstream and downstream water level follows the same trend as the graph of the remaining error. It is likely that an error in the measurements (for example a calibration error or change in set-up after the 8th of May 2017) causes the large residual after the optimalisation process. Since the error is significantly large, the results for the Manning coefficient are not reliable and therefore the years 2017-2021 will not be considered for the rest of the analysis.

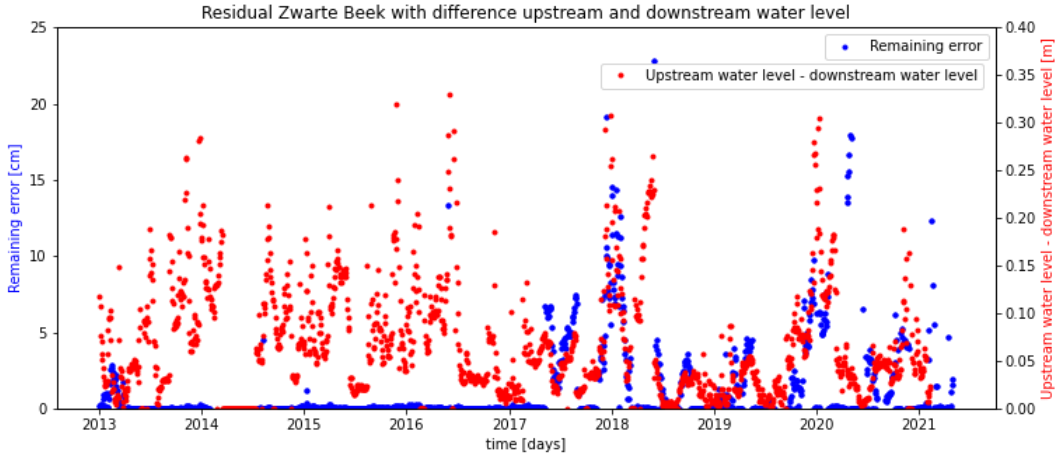

Figure 30 - Residual Zwarte Beek after the optimalisation process

Figure 31 shows the residual for the Baakse Beek. Here the remaining error remains smaller than 0.02 cm for almost all days. There are a couple of days where the remaining error is significantly large, but is issue is not structurally the case like for the Zwarte Beek.

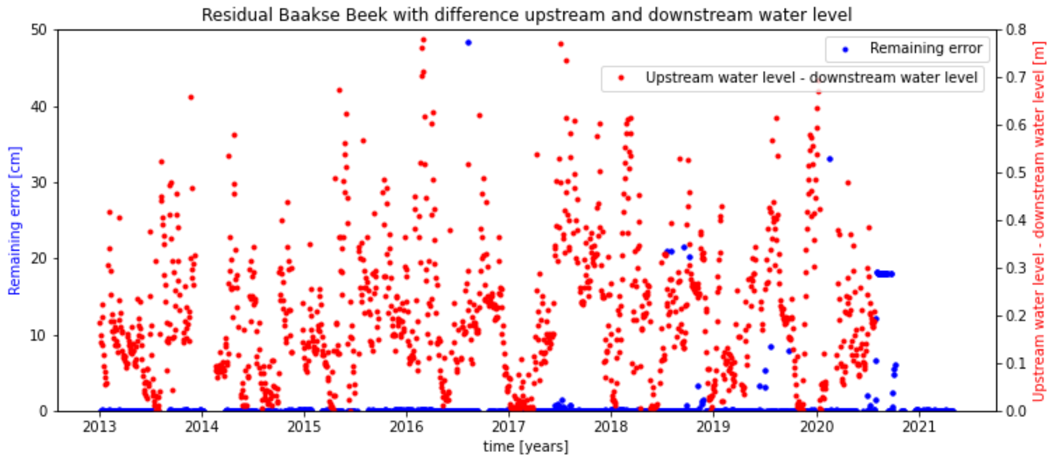

Figure 31 - Residual Baakse Beek after the optimalisation process

Figure 32 shows the Manning coefficient over time for the Baakse Beek and Zwarte Beek for the years 2013 up until 2016. The years 2017-2020 are not shown in this figure since the results of the Zwarte Beek are not reliable as explained above. Also here an increase in the Manning coefficient can be seen around May and June of each year, where the increase for the Baakse Beek is larger compared to the Zwarte Beek.

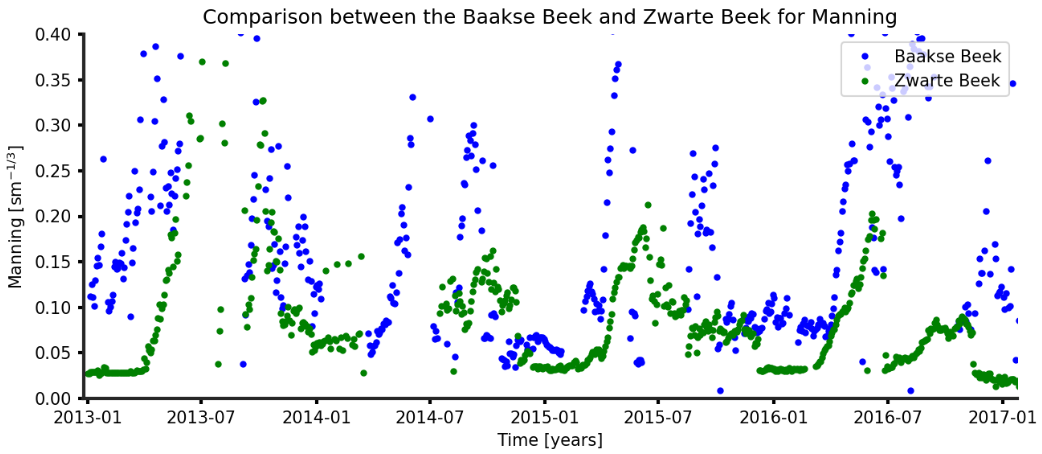

Figure 32 - Manning coefficient over time (2013-2016) for both Baakse Beek and Zwarte Beek

Figure 33 shows the vegetation parameter α for both the Baakse Beek and Zwarte Beek in the years 2013-2017. The vegetation parameter is calculated using Equation 3. Here an increase in the vegetation parameter can be seen during April, May, and June of each year. This means that during those periods, vegetation influences the hydraulic roughness more compared to the periods where the vegetation parameter is low. Both the Zwarte Beek and Baakse Beek have realistic values of the Manning coefficients most of the time. The vegetation parameter however, is relatively low for both trajectories compared to the vegetation parameter of other streams (Penning, Berends and Gaytan Aguilar, 2020). A trend can be seen (an increase during spring and summer), but the values itself are low. Low values of the vegetation parameter α means that vegetation does not have much influence on the hydraulic roughness.

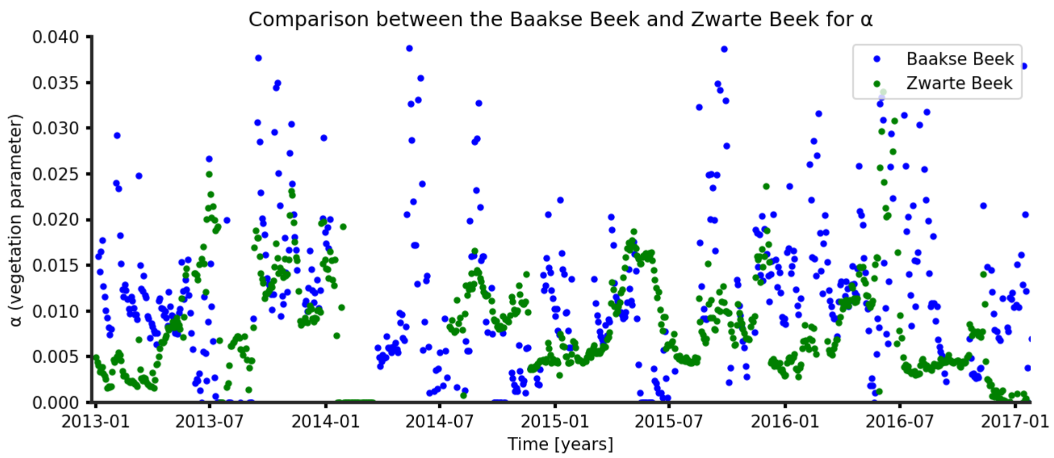

Figure 33 - Vegetation parameter (2013-2017) for Baakse Beek and Zwarte Beek

Even though the vegetation parameter is low for both water courses and the vegetation thus does not influence the hydraulic roughness a lot, this does not mean that there is not a lot of vegetation present.

Figure 34 shows the Baakse Beek in 2013 in March (left) and in the beginning of June (right). As can be seen in this figure, the stream is overgrown with vegetation after a couple of months.

Figure 34 - Baakse Beek 2013 in March (left) and beginning of June (right)

Figure 35 is a photo taken in the beginning of June 2021, right before the mowing took place. Also this picture shows that vegetation is clearly present.

Figure 35 - Baakse Beek in June 2021

The same holds for the Zwarte Beek as can be seen in Figure 36. The left photo is taken in March 2013 and the photo on the right is from the beginning of June in 2013. Also here it can clearly be seen that there is vegetation growth during those months. A low vegetation parameter does not necessarily mean that there is little vegetation present, but the vegetation that is present, does not influence the hydraulic roughness a lot.

Figure 36 - Zwarte Beek in 2013 in March (left) and beginning of June (right)

5.2 Markov Chain Monte Carlo

In Section 4.2 and Section 4.3, the Beekruwheidsmodel is applied on both streams with a prior parameter distribution. Here, the mean of the parameter distributions for α_{max}, r and t_m are manually chosen such that the measured data points lie within the confidence interval of the Beekruwheidsmodel. The Markov Chain Monte Carlo algorithm is a method to determine the values of those parameters more accurately. In that way, the band width of the Beekruwheidsmodel will decrease and σ of each normal distribution will decrease. Combinations of parameter values that give results close to the real data are tried to find.

For both the Baakse Beek and Zwarte Beek, it was not possible to apply the Markov Chain Monte Carlo algorithm successfully. The algorithm was not able to find one set of parameters that gives the right results. A possible cause could be the issue that multiple combinations of the parameters give an acceptable result as described in Section 4.2 and Section 4.3. An example of the not-working algorithm is shown in Figure 37 for the Zwarte Beek in 2016. All other results can be found in Appendix F. In the left columns, the graphs do not follow the trend that they are supposed to follow. A well-functioning Markov Chain Monte Carlo would have shown a convex graph with its maximum in the domain. Also the dotted line and solid line should follow the same trend. The Markov Chain Monte Carlo algorithm for the Zwarte Beek in 2016 has 439 divergences while a value of 0 divergences is optimal. Also the other years and the case of the Baakse Beek show the same results.

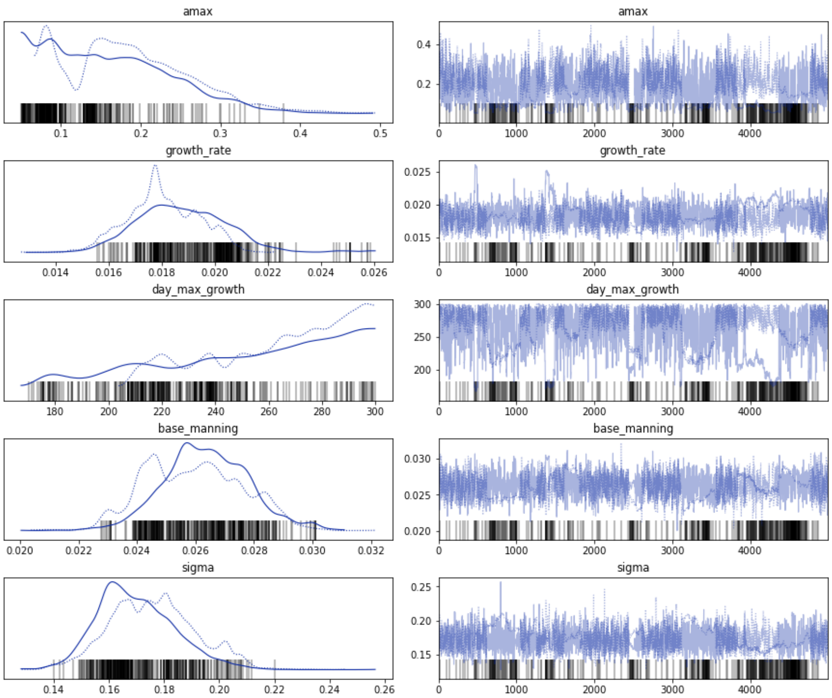

Figure 37 - Markov Chain Monte Carlo calibration for the Zwarte Beek in 2016, first section

Figure 38 shows the results of the Beekruwheidsmodel after applying the Markov Chain Monte Carlo Algorithm. The measured data points (in red) do not lie within the confidence intervals (blue coloured planes). This is the result of the non-functioning algorithm: the algorithm was not able to determine likely values for each of the parameters.

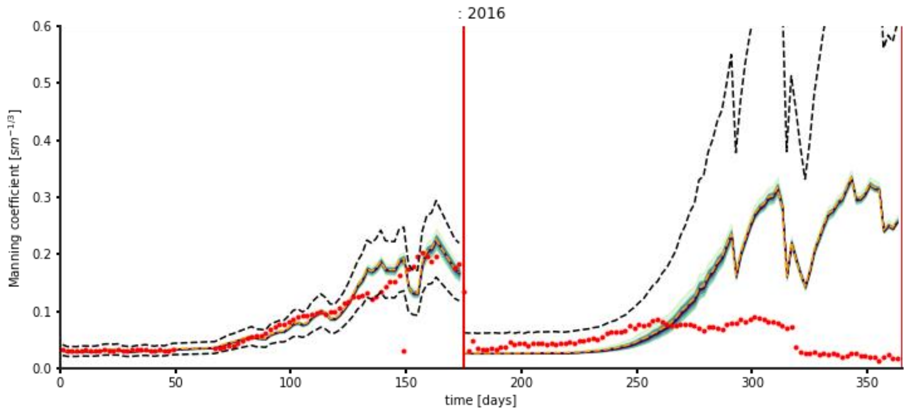

Figure 38 - Zwarte Beek 2016 after applying the Markov Chain Monte Carlo algorithm

There can be multiple causes for why the Markov Chain Monte Carlo algorithm is not be working correctly for the Baakse Beek and Zwarte Beek. These are discussed in the upcoming sections.

5.3 Comparison to the Leijgraaf

In 2020, the Beekruwheidsmodel was applied on the Leijgraaf, a stream in the south of the Netherlands (Penning, Berends and Gaytan Aguilar, 2020). The results of this research show that the Beekruwheidsmodel can model the influence of vegetation on the hydraulic roughness for the Leijgraaf. Also the Markov Chain Monte Carlo algorithm works fine in case of the Leijgraaf. Comparing the situation of the Leijgraaf with the Baakse Beek and Zwarte Beek could help with understanding why the Markov Chain Monte Carlo algorithm is not working correctly for the Baakse Beek and Zwarte Beek.

The Leijgraaf is a stream in Noord-Brabant (south of the Netherlands) which contains different sections between weirs. The weirs control the water levels of the sections. The sections between the weirs differ in length: the shortest section has a length of around 600 meters while the longest section is around 3300 meters long. The length of the Leijgraaf is thus comparable of the length of the Baakse Beek (3469 m) and Zwarte Beek (1324 m), as can also be seen in Table 7. The average discharge of the Leijgraaf is 0.8 m^3s^{-1} with a peak discharge of 2 m^3s^{-1}. This discharge is substantially higher compared to the Baakse Beek (0.096 m^3s^{-1}) and the Zwarte Beek (0.180 m^3s^{-1}).For the Leijgraaf, data is available from 2005 up until 2020 including a SOBEK model.

Table 7 - Comparison characteristics Leijgraaf, Baakse Beek and Zwarte Beek

	Leijgraaf	Baakse Beek	Zwarte Beek
Length	600 – 3300 m	3469 m	1324 m
Average yearly discharge	0.8 m^3s^{-1}	0.096 m^3s^{-1}	0.180 m^3s^{-1}

In the Leijgraaf, four different plant species are present: *Potamogeton pectinatus* (Dutch: schedefonteinkruid), *Sparganium emersum* (Dutch: kleine egelskop), *Sagittaria sagittifolia* (Dutch: pijlkruid) and *Elodea nuttallii* (Dutch: smalle waterpest) (Penning, Berends and Noorlandt, 2018).*Sparganium emersum* and *Sagittaria sagittifolia* are the two types that are the most common in the Leijgraaf. *Sparganium emersum* is growing both submerged (when the flow velocity is high) and emergent (next to banks). *Sagittaria sagittifolia* grows in shallow streams with both submerged, floating, and emergent leaves. All four species have strongly reduced shoot biomass outside the growing season. E. nuttallii hibernates with shoots lying at the bottom of the watercourses, the other three allocate their carbohydrates to belowground storage organs buried in the sediment. As a consequence, shoots die off at the end of the growing season. It is unknown what the vegetation types are in the Baakse Beek and Zwarte Beek, but future research in comparing the vegetation types between the Leijgraaf, Baakse Beek and Zwarte Beek could be helpful to understand if and how the vegetation types influence the value of the vegetation parameter.

The discharge in the Leijgraaf is thus substantially larger compared to the Baakse Beek and Zwarte Beek. The value of the Manning coefficient on the other hand, is of the same size for both the Baakse Beek, Zwarte Beek and the Leijgraaf. This can also be seen in Figure 39, where the Manning coefficient is plotted for all three streams over time.

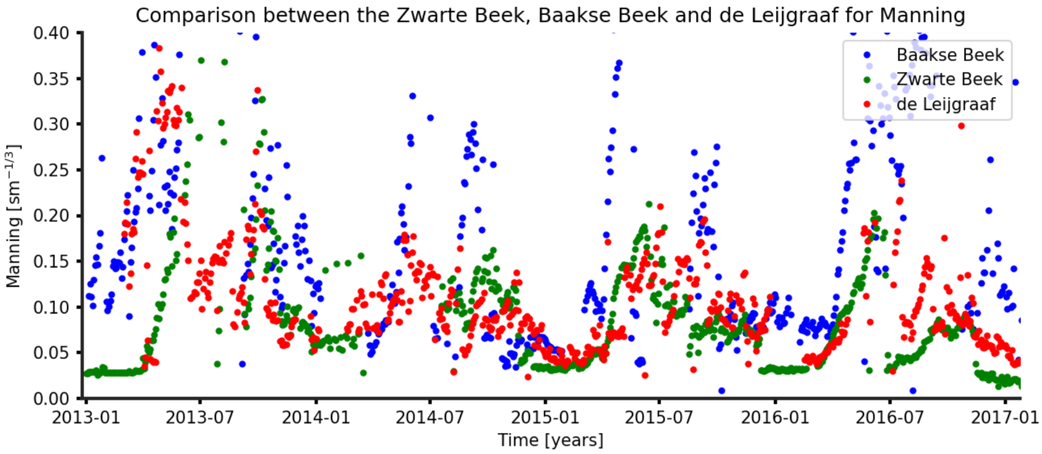

Figure 39 - Comparison Manning coefficient Leijgraaf

The discharge is significantly larger for the Leijgraaf compared to the other two streams, while the Manning coefficient is of the same size. This results in a vegetation parameter α that is substantially larger compared to the value of the vegetation parameter of the Baakse Beek and Zwarte Beek. This can also be seen in Figure 40, where the vegetation parameter is plotted over time.

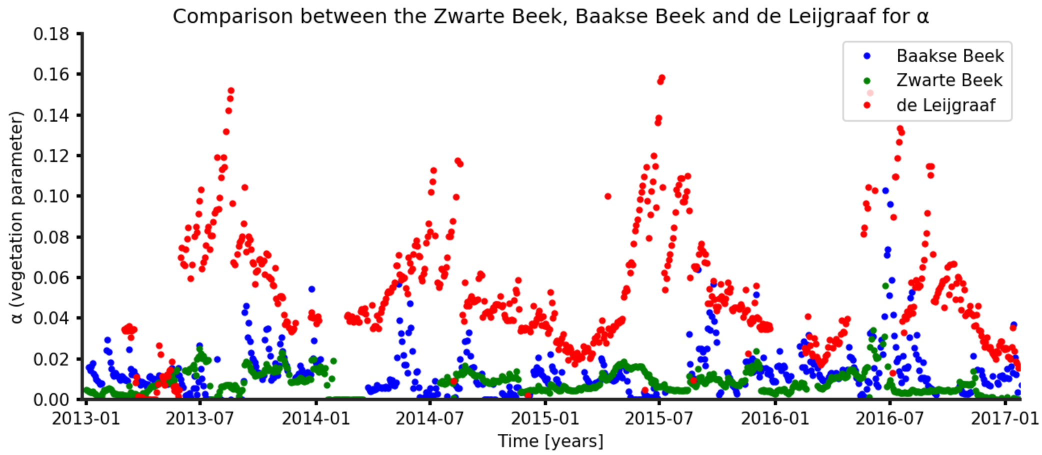

Figure 40 - Comparison vegetation parameter Leijgraaf

In Figure 49, the vegetation parameter α for both the Leijgraaf, Baakse Beek and Zwarte Beek are shown. For the Baakse Beek, the value of α varies between 0 and 0.06 and for the Zwarte Beek, the value of α varies between 0 and 0.03. This is around 10 times smaller compared to the variation of α for the Leijgraaf, where the value of α varies between 0 and 0.2. Due to the low discharges in the

Baakse Beek and Zwarte Beek, the size of α is significantly smaller than the size of the Manning coefficient for those two streams. This does not hold for the Leijgraaf where the value of Manning coefficient is around the same size as the vegetation parameter α.

Figure 41 shows the Markov Chain Monte Carlo algorithm for the Leijgraaf which is working correctly: the distributions for the parameters are smaller and the Beekruwheidsmodel is predicting the influence of vegetation on the hydraulic roughness more accurately. After the Markov Chain Monte Carlo algorithm, the different distributions have become smaller (blue coloured planes in the graph). For the Zwarte Beek in 2016 in Figure 38, those distributions also have become smaller, but the measured data points (red) do not lie in those confidence intervals. This means that the determination of the parameters is not done correctly.

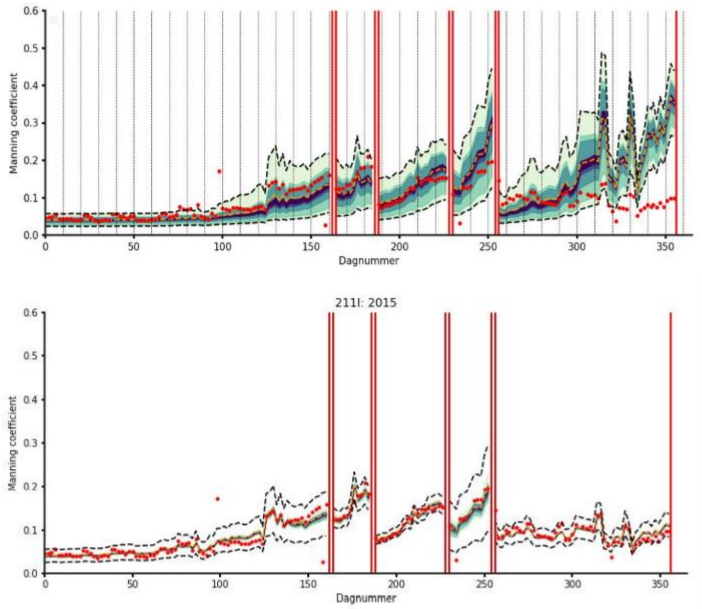

Figure 41 - The prior and posterior distributions for the Leijgraaf in 2015 (after a successful Markov Chain Monte Carlo algorithm)

The rather small values of the vegetation parameter α for the Baakse Beek and Zwarte Beek might complicate the determination of the parameters for the beekruwheidsmodel. To test the sensitivity of the vegetation parameter α compared to different discharges and Manning coefficients, a sensitivity analysis was done.

5.4 Sensitivity analysis vegetation parameter

In Figure 42, the sensitivity analysis for α compared to different Manning Coefficients and discharges can be seen. The points in the graph belong to the cases Leijgraaf (red), Baakse Beek (blue) or Zwarte Beek (green). Each point belongs to a day between the 1st of January 2013 and the 1st of January 2021 with its corresponding discharge and Manning coefficient. The value of the vegetation parameter α is calculated for each day using Equation 3 and plotted against the corresponding Manning coefficient. Also in this graph it can be seen that the range in Manning coefficient is about the same for all three streams while the range of the vegetation parameter α is different for the Leijgraaf. In case of the Leijgraaf, the spreading in α is larger and more variation can be seen (see also Figure 40).

The lines in this graph in Figure 42 show the relationship between the Manning coefficient and the vegetation parameter α for different constant discharges. It can be seen that smaller discharges result in a smaller variation in the vegetation parameter α with the same range of the Manning coefficient compared to larger discharges. This corresponds to the hypothesis described above: lower discharges cause less variation and dynamics in the value of the vegetation parameter α. This makes the Beekruwheidsmodel more sensitive to errors for lower discharges: a small error in the Manning coefficient causes a completely different value for the vegetation parameter α.

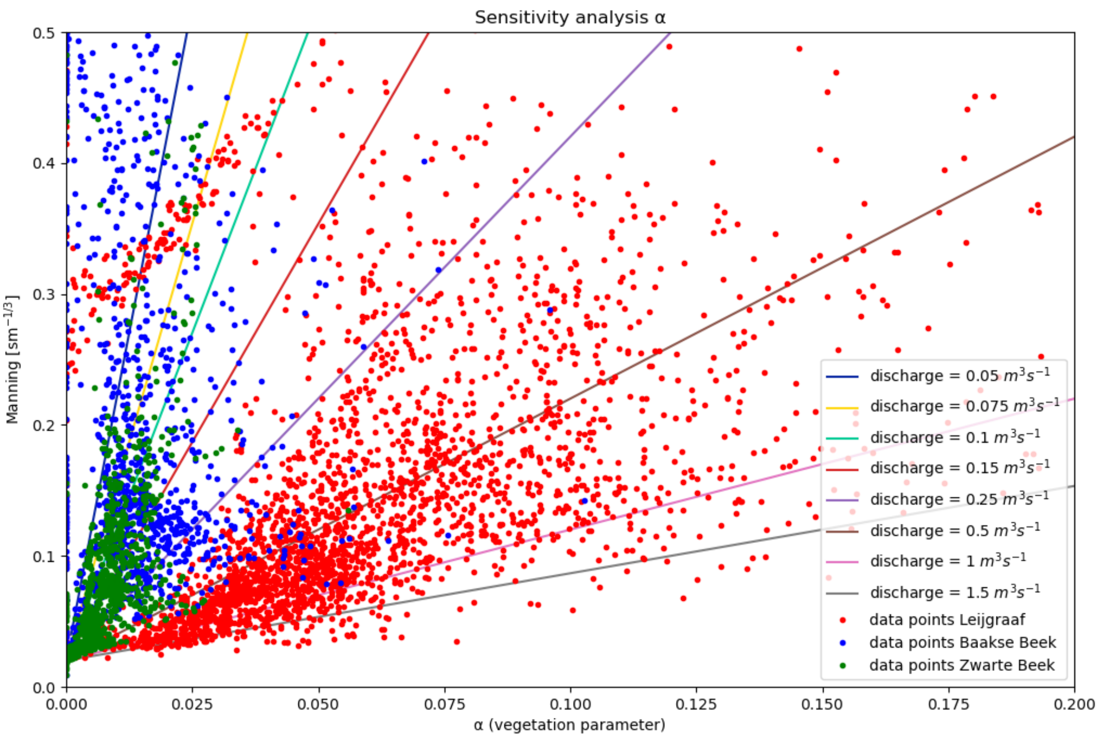

Figure 42 - Sensitivity analysis for α with different Manning coefficients

5.5 Uncertainty in the measurement data

As explained in Section 5.4, a small error in the measurement data can have a large influence in the value of the vegetation parameter in case the discharge is small. To get a better idea of the consequences of this, error bars are plotted with the measurement uncertainty taken into account. According to G. van den Houten, Hydrologist and coordinator of the hydrologic monitoring system at Waterschap Rijn & IJssel, it is likely that the uncertainty of the measuring equipment is around 2 centimetres for water levels. This means that the actual water level could be 2 centimetres higher or lower than is stated in the database. The size of the measurement uncertainty in the discharge measurements, is dependent on the discharge itself. The higher the discharge, the smaller the relative uncertainty. For this analysis, only the uncertainty in the water level measurements is taken into account. For future research, also the uncertainty in the discharge measurements could be taken into account.

To determine the consequences of the measurement uncertainty, the Manning coefficient is determined again using the optimisation script and SOBEK model but this time with an upstream water level that is 2 centimetres lower and higher compared to the original water levels. Adding 2 centimetres to the measurements of the upstream water levels results in the maximum possible Manning coefficient. Subtracting 2 centimetres from the upstream water level results in the minimum possible Manning coefficient. In this way, a band width is created with all possible values for the Manning coefficient per day. For the Baakse Beek in 2016, this is shown in Figure 43 below.

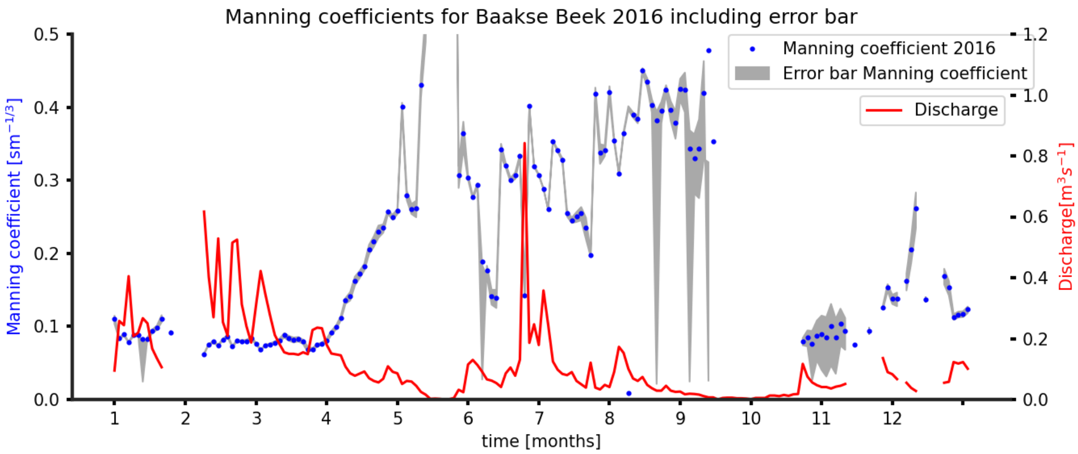

Figure 43 - Possible Manning coefficients with measurement uncertainty of 2 cm for Baakse Beek in 2016

The blue dots are the original Manning coefficients without changing the water levels. The grey plane represents the band width of all possible values of the Manning coefficient with a measuring uncertainty of 2 cm. The red graph shows the discharge during that year. All other years can be found in Appendix D. It can be seen that in general, the Manning Coefficient does not change much when the upstream water level is increased or decreased by 2 cm. This means that a measuring error of 2 cm will not influence the results that much. For some days, the band width suddenly increases. For those days, the optimalisation script is not able to determine the Manning coefficient with a small error: the residual after many iterations remains large. For the Zwarte Beek, this is the case even more often. Therefore, this process is explained via an example of the Zwarte Beek in the year 2015 below.

For the Zwarte Beek in 2015, the Manning coefficient with its error bars over time is shown in Figure 44. The blue dots show the original data points. The grey plane represents the possible values of the Manning coefficient in case there is a measuring error, with a maximum measuring error of 2cm. The red graph shows the discharge during that year. All other years can be found in Appendix D.

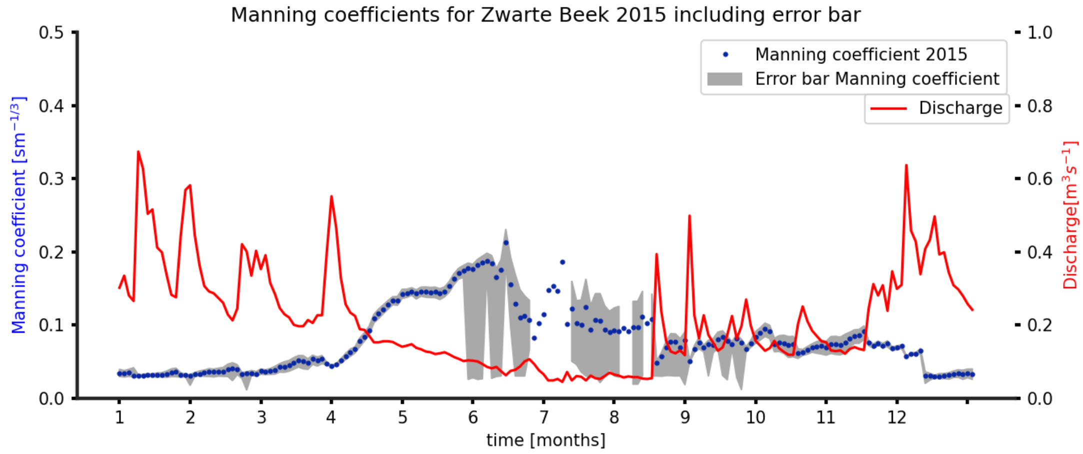

Figure 44 - Possible Manning coefficients with measurement uncertainty of 2 cm for Zwarte Beek in 2015

As can be seen in Figure 44, the grey error bar becomes large after 6 months. This is also the moment when the discharge is low. It can thus be seen here that when the discharge is low, a measuring error of 2 cm will change the value of the Manning coefficient completely. This is not only due the sensitivity in Equation 5, but also due to the SOBEK model and optimalisation script that have a hard time calculating the Manning coefficient during this period. It stands out the error bars suddenly become large after 6 months (27th of May 2015), while there is no sudden drop in discharge at that moment. The exact reason for this could not be found, but it is possible that this is caused by an error the SOBEK model. For this day, the residual after many iterations remains around 12 cm which is substantially large. This can also be seen in Figure 45. The reason why this residual remains this large, could not be found and remains unknown.

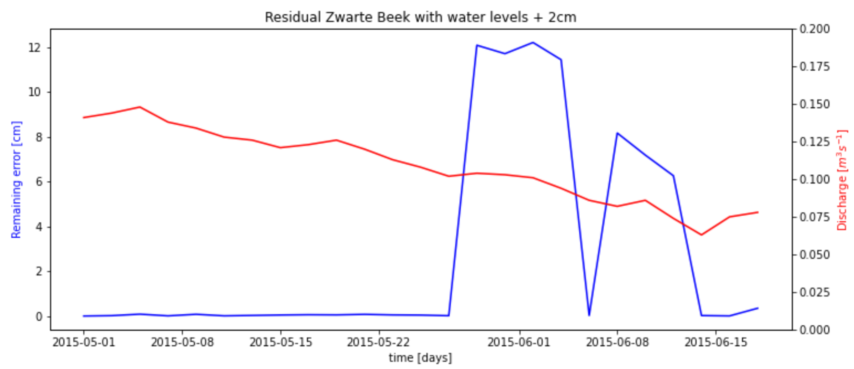

Figure 45 - Remaining error after optimalisation with water levels + 2cm

Since the optimalisation script is not able to return a Manning coefficient for this period with a small remaining error, it is possible that the actual lower boundary of the Manning coefficient lies higher than shown in the graph in Figure 44. This could mean that the band width increases not as much as shown in the graph.

The second thing that stands out when looking at Figure 44 is that the original data points (blue) lie mostly in the top half of the grey error bar. This means that an underestimated water level (reality is +2cm than database) has more effect on the Manning coefficient than an overestimated water level (reality is -2cm than database). If the lower boundary of the band width is actually an error in the optimalisation script and SOBEK model, it is possible that the blue data points actually lie in the middle in the band with instead of in the top halve.

Figure 46 shows the same principle as Figure 44, but this time it is the calculated error bars for the vegetation parameter. It can be seen that the trend in error bars is the same as for the error bars for the Manning coefficient, but the band width is a bit larger. The sudden increases in band width are the case for all years of the Zwarte Beek, which can be found in Appendix D. Note that the uncertainty in the discharge is not taken into account for this calculation. Taking that uncertainty into account as well, will probably increase the band width even more.

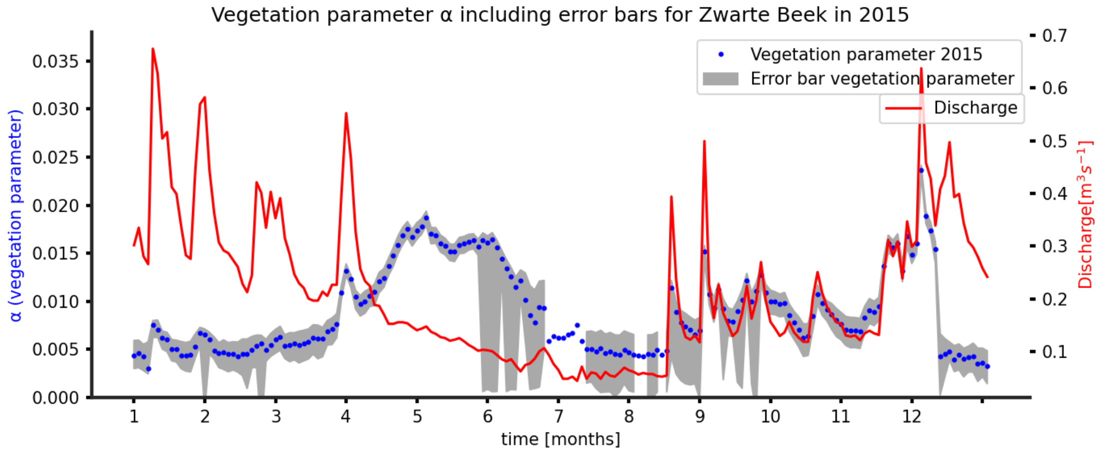

Figure 46 - Possible vegetation parameter with measurement uncertainty of 2 cm for Zwarte Beek in 2015

It can be concluded that a measurement error of 2 cm in general does not influence the Manning coefficient a lot. For the vegetation parameter, the band width increases a bit but the trend in the vegetation parameter can still clearly be seen in the grey plane. A possible measurement error of 2cm can thus not explain why the spreading in the vegetation parameter is significantly smaller for the Baakse Beek and Zwarte Beek compared to the Leijgraaf. However, for some days, the SOBEK model and the optimalisation script are not able to calculate the Manning coefficient accurately. After many iterations, the residual remains significantly large which means that the value of the Manning coefficient might not be accurate. The reason for this is unknown and further research is necessary to solve this issue.

5.6 Constant vegetation parameter

As explained in Section 4.2 and Section 4.3, multiple combinations of the three parameters α_{max}, r and t_m all lead to a prior distribution that follows the trend of the measured Manning coefficients. This could be a reason why the Markov Chain Monte Carlo algorithm is not working. If multiple combinations all give an acceptable result, the algorithm will simply return the first acceptable combination instead of the combination with the actual parameters.

A possible cause of why multiple combinations of the parameters are possible to get to the same vegetation parameter α, is that the vegetation parameter has a constant value. As can be seen in Figure 42, the variation in α is significantly less for the Baakse Beek and Zwarte Beek compared to the variation in α for the Leijgraaf. This variation could be so small, that a constant value for the vegetation parameter gives a better fit to the data than a normal distribution for the different parameters. To test this hypothesis, the Beekruwheidsmodel is adapted to a constant value for the vegetation growth parameter instead of the different elements in a normal distribution as described in Equation 6.

The Beekruwheidsmodel is adapted by changing the value of α to 0.02, which looks like a good assumption for the Baakse Beek in the year 2013 when looking at Figure 17. In Figure 47, the results are plotted for a constant vegetation parameter α of 0.02 (top) and the normally distributed parameters as in the original Beekruwheidsmodel (bottom). As can be seen in the figure, the Beekruwheidsmodel does not estimate the vegetation growth better with a constant value for the vegetation parameter because the top graph does not fit the data better compared to the bottom graph. Also for other values of the vegetation parameter, the model does not fit the data better than the original model with a distributed value for the vegetation parameter.

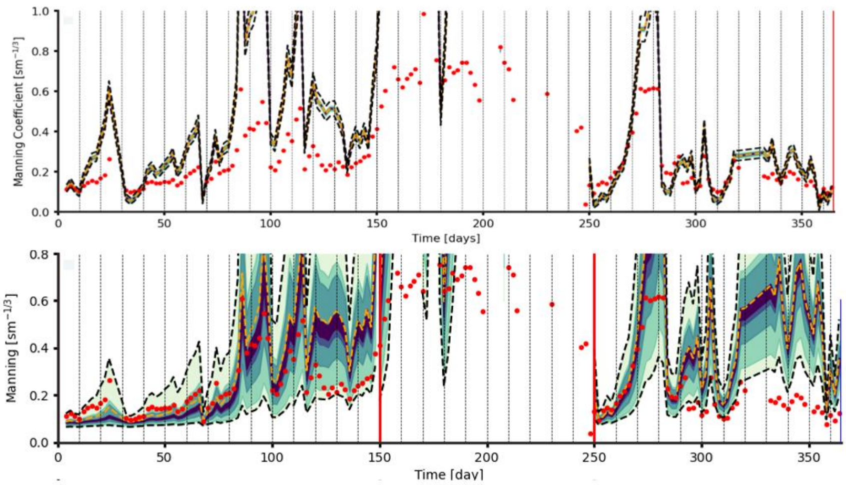

Figure 47 - Beekruwheidsmodel with a constant value for the vegetation parameter versus a normal distribution for the Baakse Beek in 2013

Figure 48 shows the same principle for Zwarte Beek in 2015 with a constant value of 0.005 for the vegetation parameter instead of a normal distribution. This value of 0.005 is based on the value of the vegetation parameter in Figure 25. Also here the data does not fit the Beekruwheidsmodel. Adapting the value of the vegetation parameter does not make the model fit the data better. In conclusion, the variation in α is smaller for the Baakse Beek and Zwarte Beek compared to the Leijgraaf, but not so small that a constant value for the vegetation parameter gives better results.

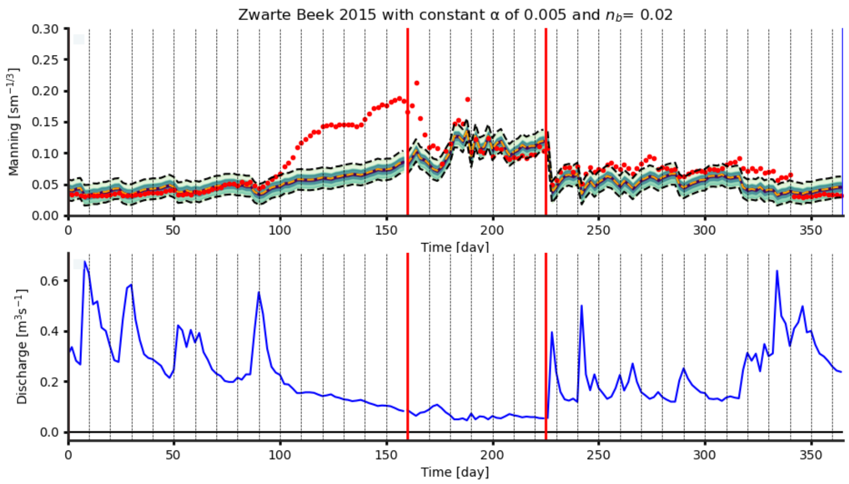

Figure 48 - Beekruwheidsmodel with constant vegetation parameter for Zwarte Beek 2015

6. Conclusion & recommendations

The goal of this thesis is to answer the following research question: *What is the temporal and spatial variation of the influence of vegetation on the hydraulic roughness in the selected streams ?* When the effects of vegetation on the hydraulic roughness and water levels are known, regional water authorities like Waterschap Rijn & IJssel can better understand the situation and use this for improving their policies regarding flood safety, biodiversity, and mowing. This thesis can be seen as a first step in improving those policies.

To answer the main research question, two streams were selected in the area of Waterschap Rijn & IJssel: the Baakse Beek and the Zwarte Beek. Those streams were chosen due to their continuous discharge all year for at least the years 2013-2017. The dimensions of the streams were found in a SOBEK model, and the data (water levels and discharge per day) were collected via the database of Waterschap Rijn & IJssel. During a field trip in April 2021, it was not yet possible to identify the vegetation types in the streams since not a lot of vegetation was visible. For further research, it could be interesting to identify the vegetation types to find a possible relationship between the vegetation types and the value a of the vegetation parameter α. Not only the vegetation types, but also monitoring the temporal change in vegetation spreading could be helpful to validate the results.

Next, the temporal variation of the hydraulic roughness is calculated for both streams using the SOBEK model and an optimisation script. For both the Baakse Beek and Zwarte Beek, realistic values were found for the Manning coefficient between 2013 and 2017. Also a trend can be seen where the Manning coefficient increases during April and May each year. Vegetation growth might be the reason for this increase in the Manning coefficient. After the year 2017, there were periods where the discharge is equal to 0 m^3s^{-1} during summer so determining the Manning coefficient is not possible. For the Zwarte Beek, the optimalisation script was not able to determine a reliable value for the Manning coefficient after May 2017. The cause of this remains unknown but an error in the measurement network could be an option.

When researching the influence of vegetation on the hydraulic roughness or just determining the hydraulic roughness, both the quality and the quantity of the data are of great importance. Several other streams in the area of Waterschap Rijn and IJssel have been investigated (Wijde Wetering, Visserij, and Groenlose Slinge) but none of these streams had data available that met the criteria for this research. For further research on vegetation growth in streams, it would be helpful if more measurement locations are added to streams that have a continuous discharge all year. If possible, it is preferred that the measurement trajectories lack instream from tributaries and are uniform in vegetation types and spreading. A longer trajectory has the benefit that an increase in the surface-water slope is better noticeable in the data, whereas shorter trajectories have the advantage that they are probably more uniform in its environment (vegetation types and spreading) and have no tributaries.

The final step in this research was to apply the Beekruwheidsmodel on the two selected streams to determine the influence of vegetation on the hydraulic roughness. For both the Baakse Beek and Zwarte Beek, it was found that the value of the vegetation parameter is relatively small. A comparison was made between the two selected streams and the Leijgraaf to find out the possible cause of this. A difference between the Leijgraaf compared to the Baakse Beek and Zwarte Beek, is its discharge and flow velocity. For further research, it would be interesting to apply the Beekruwheidsmodel on other streams with a larger flow velocity and discharge all year long.

Even though the value of the vegetation parameter is small for the Baakse Beek and Zwarte Beek, which means that vegetation does not influence the hydraulic roughness a lot, still a trend can be seen during spring and summer. For most years, an increase in the vegetation paramter can be seen during April until August. For some of the years for both the Baakse Beek and Zwarte Beek, also a drop in the vegetation parameter can be seen which could be caused by human intervention like mowing. During fall and winter, the Beekruwheidsmodel predicts a higher Manning coefficient than the measurements show. No sudden drop in the measurements can be seen here, but a more gradual decrease is present. One of the reasons for this decrease, could be decline of the aboveground vegetation. Adding mortality of vegetation in the Beekruwheidsmodel could be valuable for future research.

An attempt was made to apply the Markov Chain Monte Carlo algorithm to determine the values of the vegetation parameters more accurately. Unfortunately, the algorithm was not able to do this correctly. Multiple reasons could be the cause of the not-working Markov Chain Monte Carlo algorithm and the low value of the vegetation parameter. For example the lower discharges and flow velocities during spring and summer, the types of vegetation, an error in the measurements could be the cause of the not-working algorithm.

All in all, it can be concluded that the vegetation in both the Baakse Beek and Zwarte Beek does not influence the hydraulic roughness a lot since the value of the vegetation parameter α is relatively low under average discharge conditions. Since watercourses are strongly vegetated, plants may exert a strong influence on water levels after heavy rainfall, resulting in extreme discharges. The sensitivity analysis showed that the low discharges during spring and summer result in a high model uncertainty. With low discharges, the results are sensitive to small errors in the data. Adding more measurement locations to streams with higher discharges could be useful for future research.

7. References

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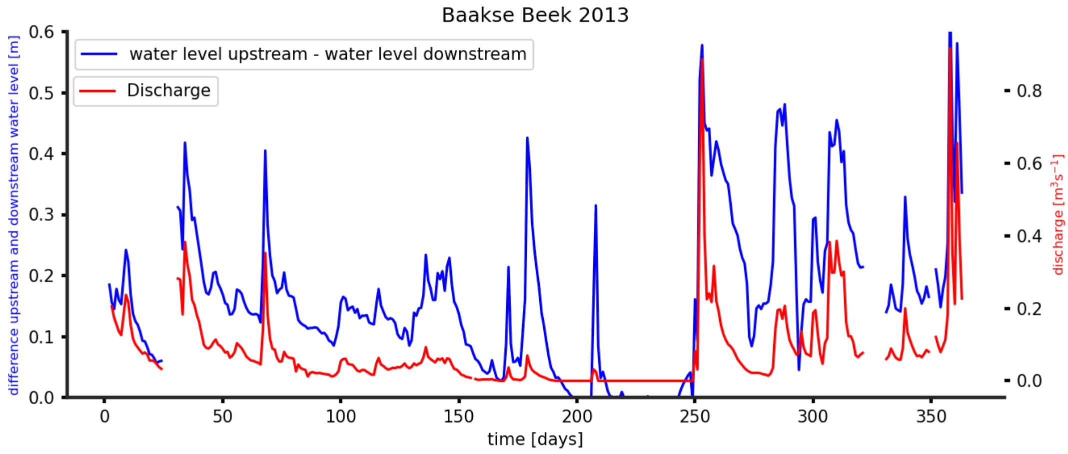
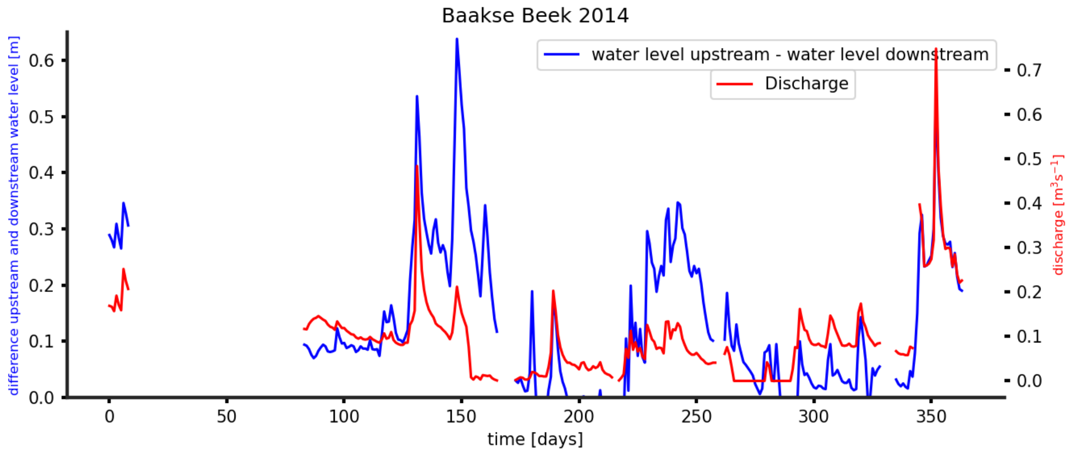
8. Appendix A – Raw data (water levels and discharge)

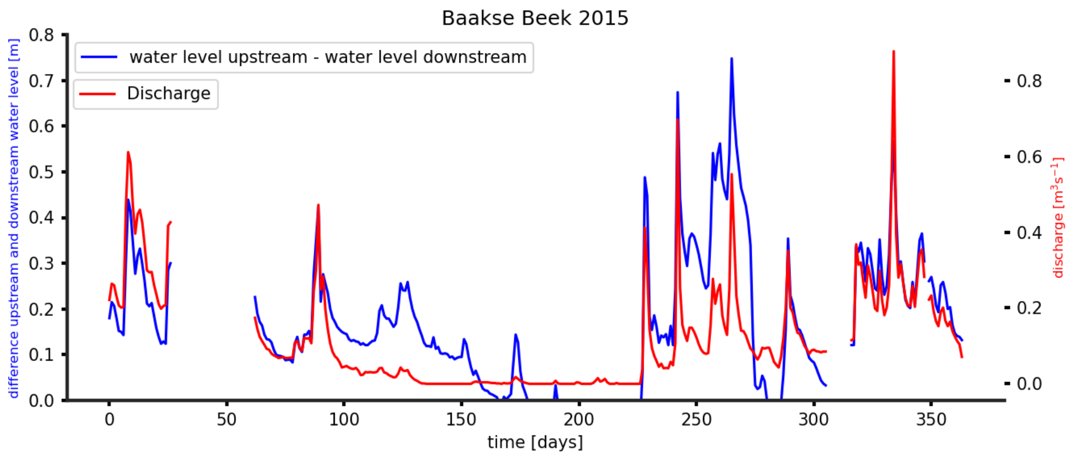
Baakse Beek 2013



Baakse Beek 2014



Baakse Beek 2015



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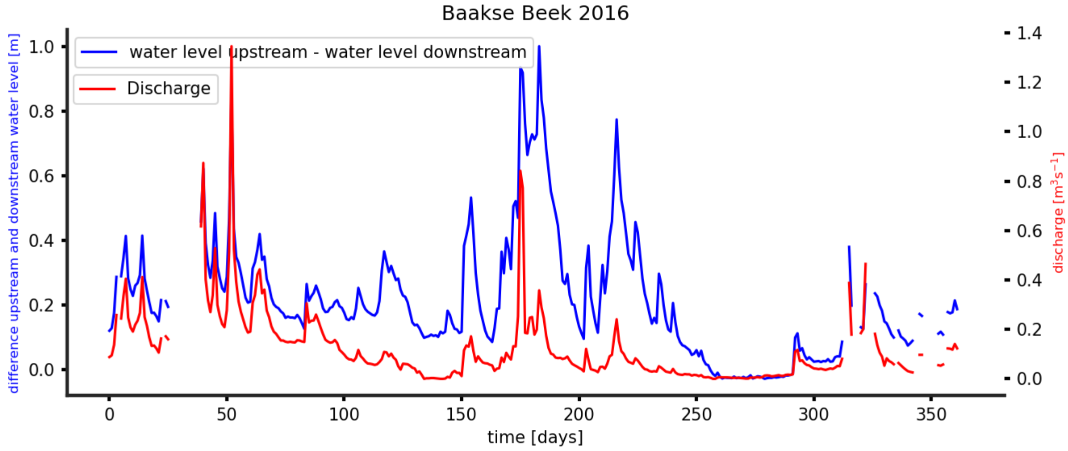

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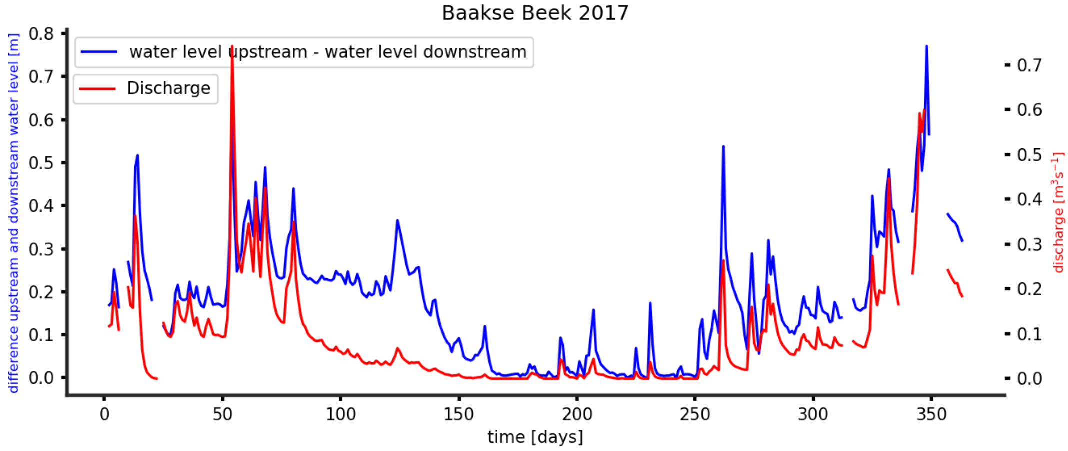
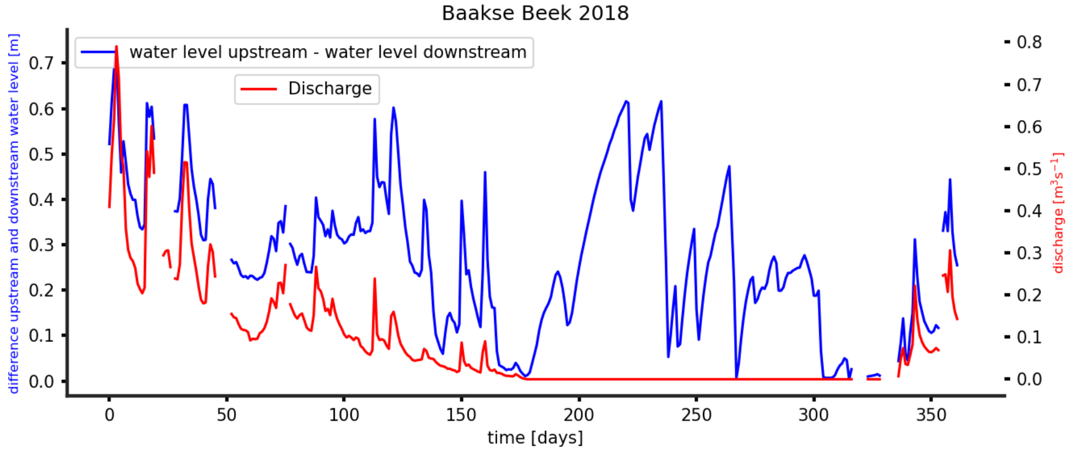


Baakse Beek 2018



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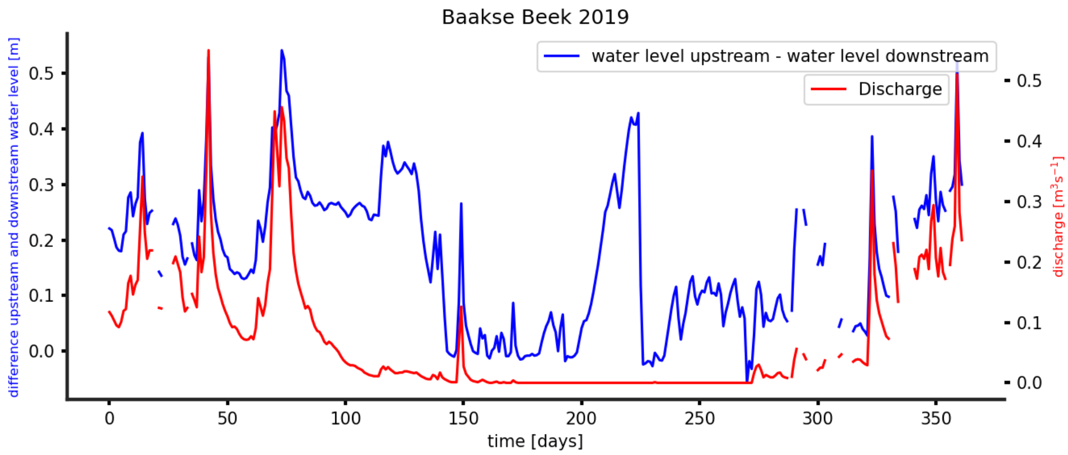
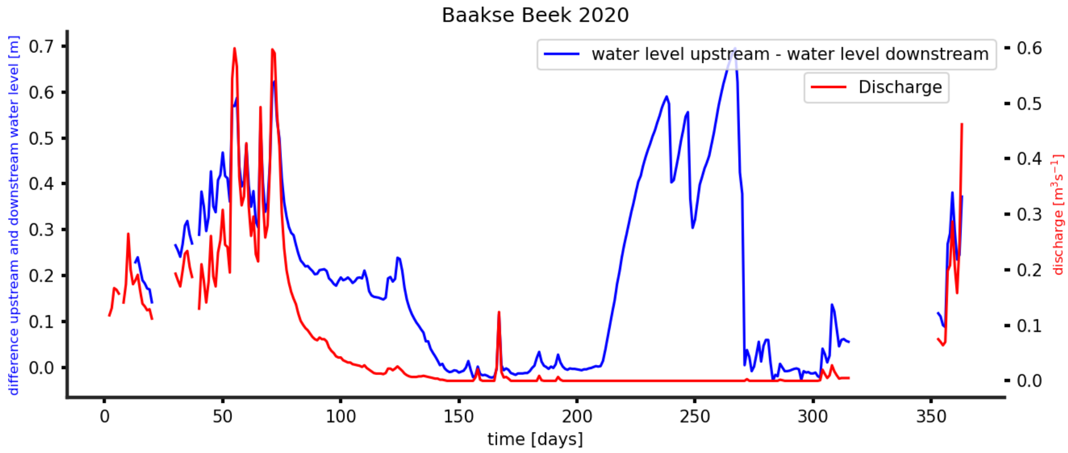
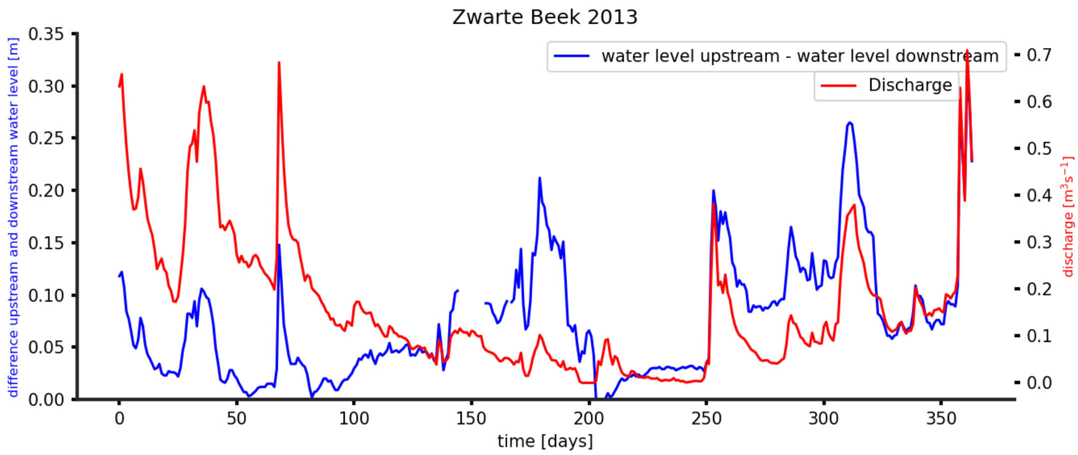


Baakse Beek 2020



Zwarte Beek 2013



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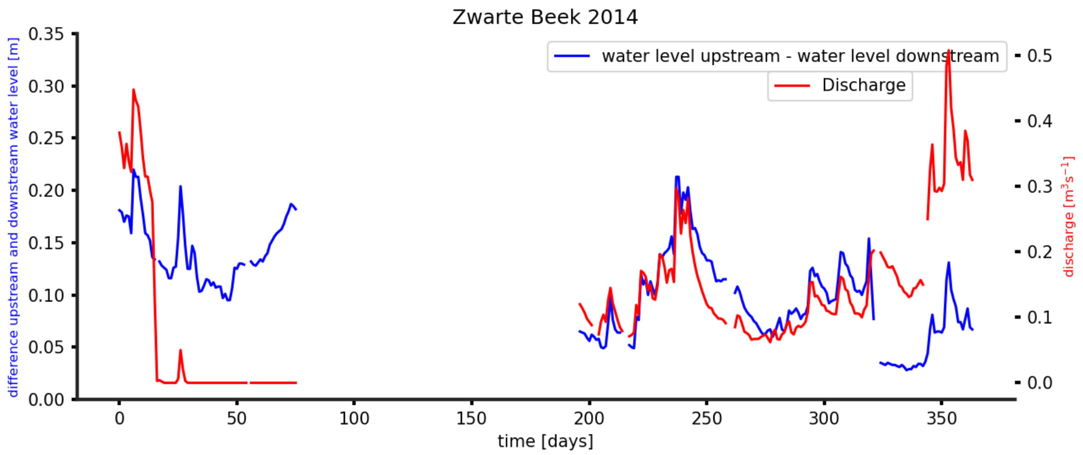

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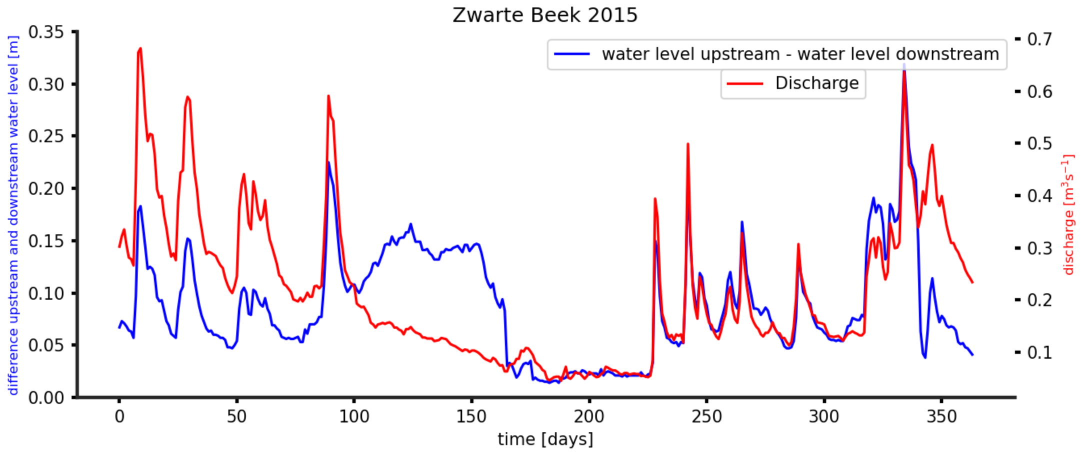

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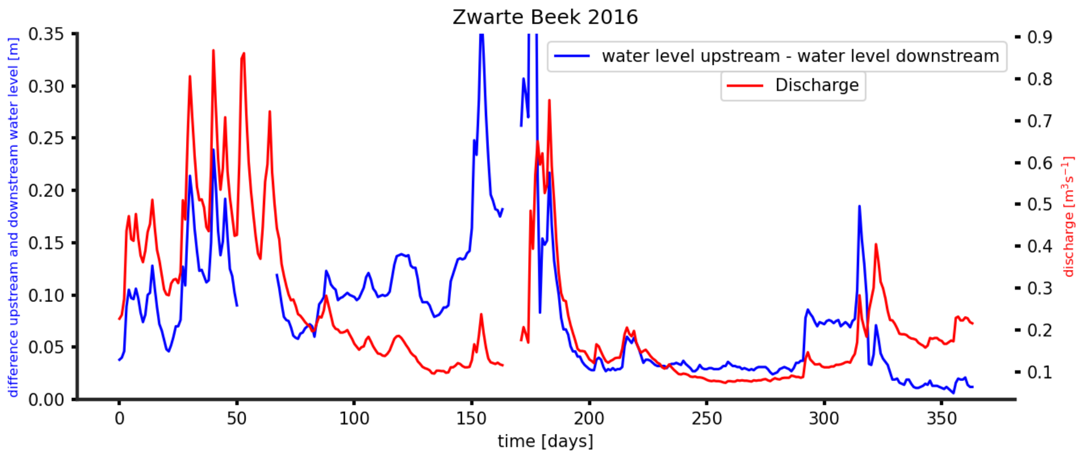

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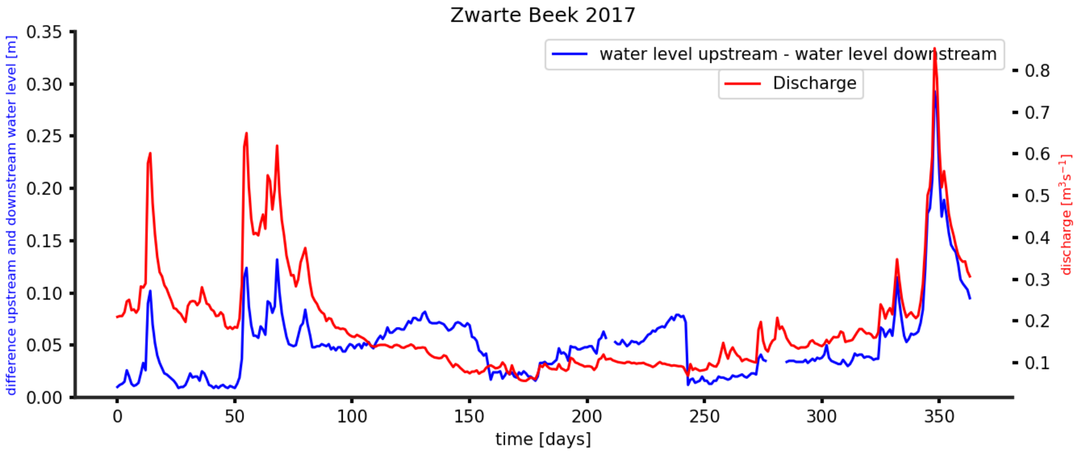

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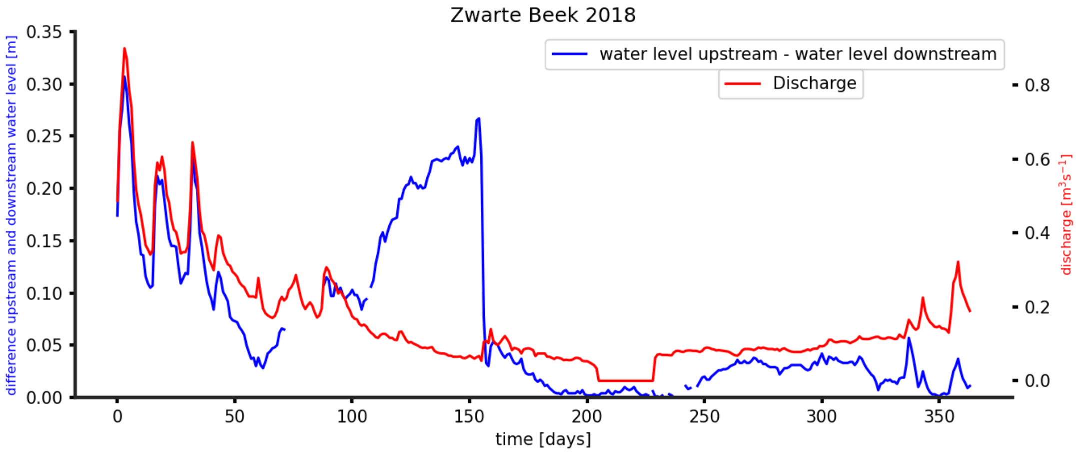

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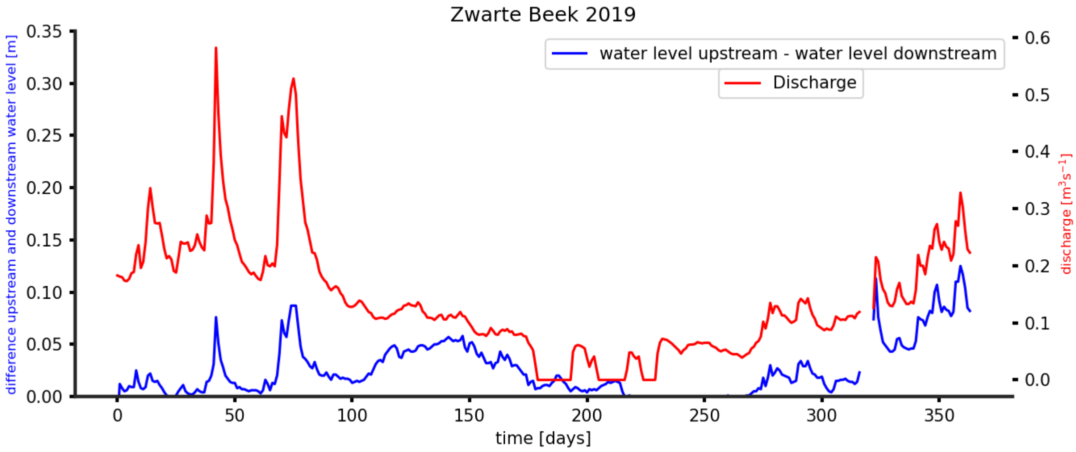

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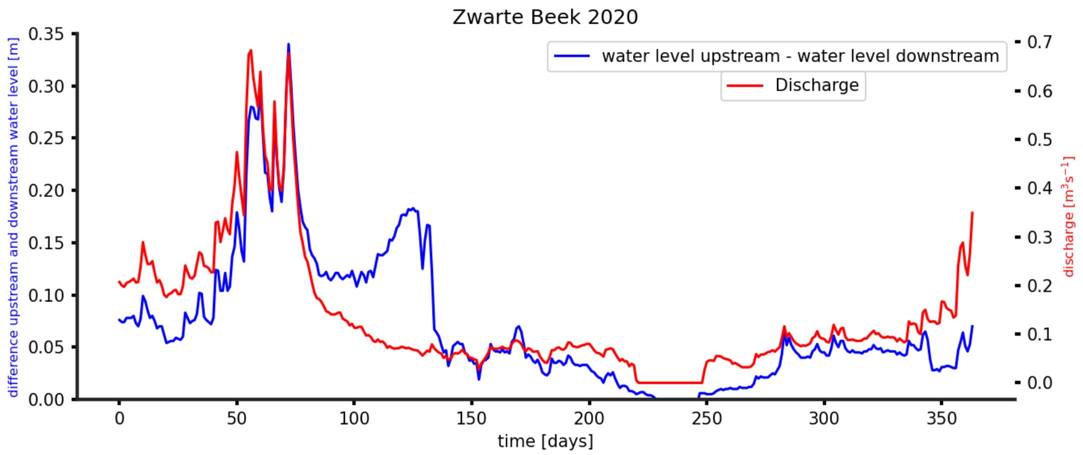

9. Appendix B – Manning Coefficients & discharge over time

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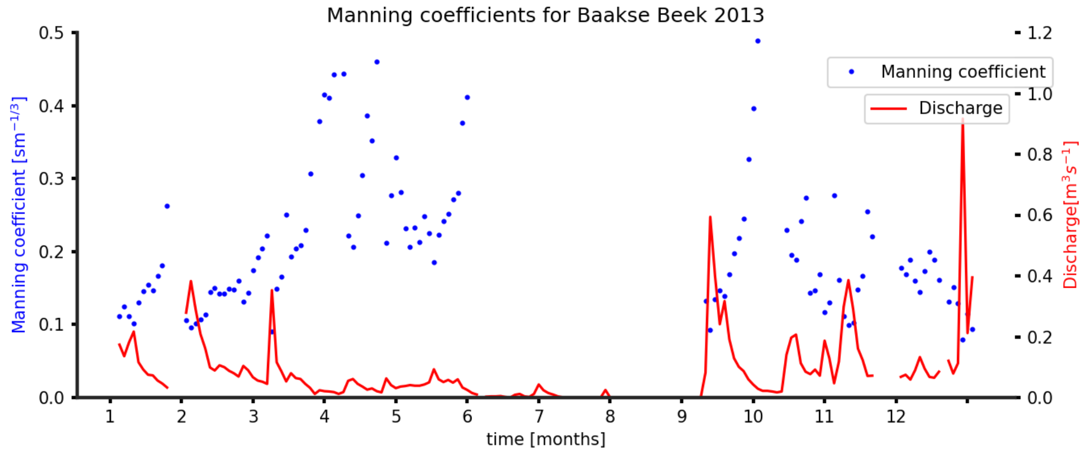

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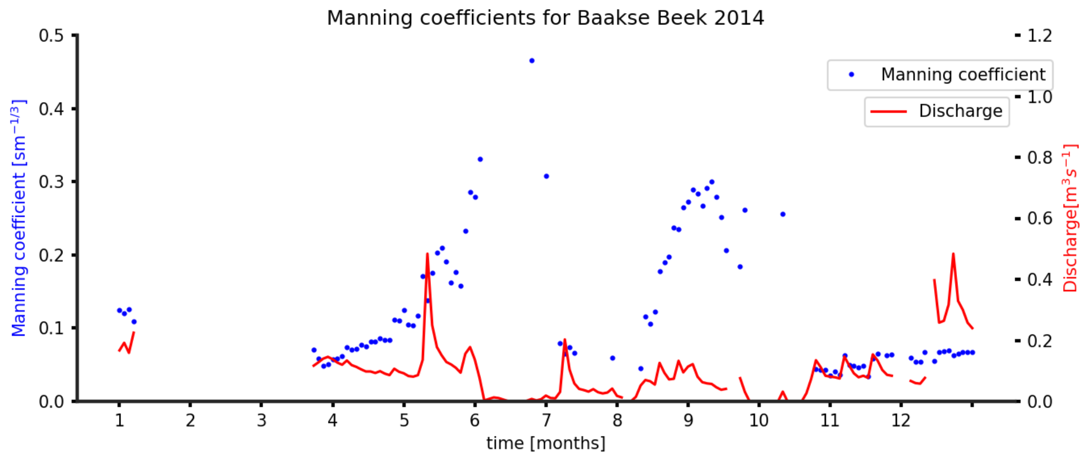

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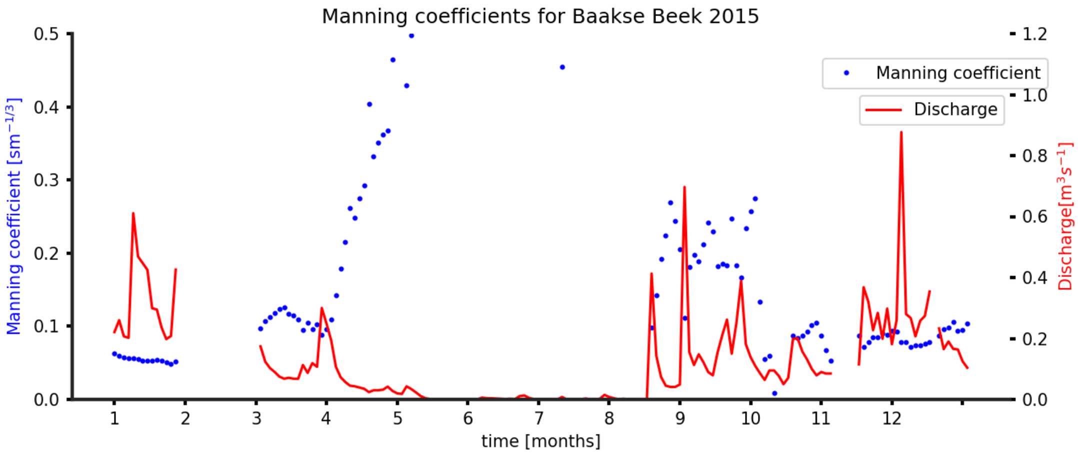

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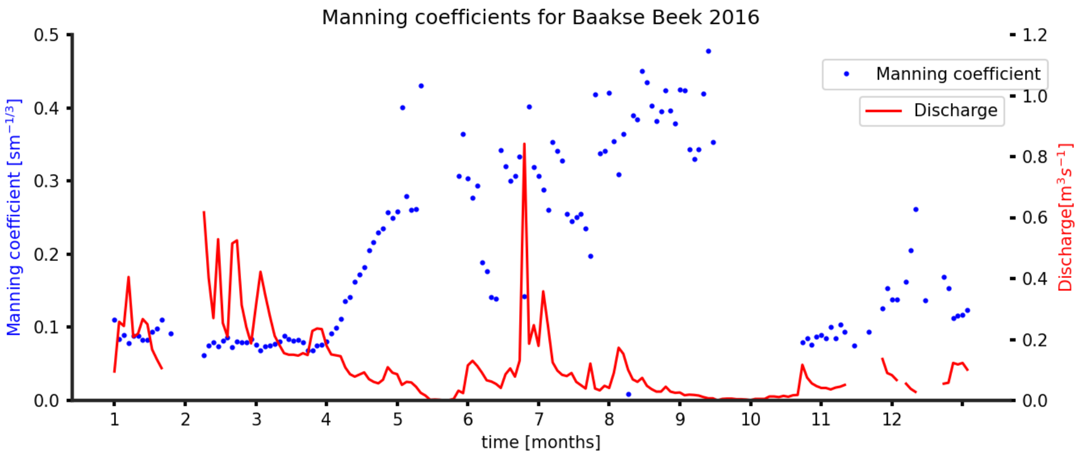

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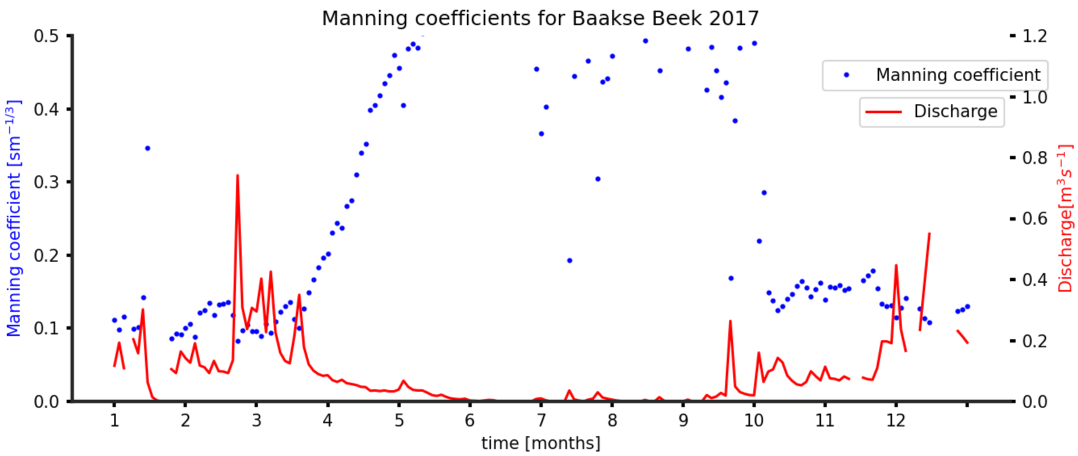

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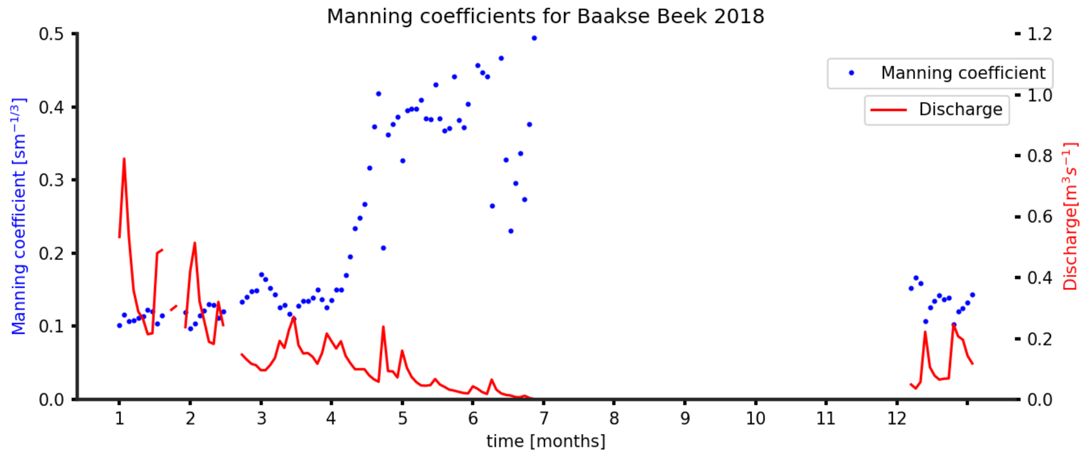

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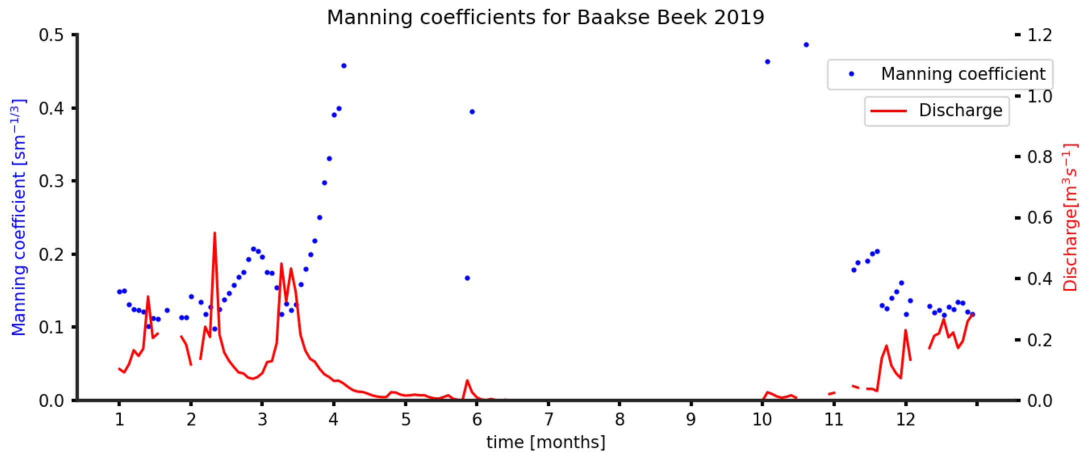

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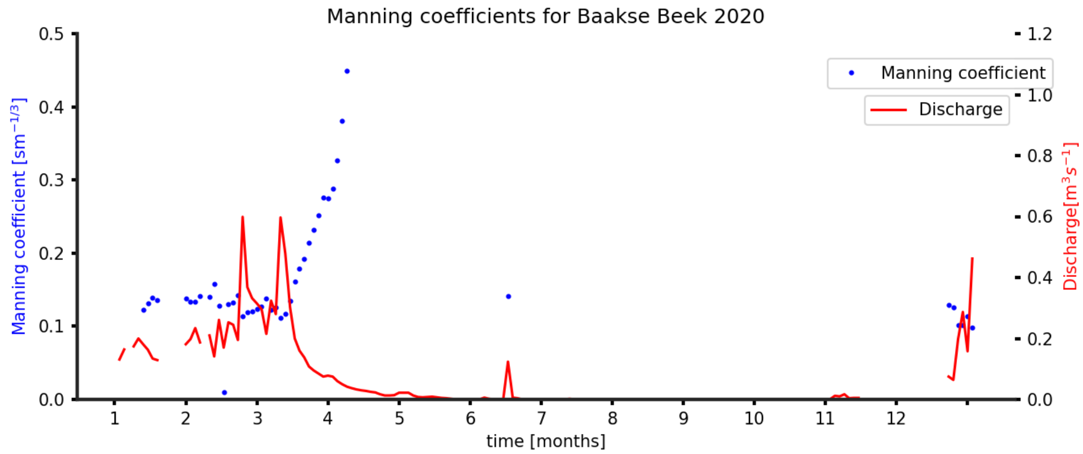

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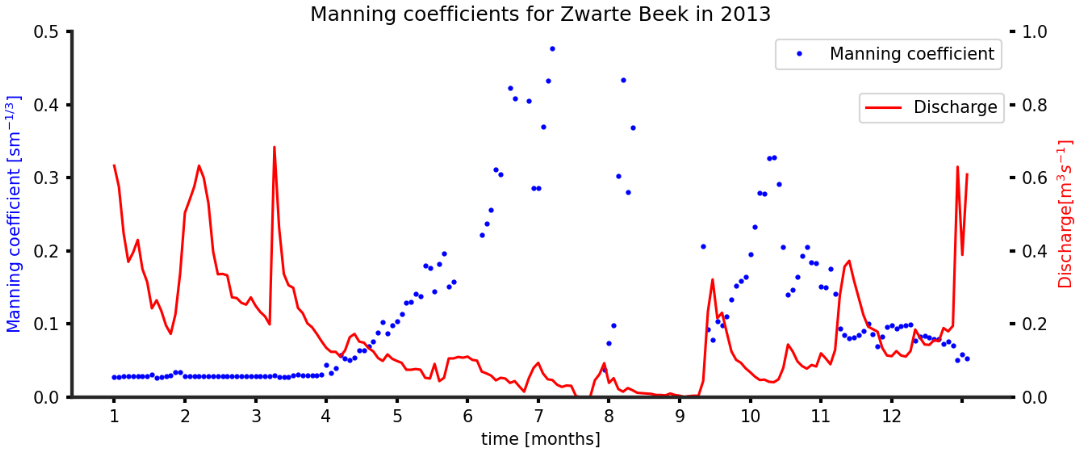

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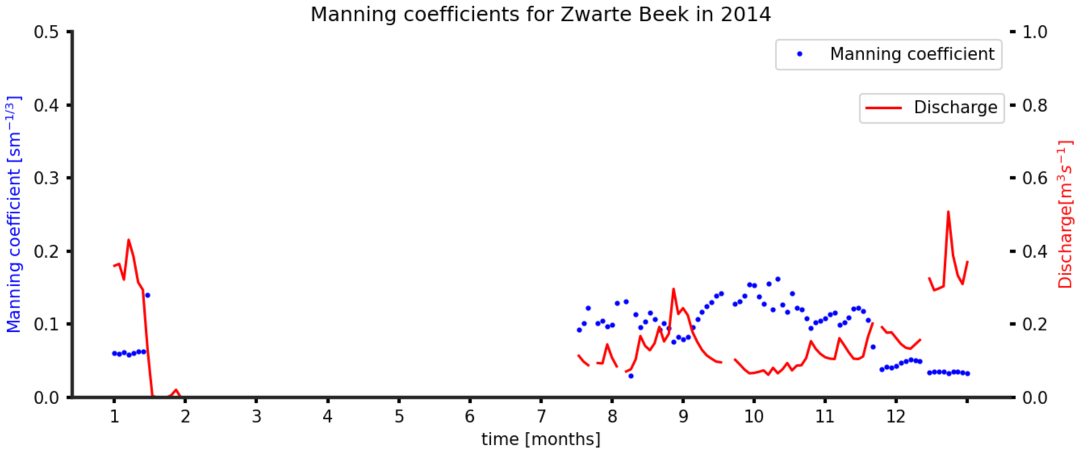

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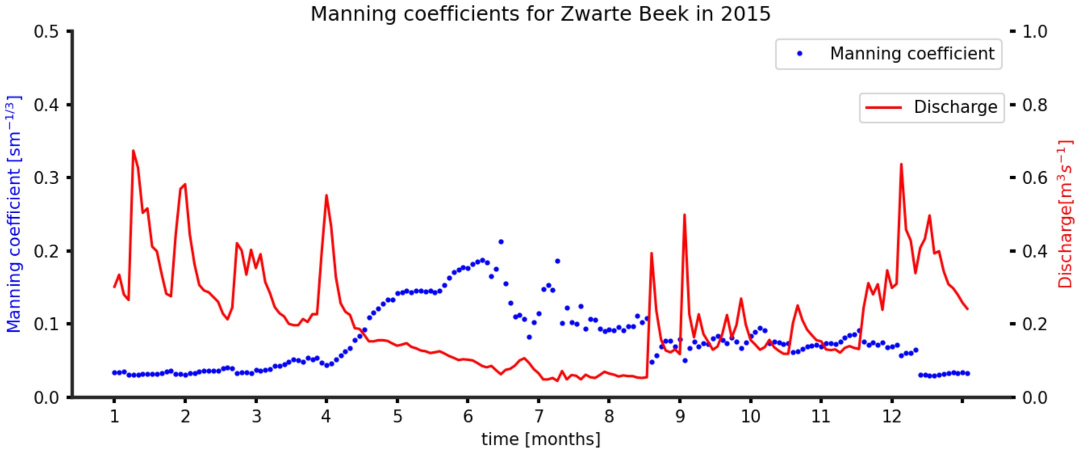

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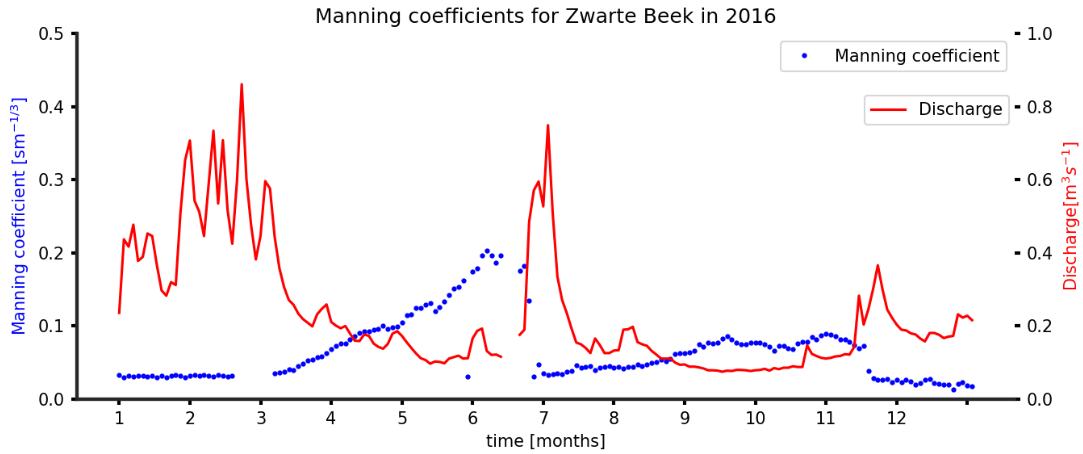

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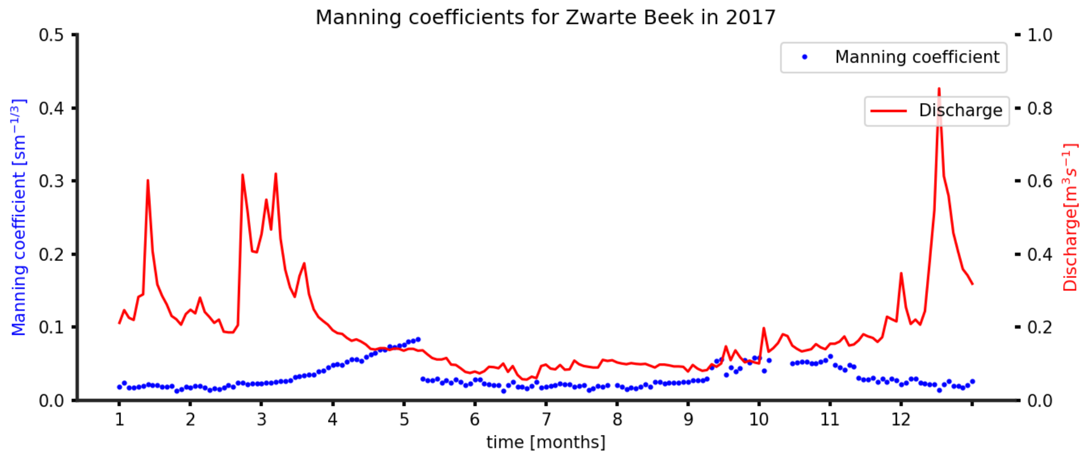

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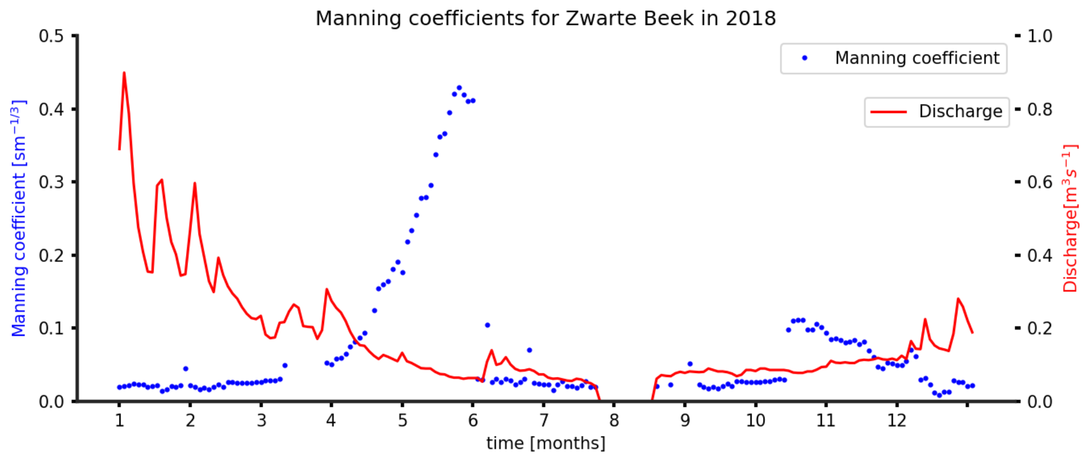

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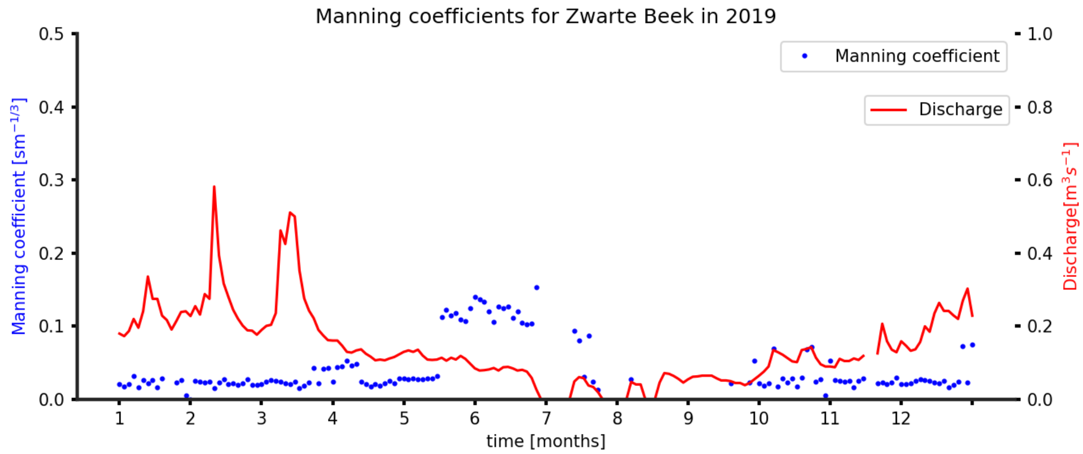

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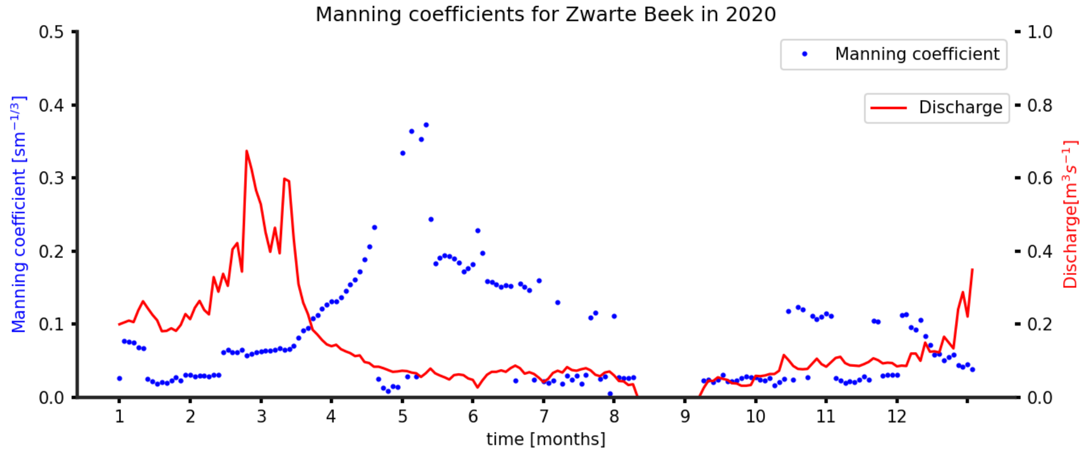
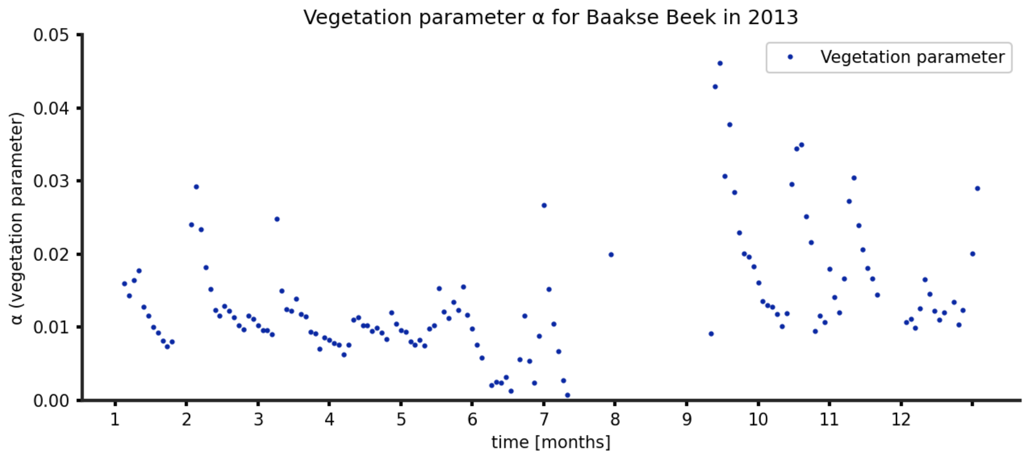


10. Appendix C – Vegetation parameter over time

Baakse Beek 2013



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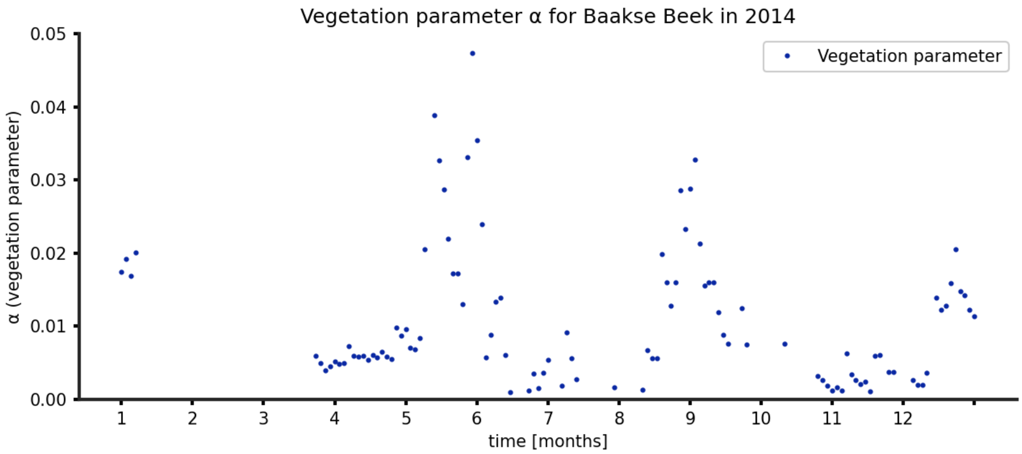

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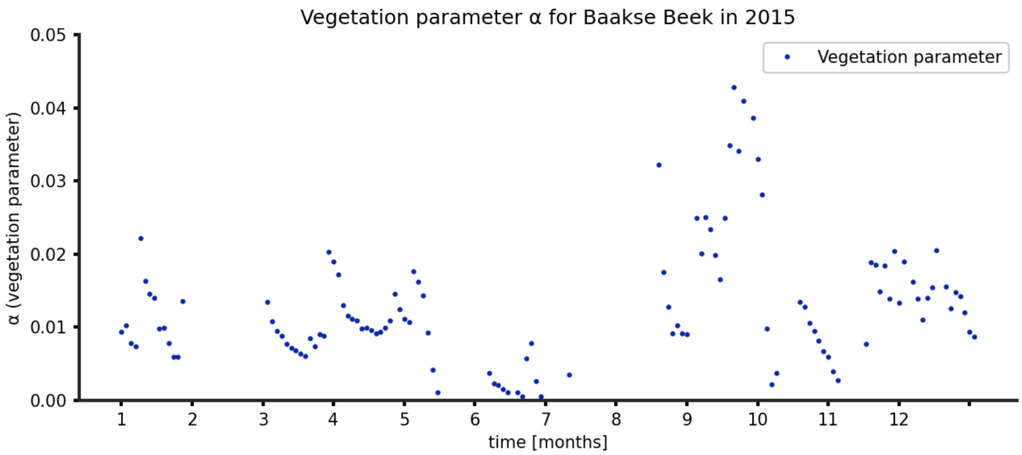

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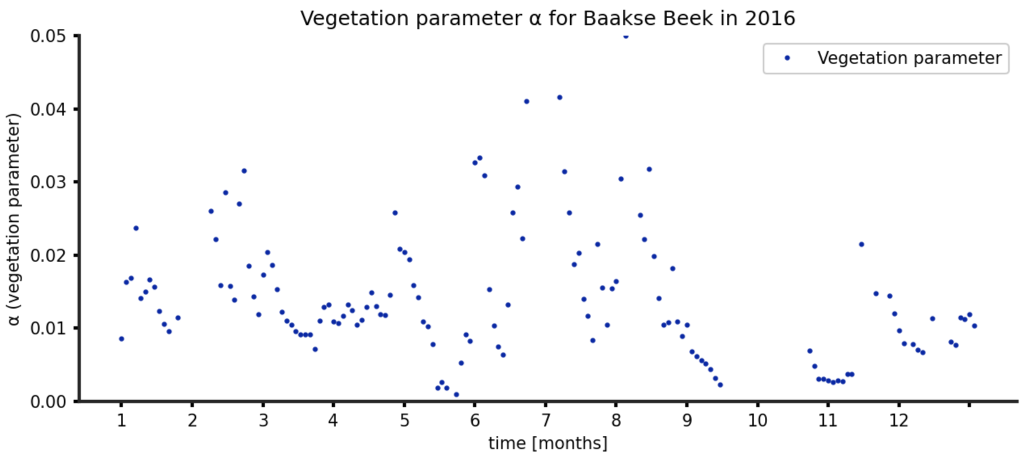

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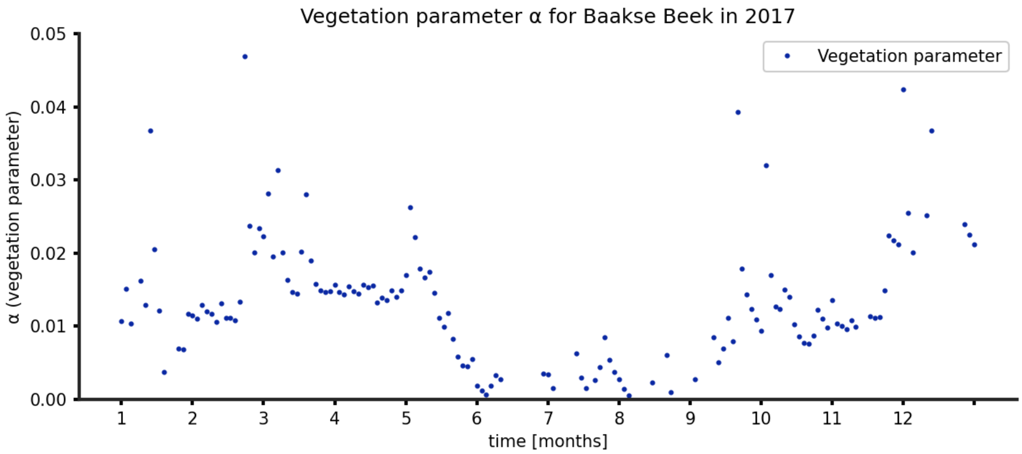

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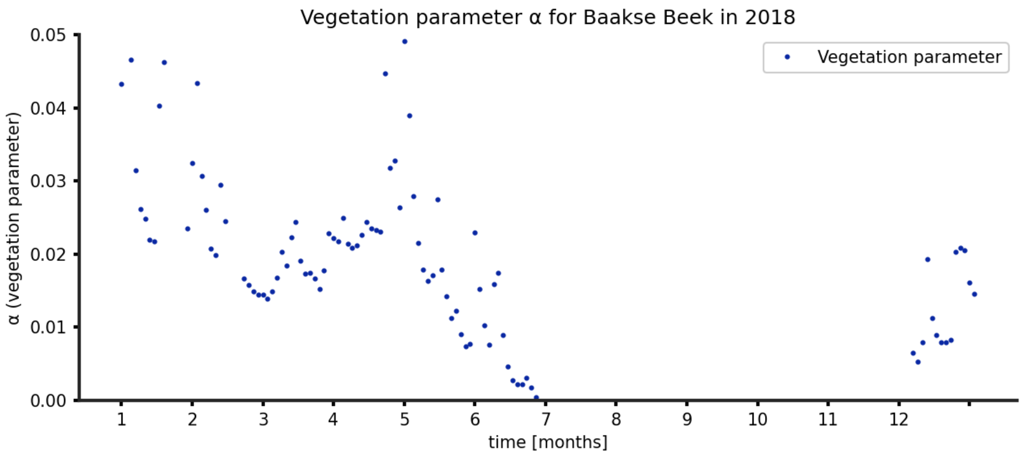

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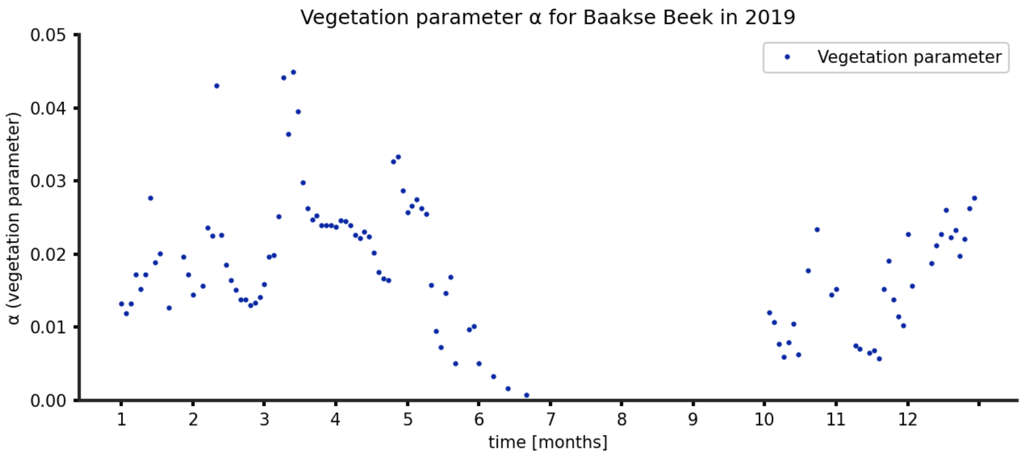

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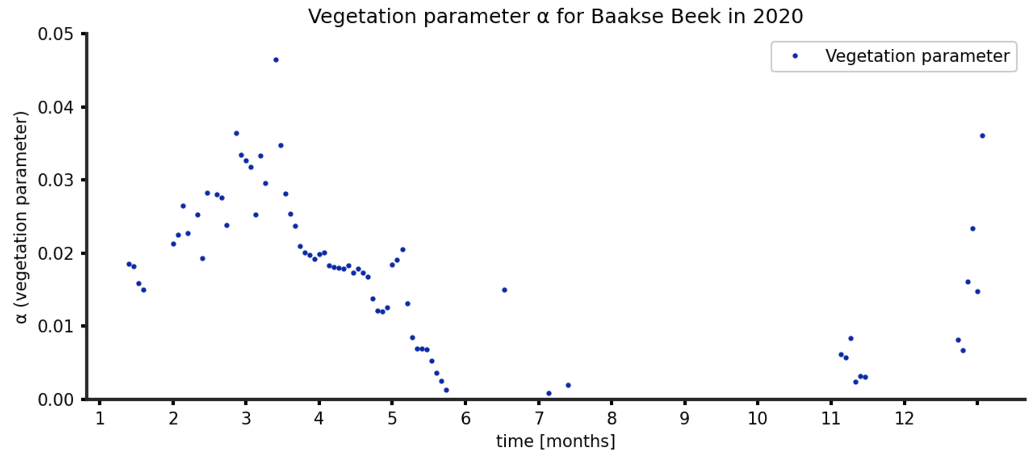

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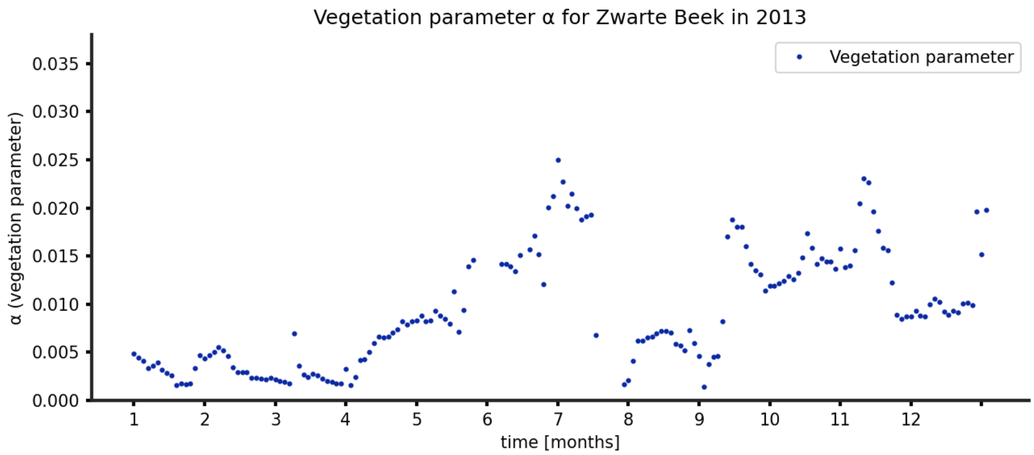

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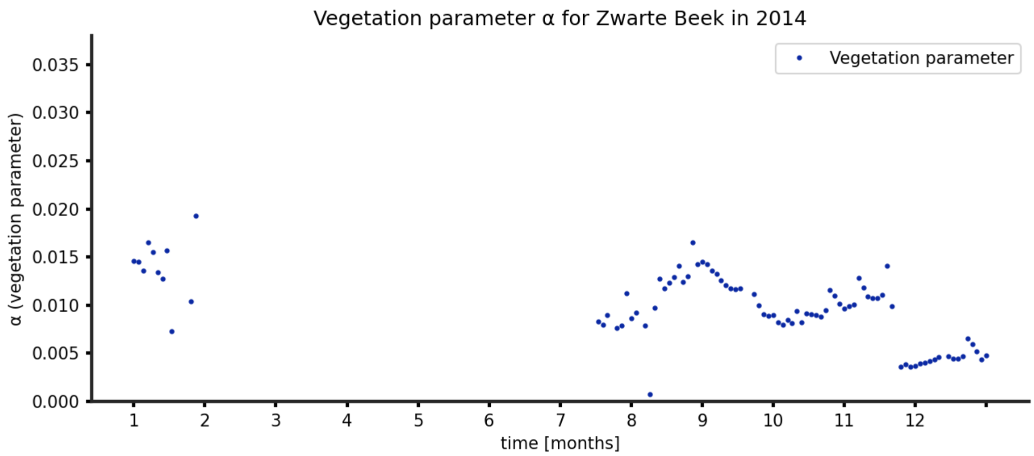

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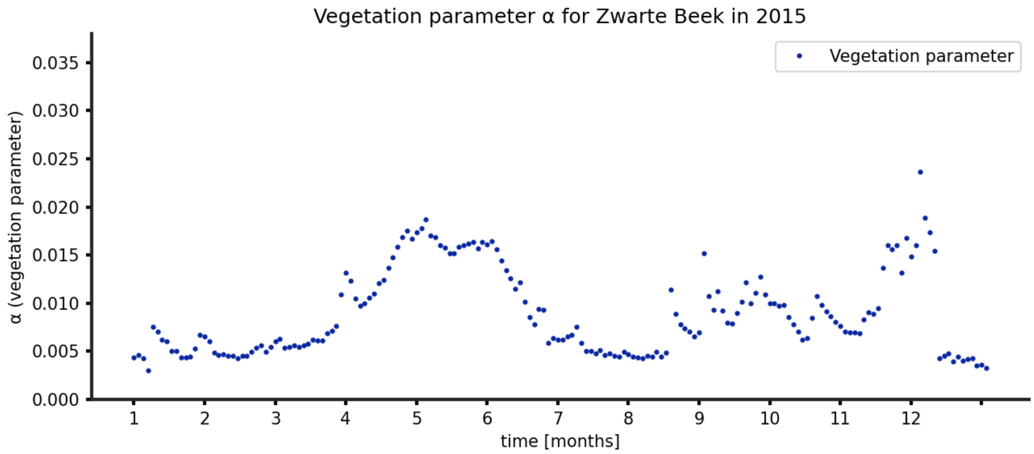

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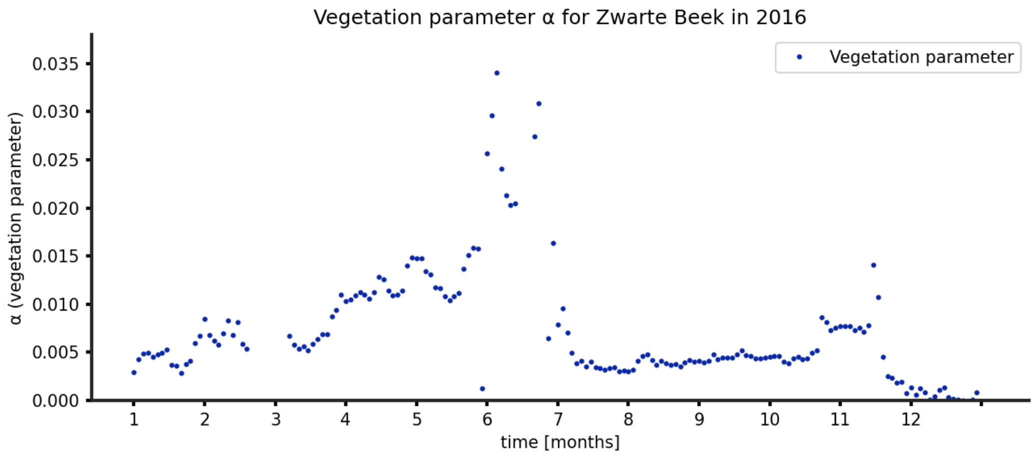

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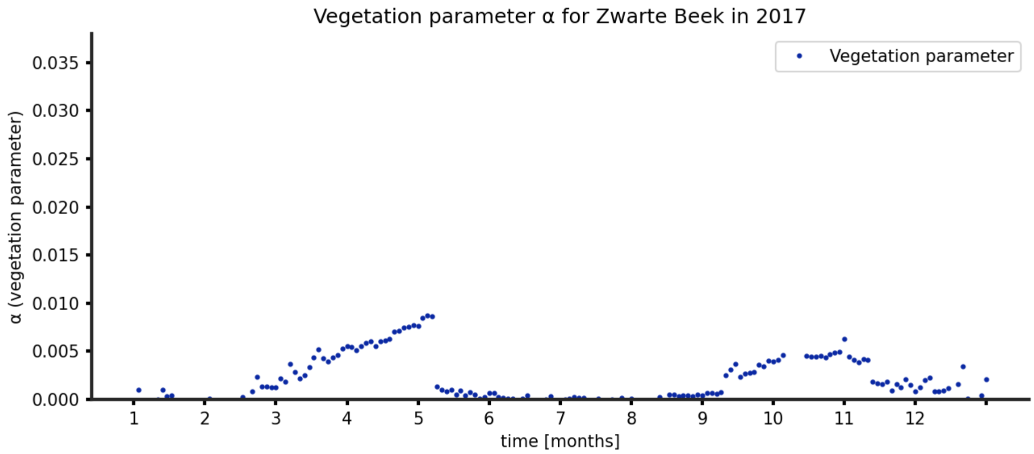

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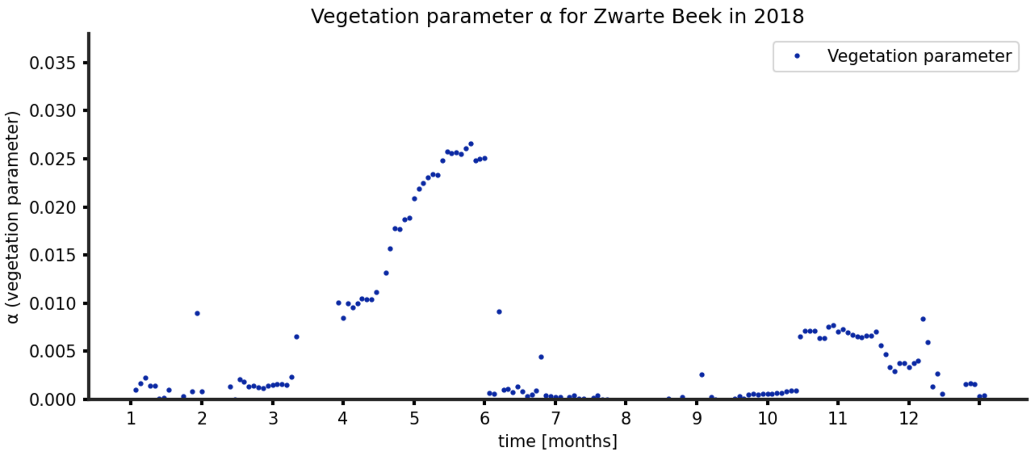

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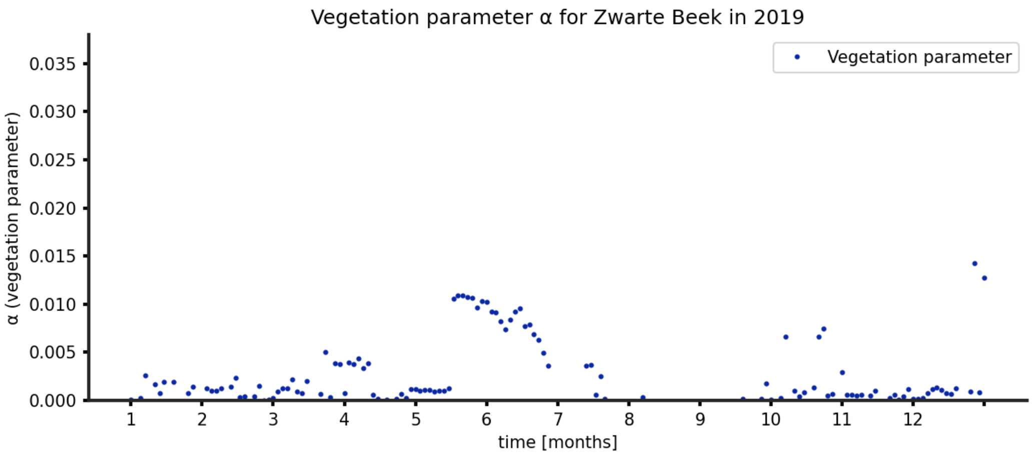

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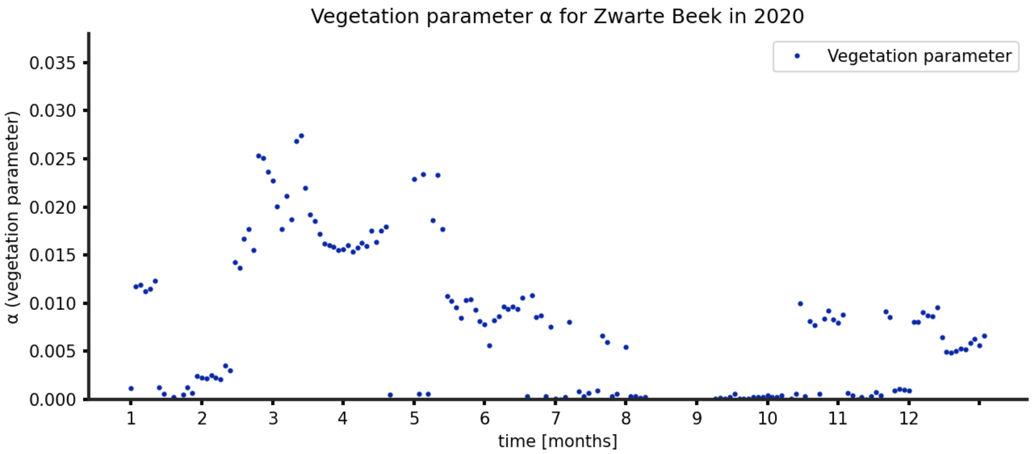

11. Appendix D – Error bars manning coefficient

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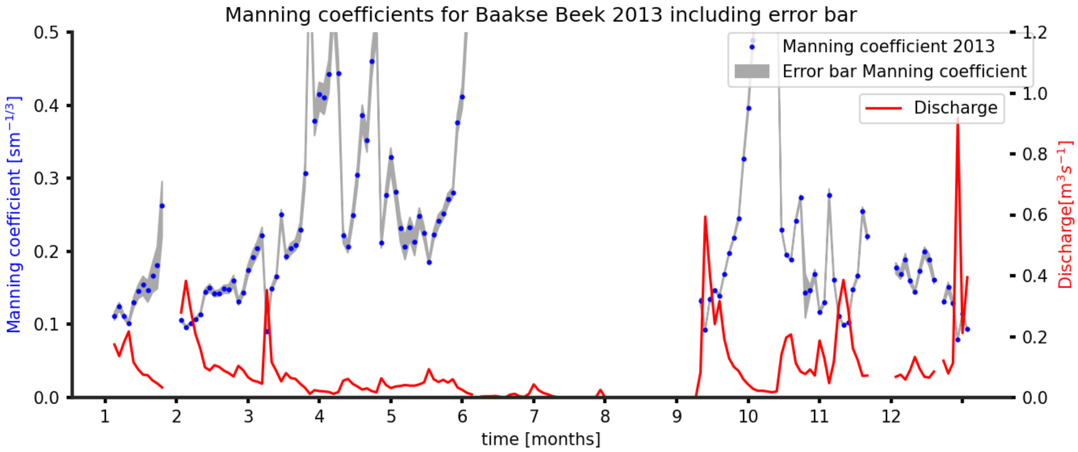

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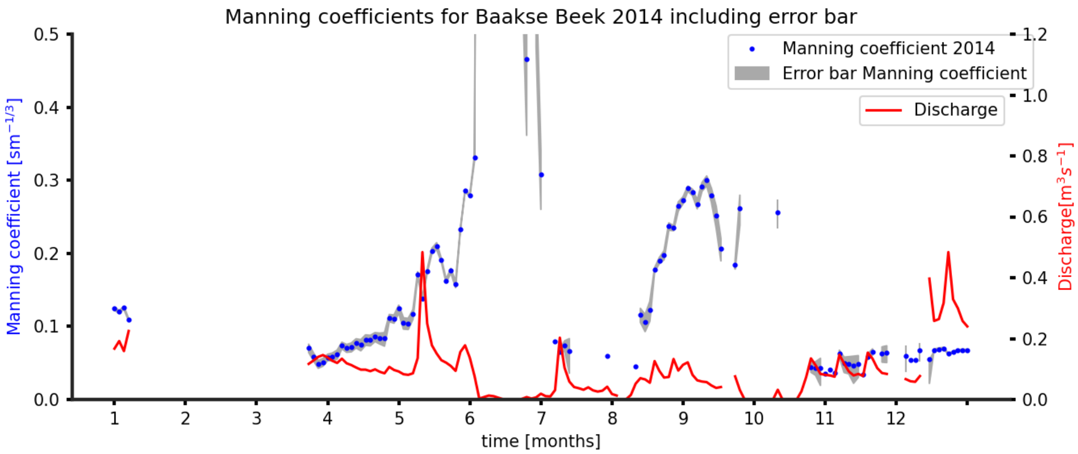
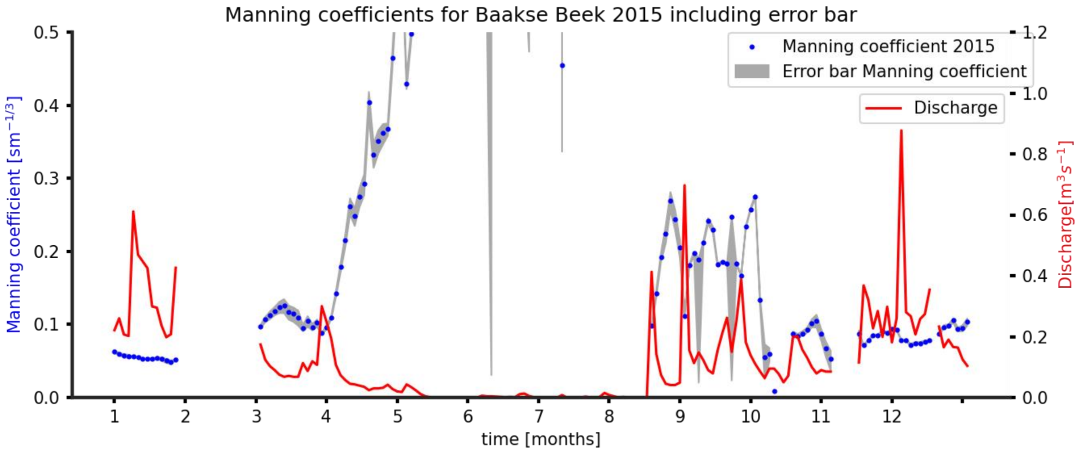


Baakse Beek 2015



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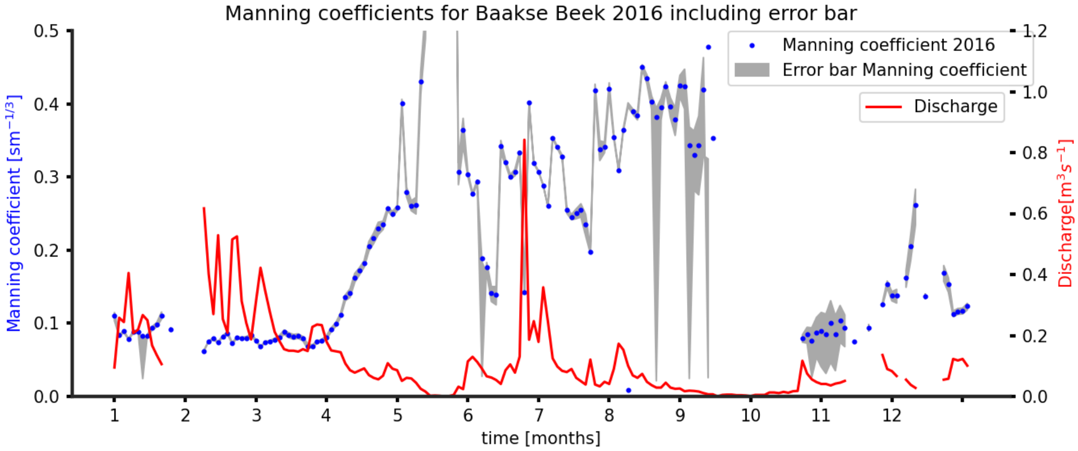

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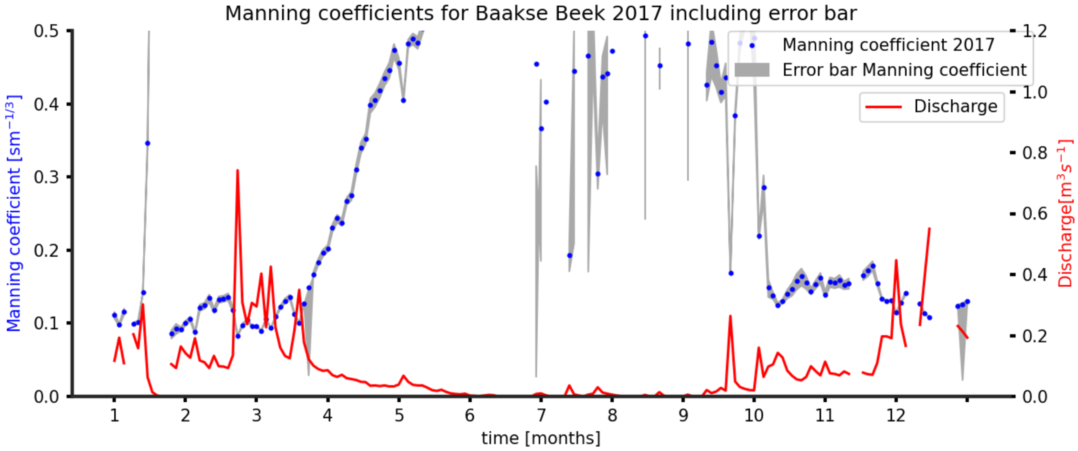

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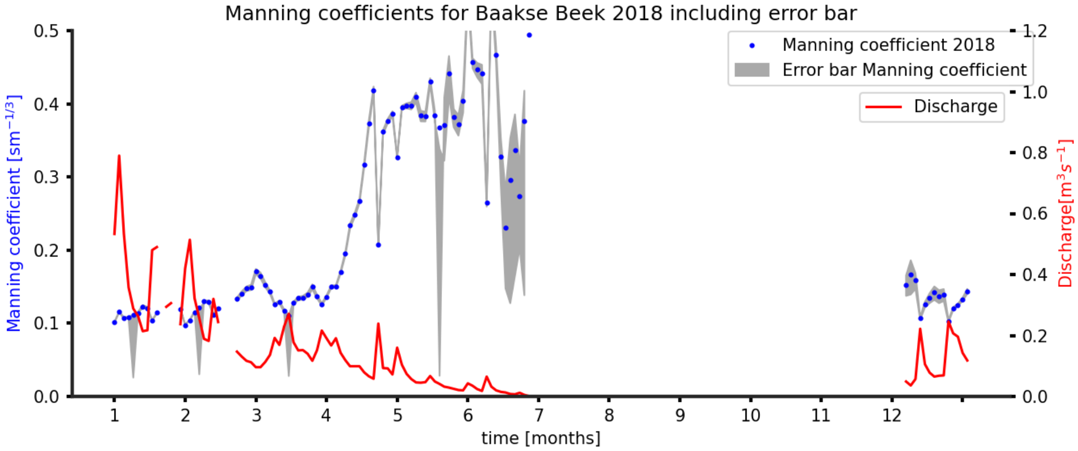

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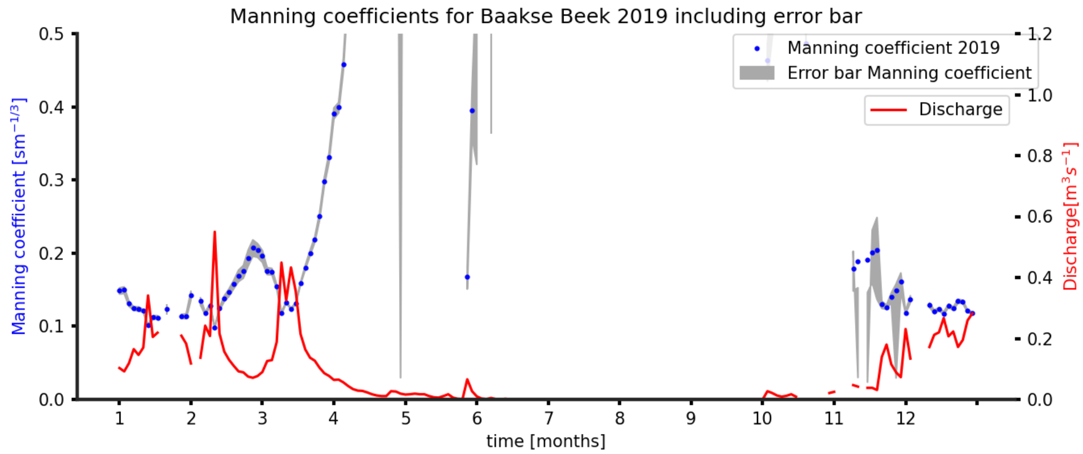

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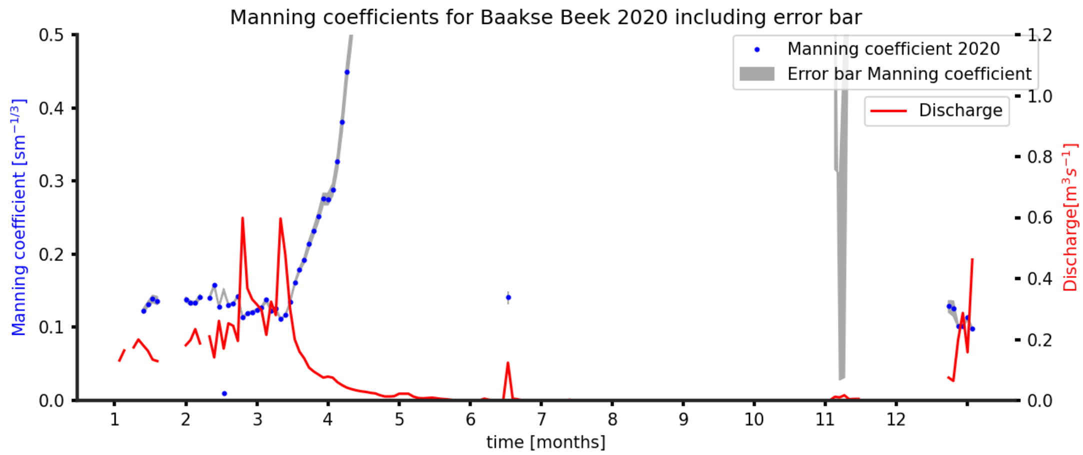
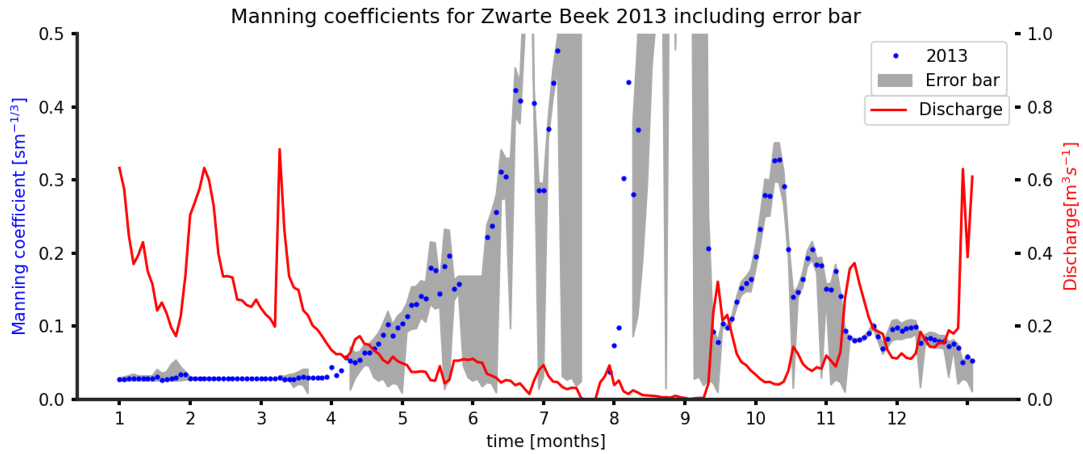
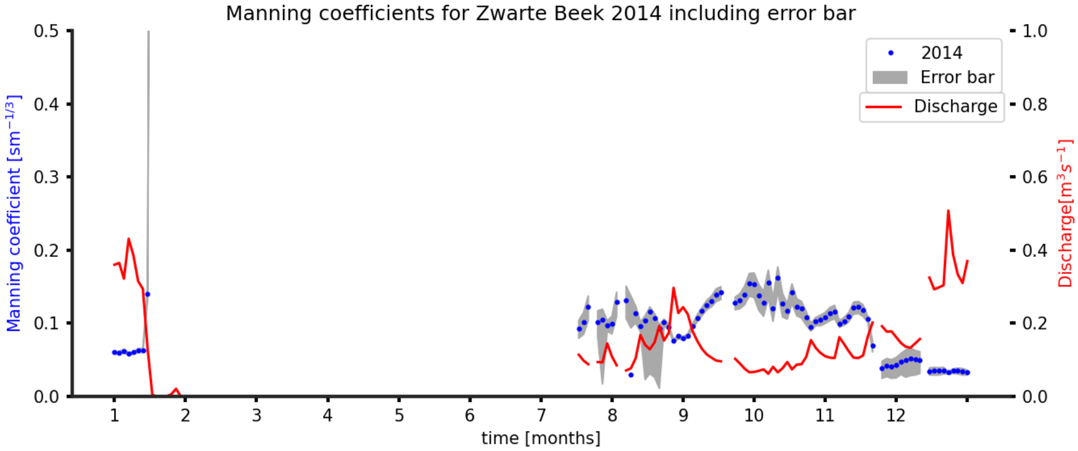


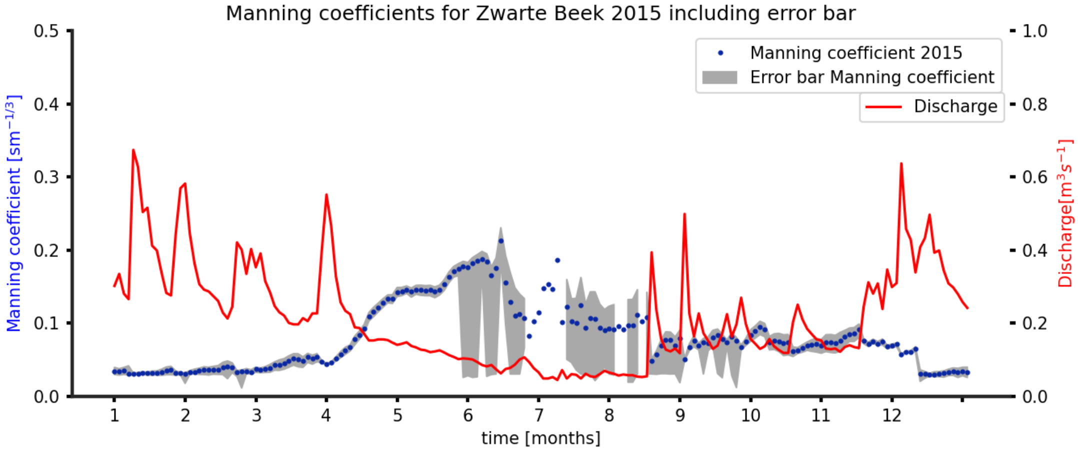
Zwarte Beek 2013



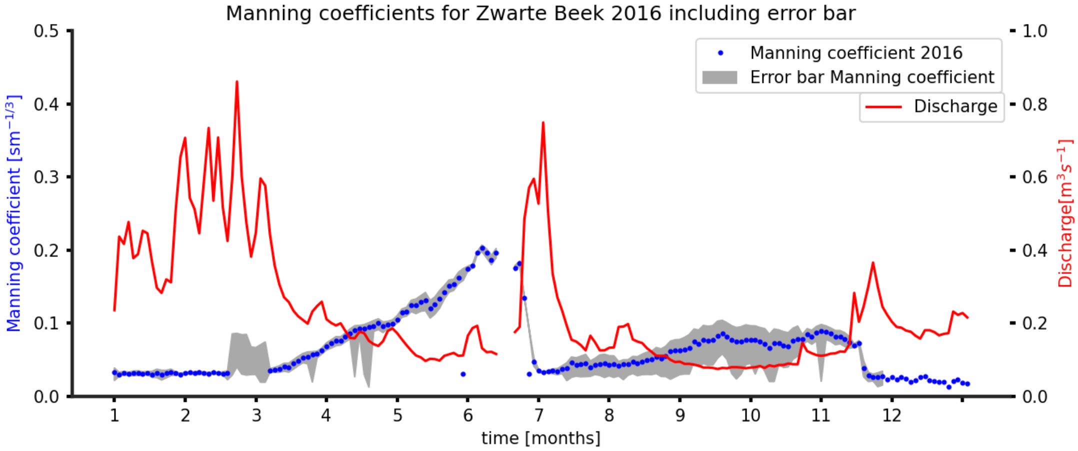
Zwarte Beek 2014



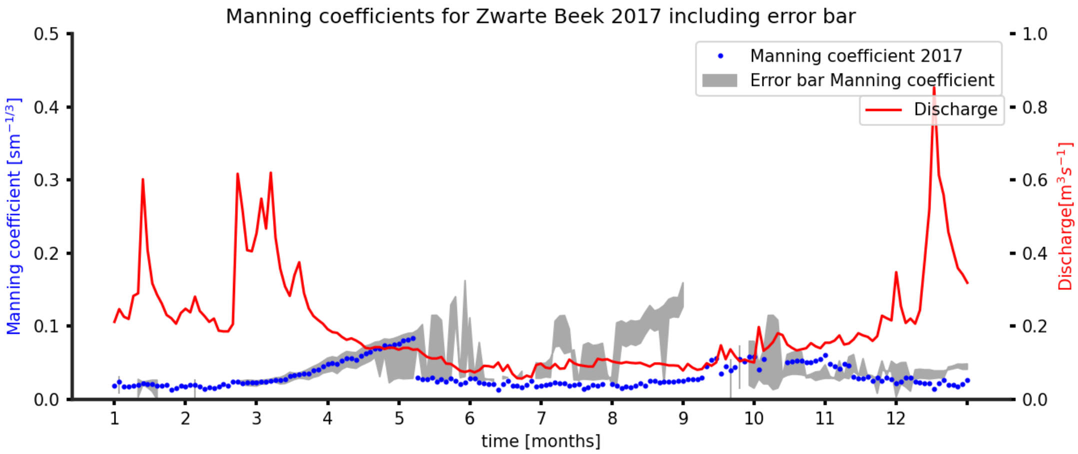
Zwarte Beek 2015



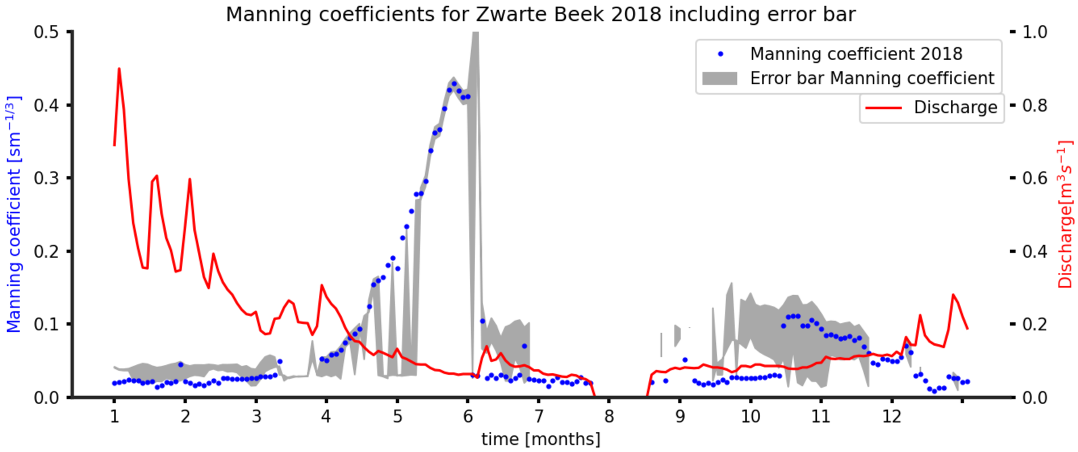
Zwarte Beek 2016



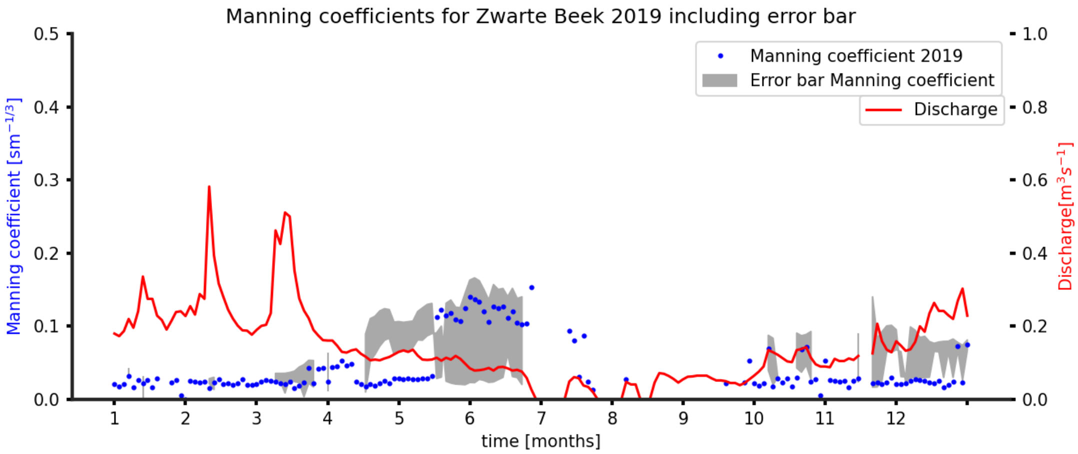
Zwarte Beek 2017



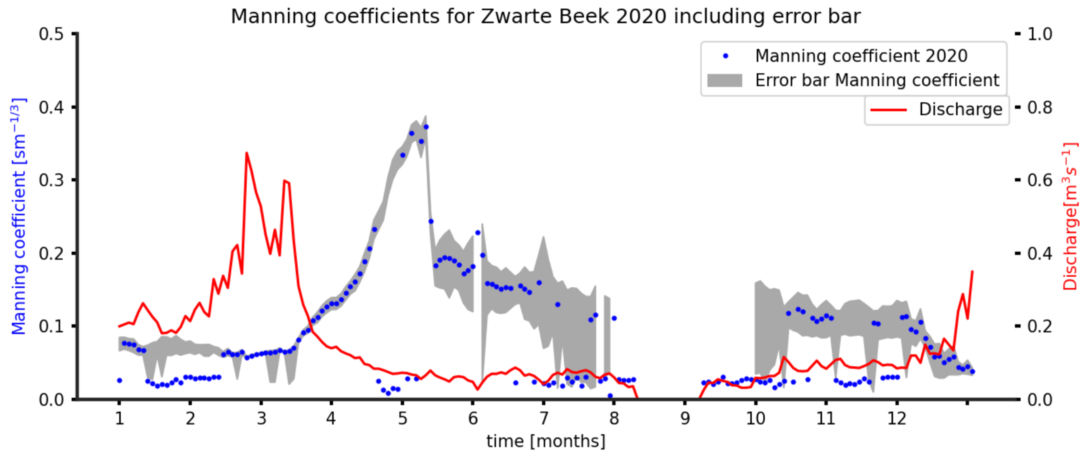
Zwarte Beek 2018



Zwarte Beek 2019

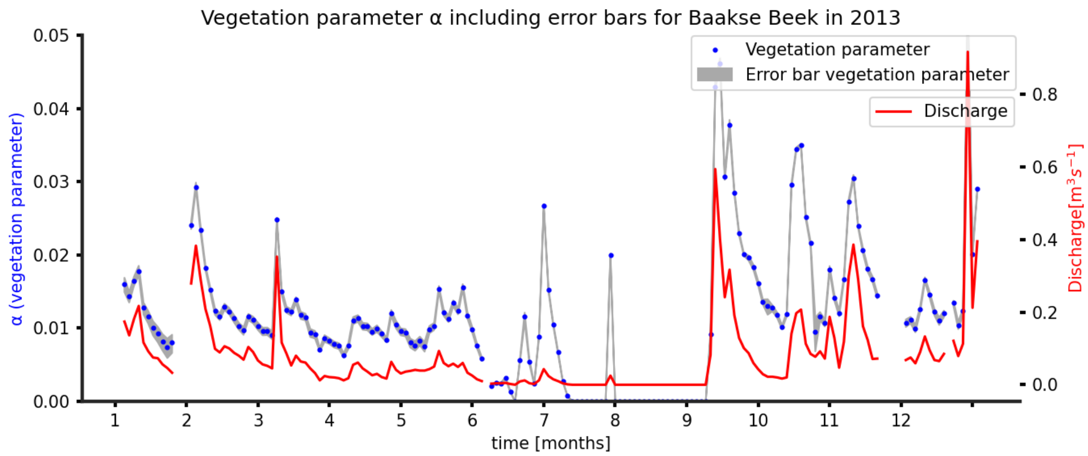


Zwarte Beek 2020

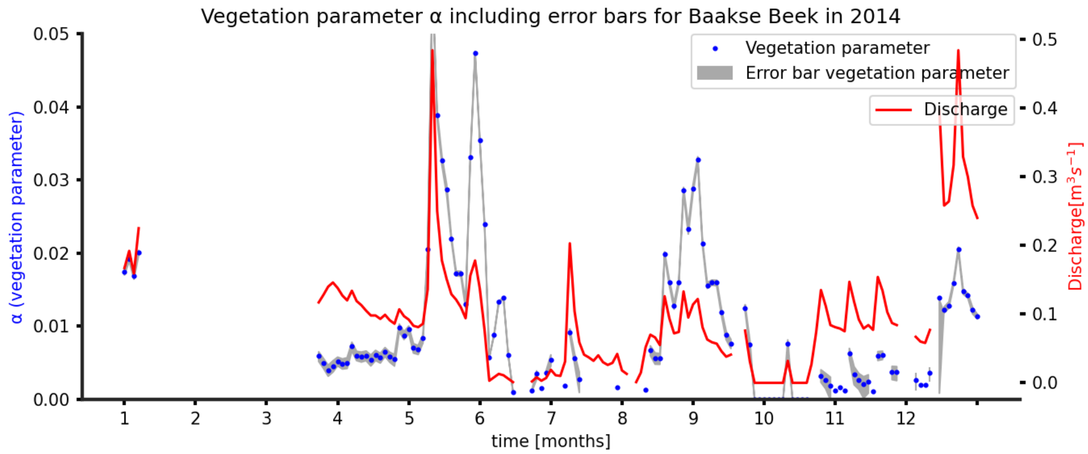


12. Appendix E – Error bars vegetation parameter

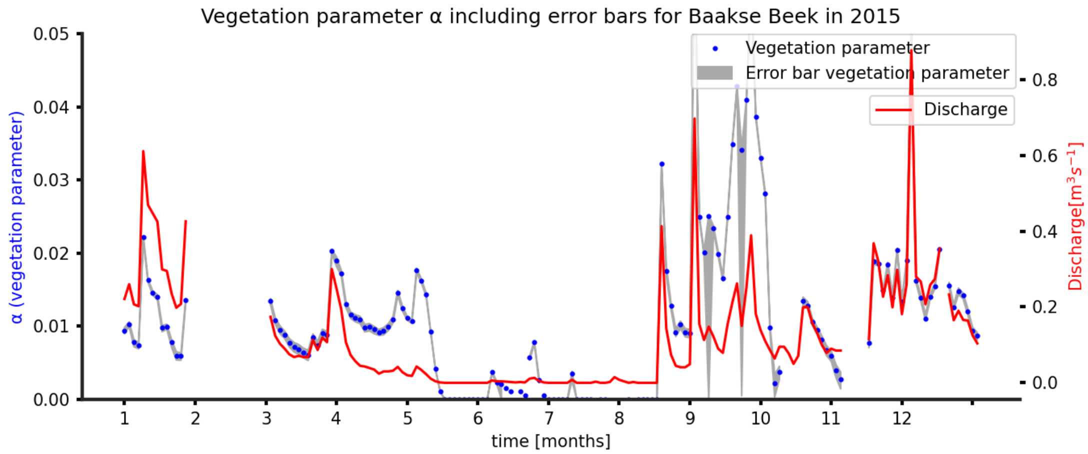
Baakse Beek 2013



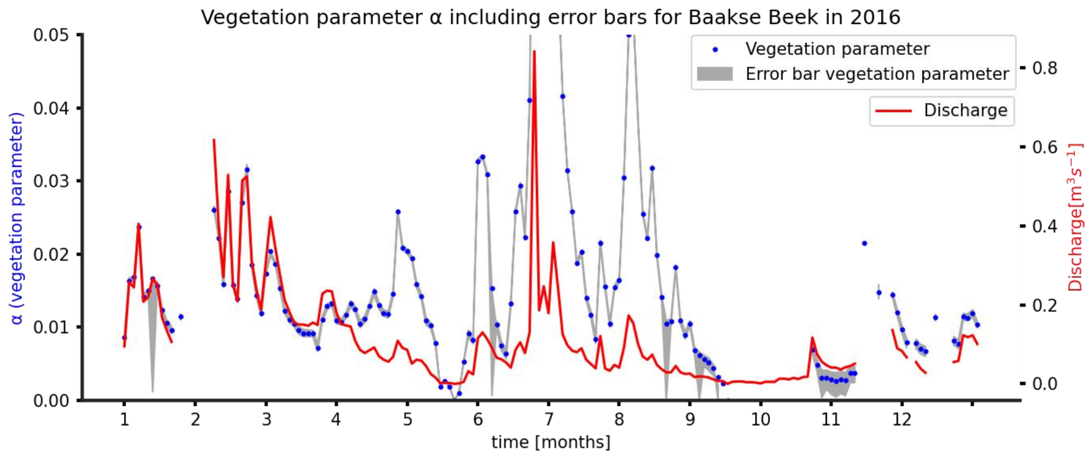
Baakse Beek 2014



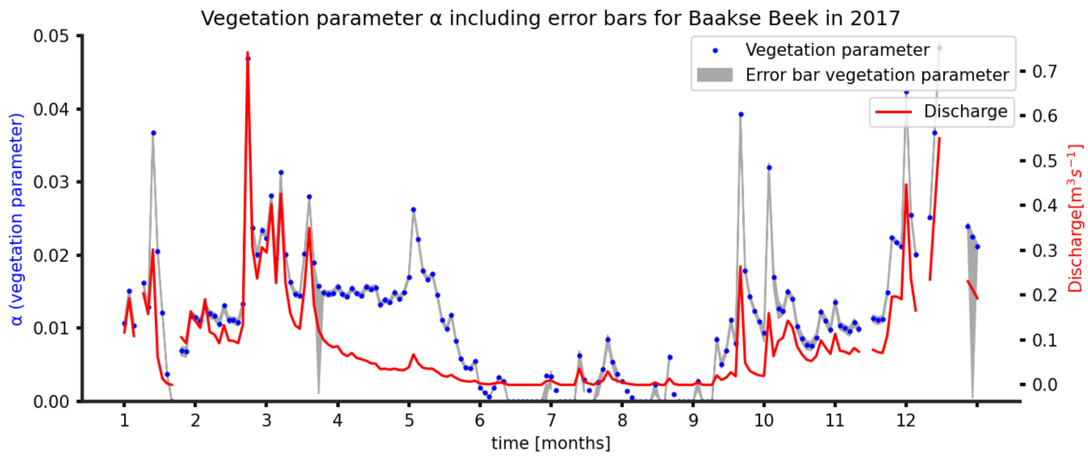
Baakse Beek 2015



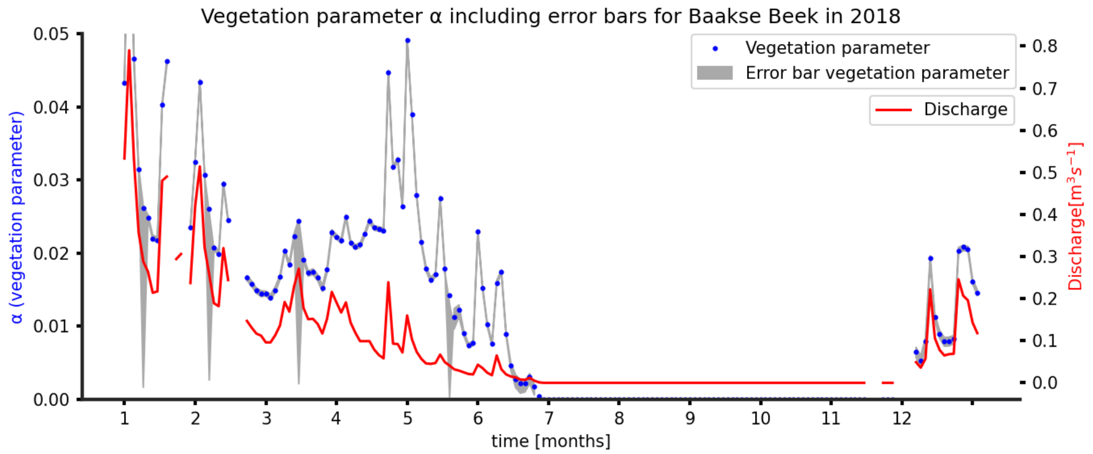
Baakse Beek 2016



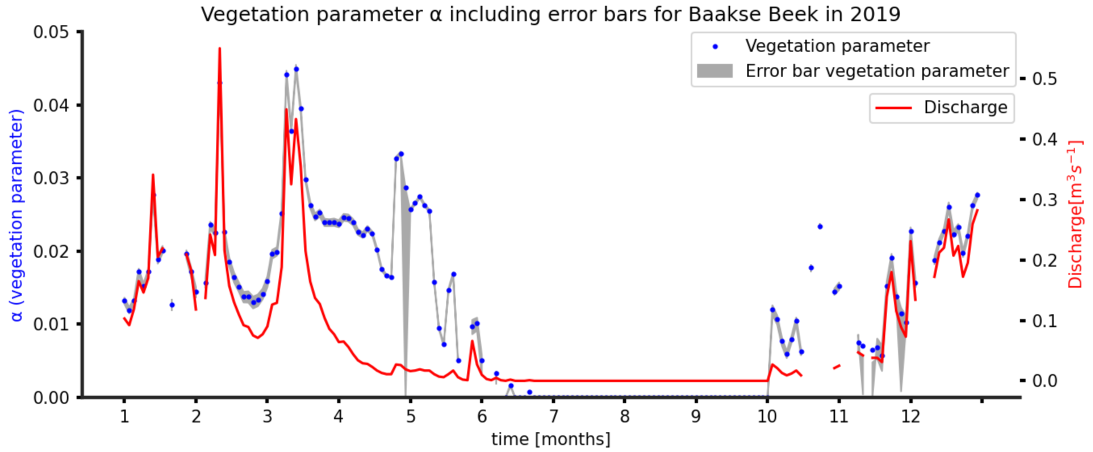
Baakse Beek 2017



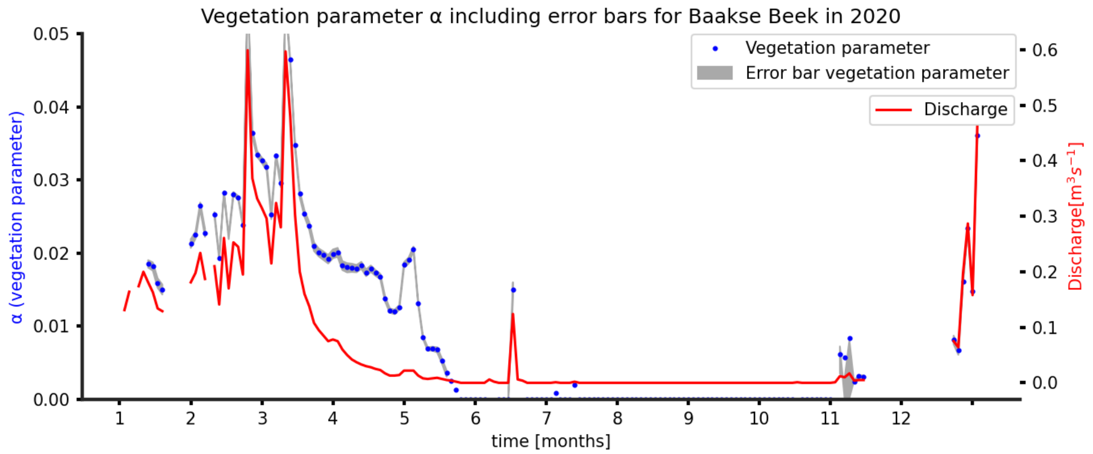
Baakse Beek 2018



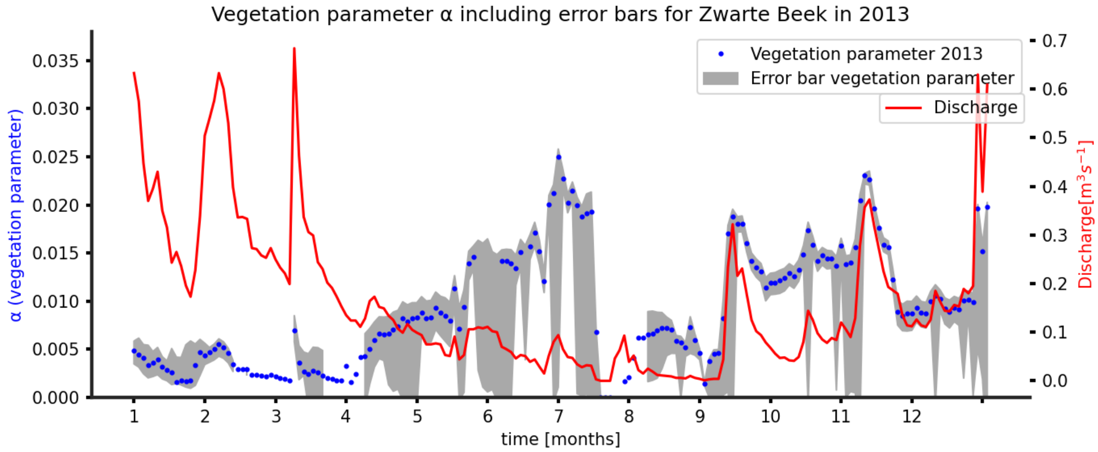
Baakse Beek 2019



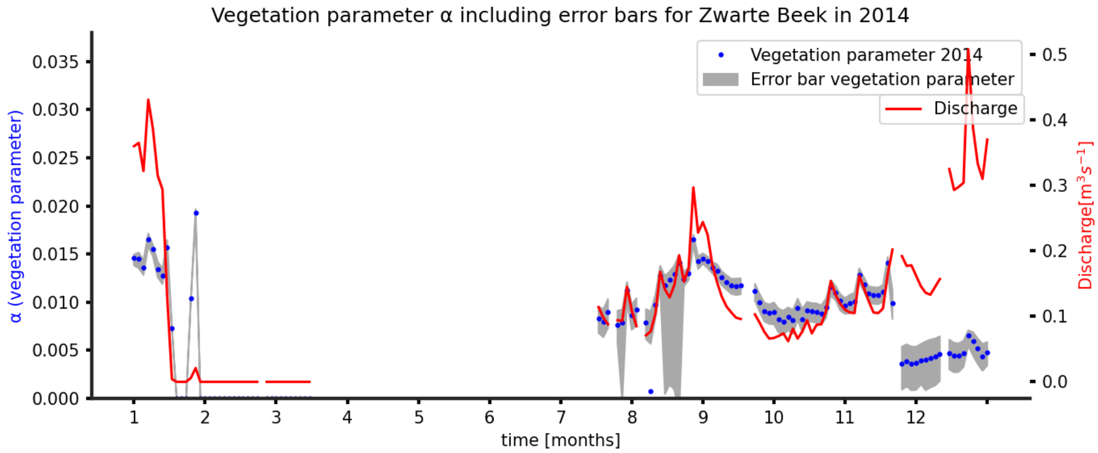
Baakse Beek 2020



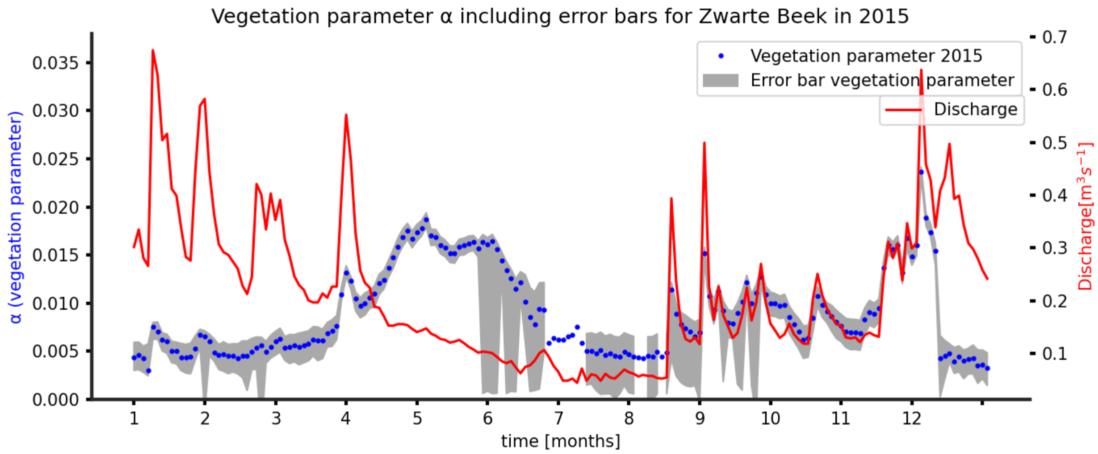
Zwarte Beek 2013



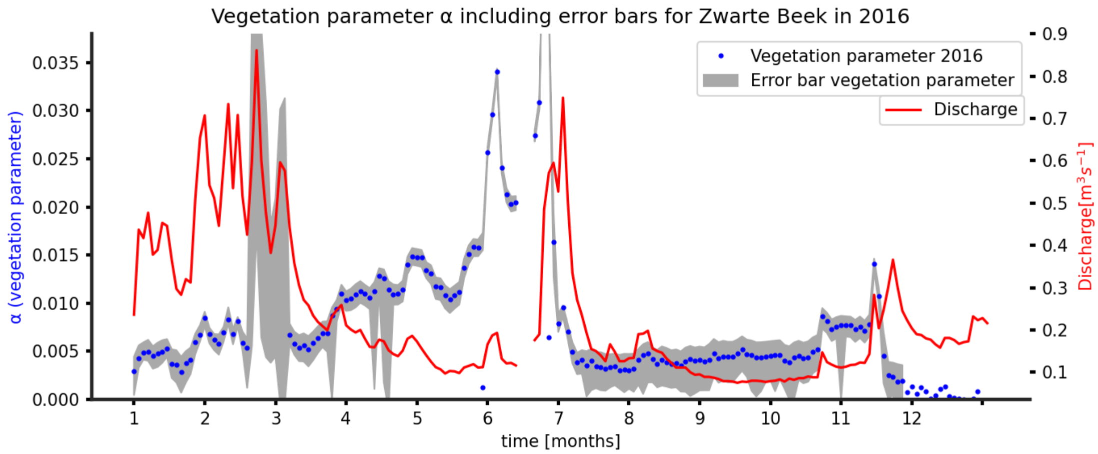
Zwarte Beek 2014



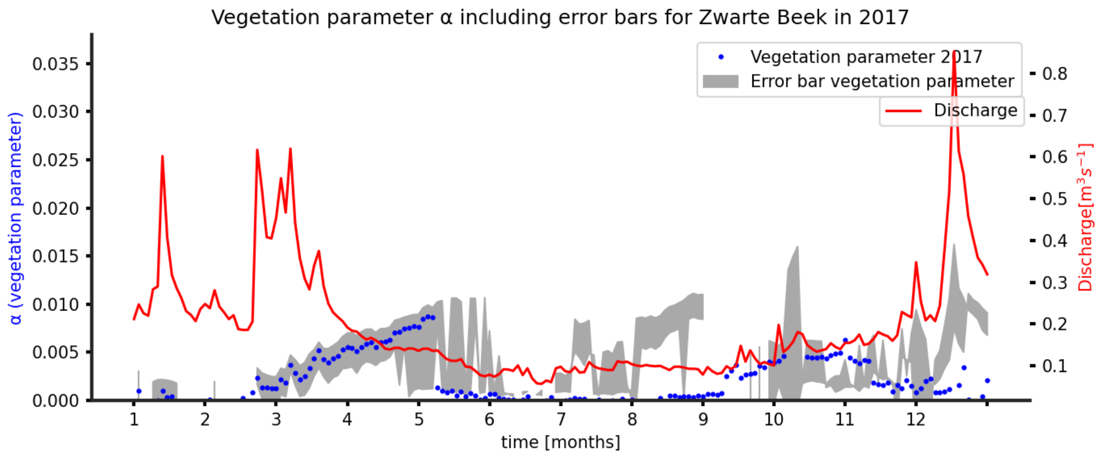
Zwarte Beek 2015



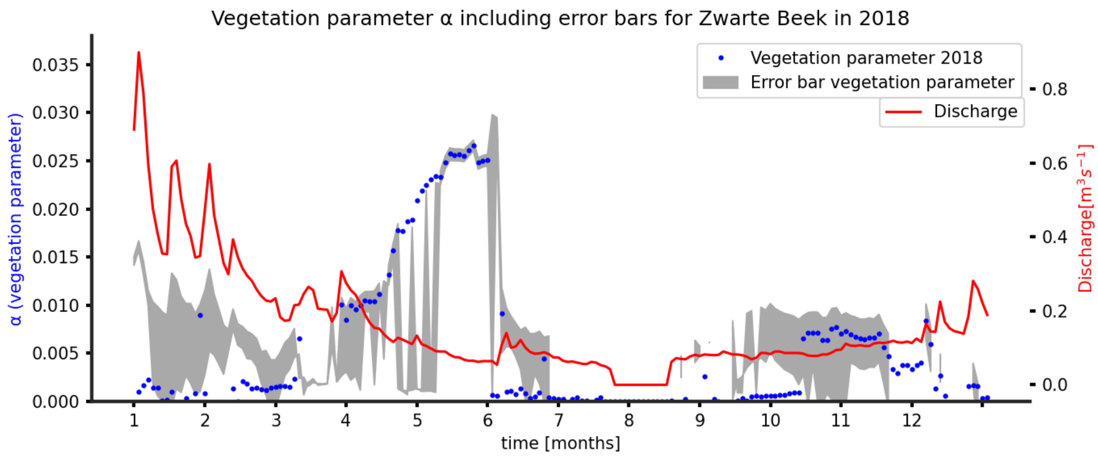
Zwarte Beek 2016



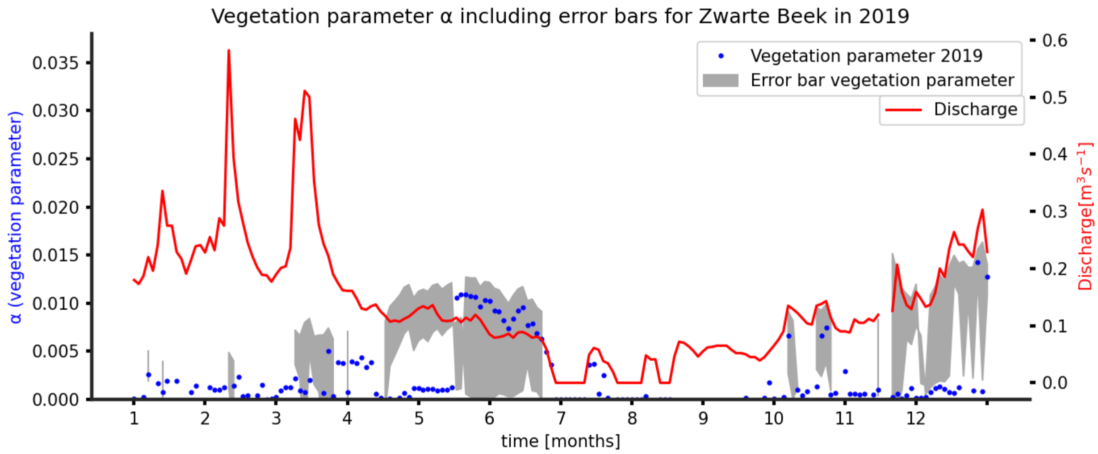
Zwarte Beek 2017



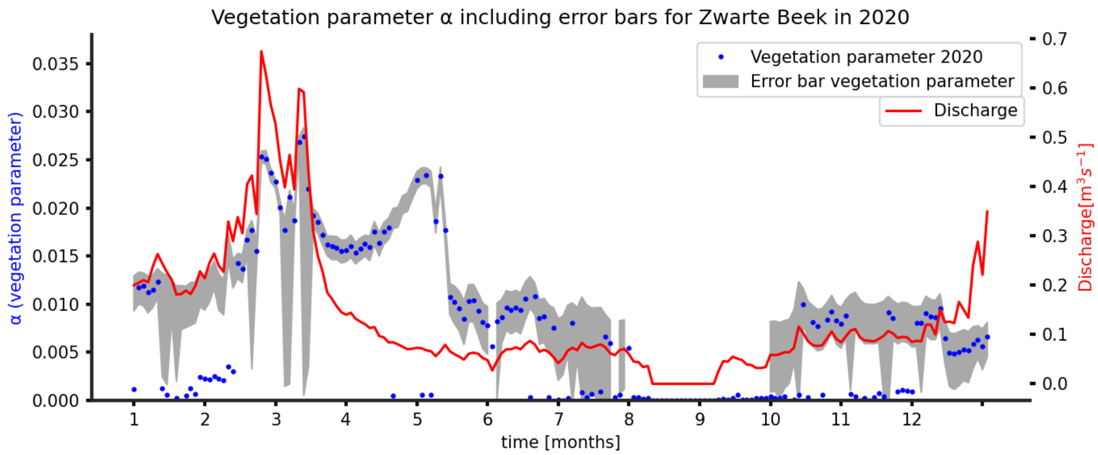
Zwarte Beek 2018



Zwarte Beek 2019

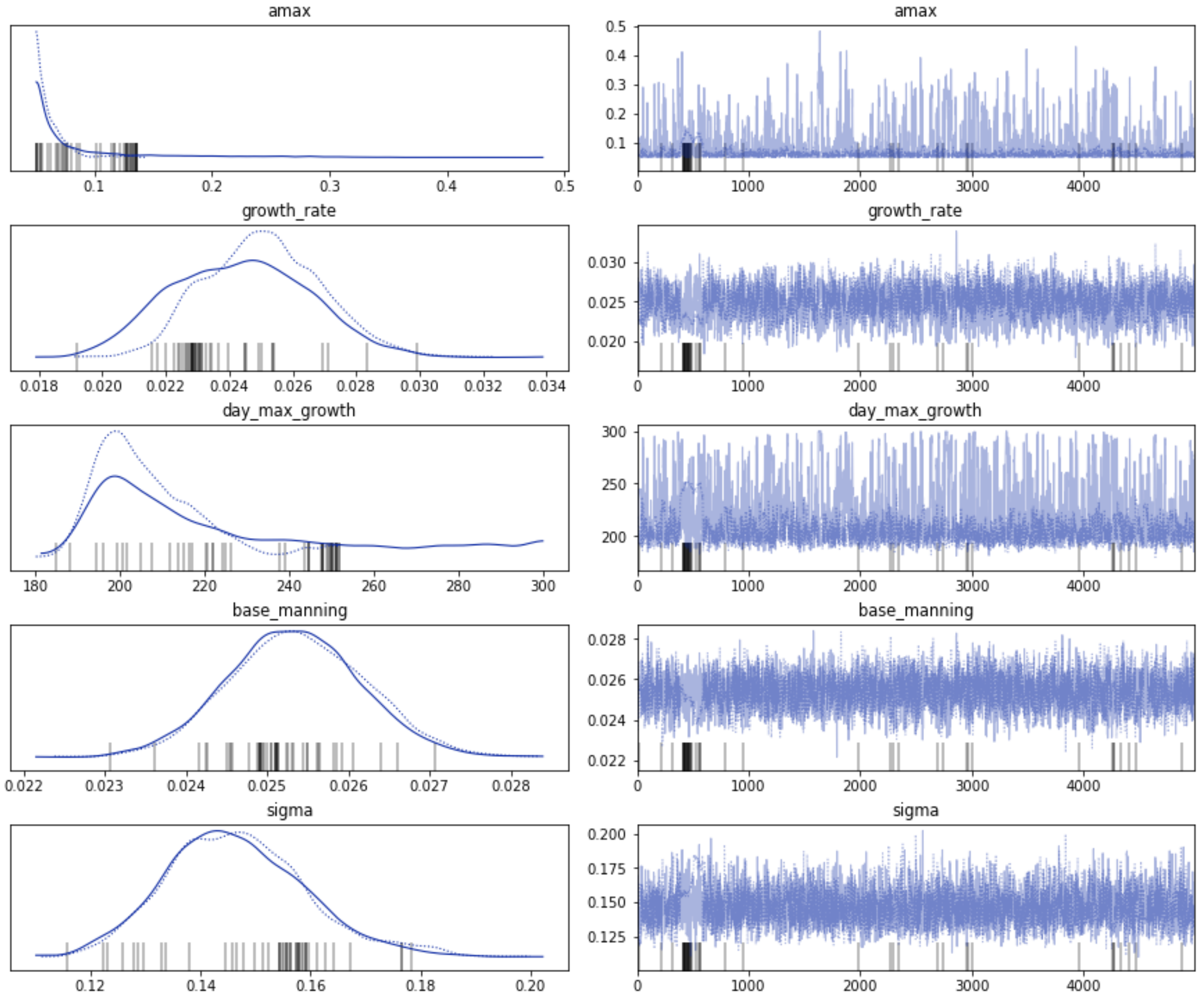


Zwarte Beek 2020

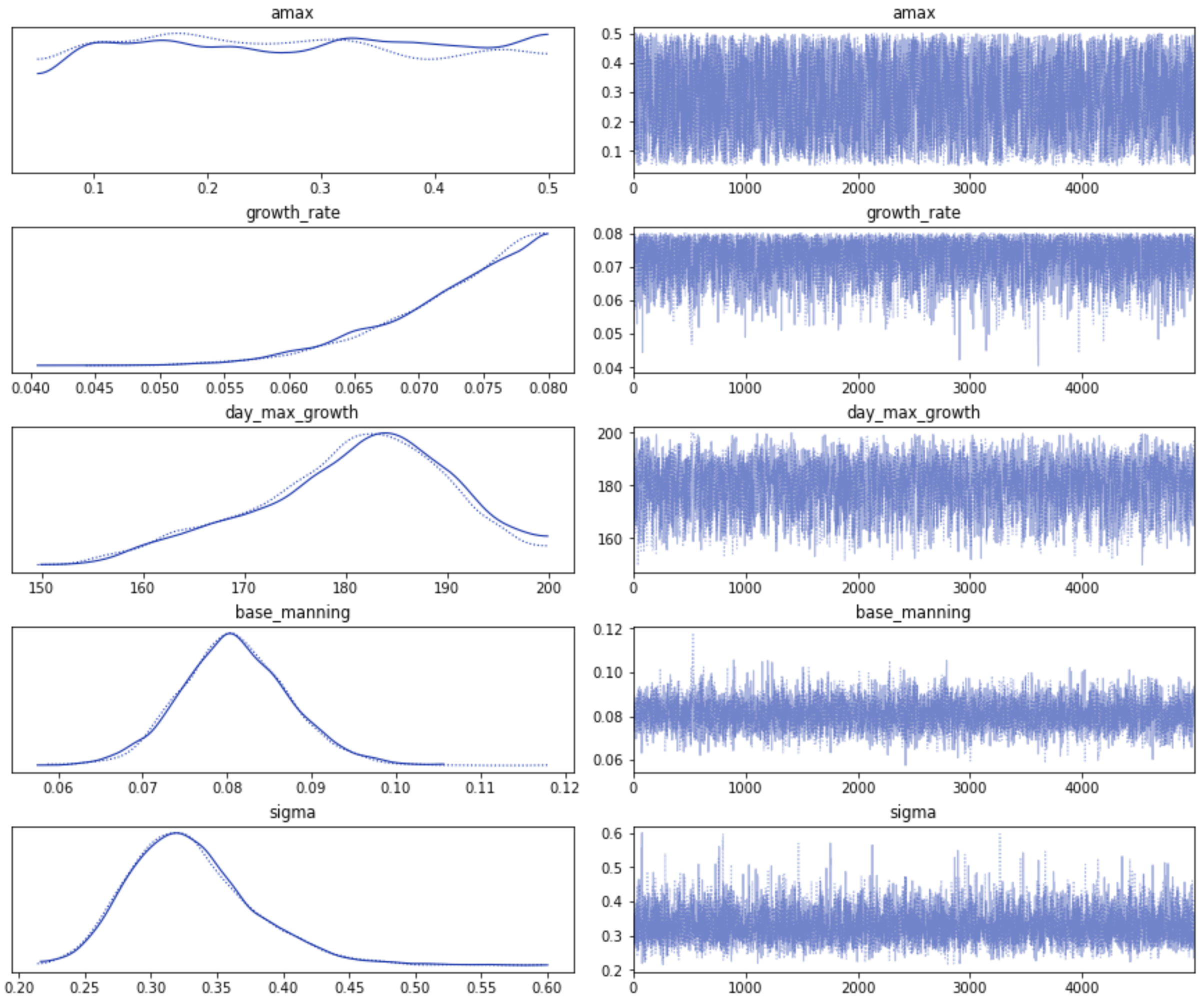


13. Appendix F – Markov Chain Monte Carlo calibration

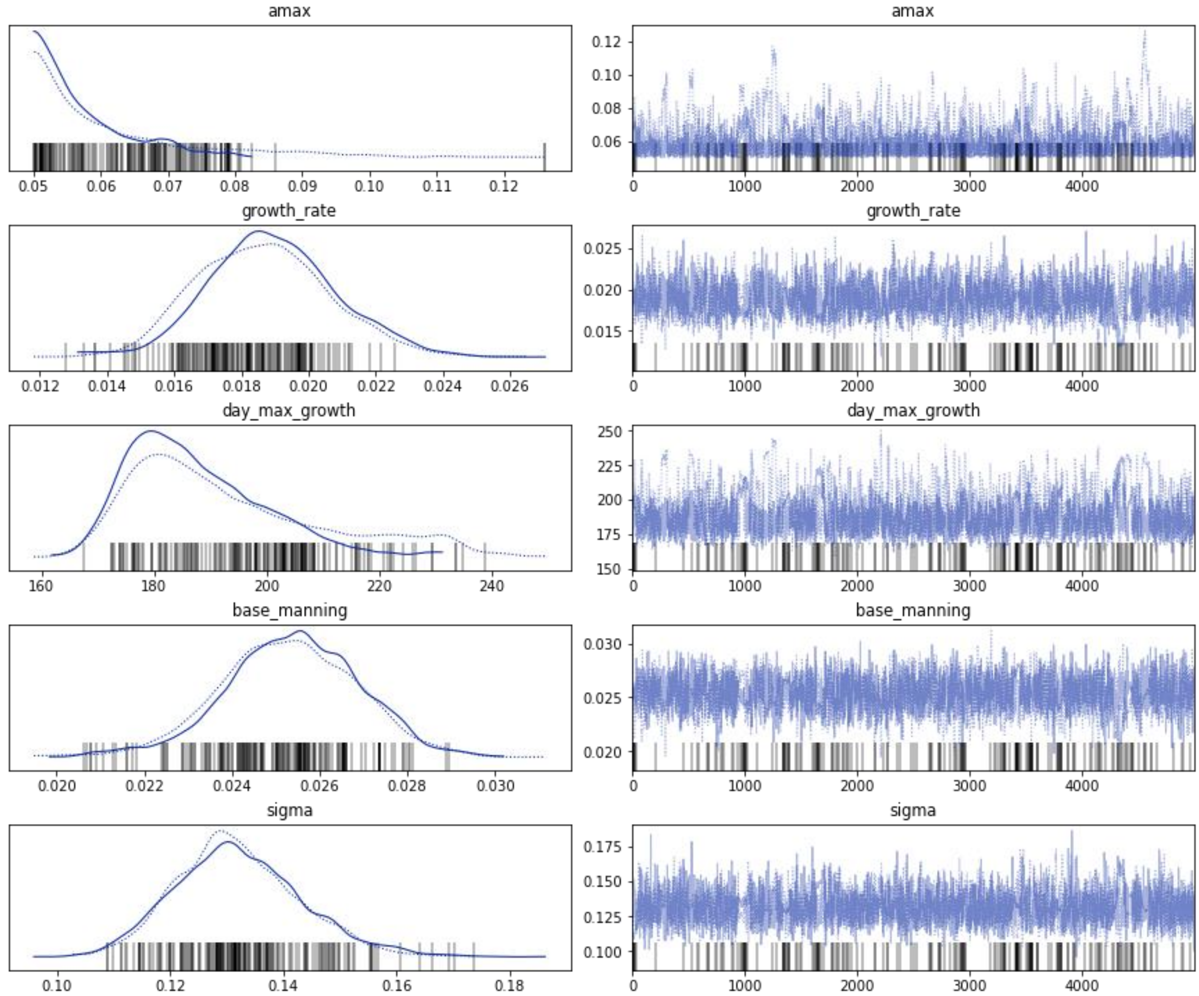
Baakse Beek 2013



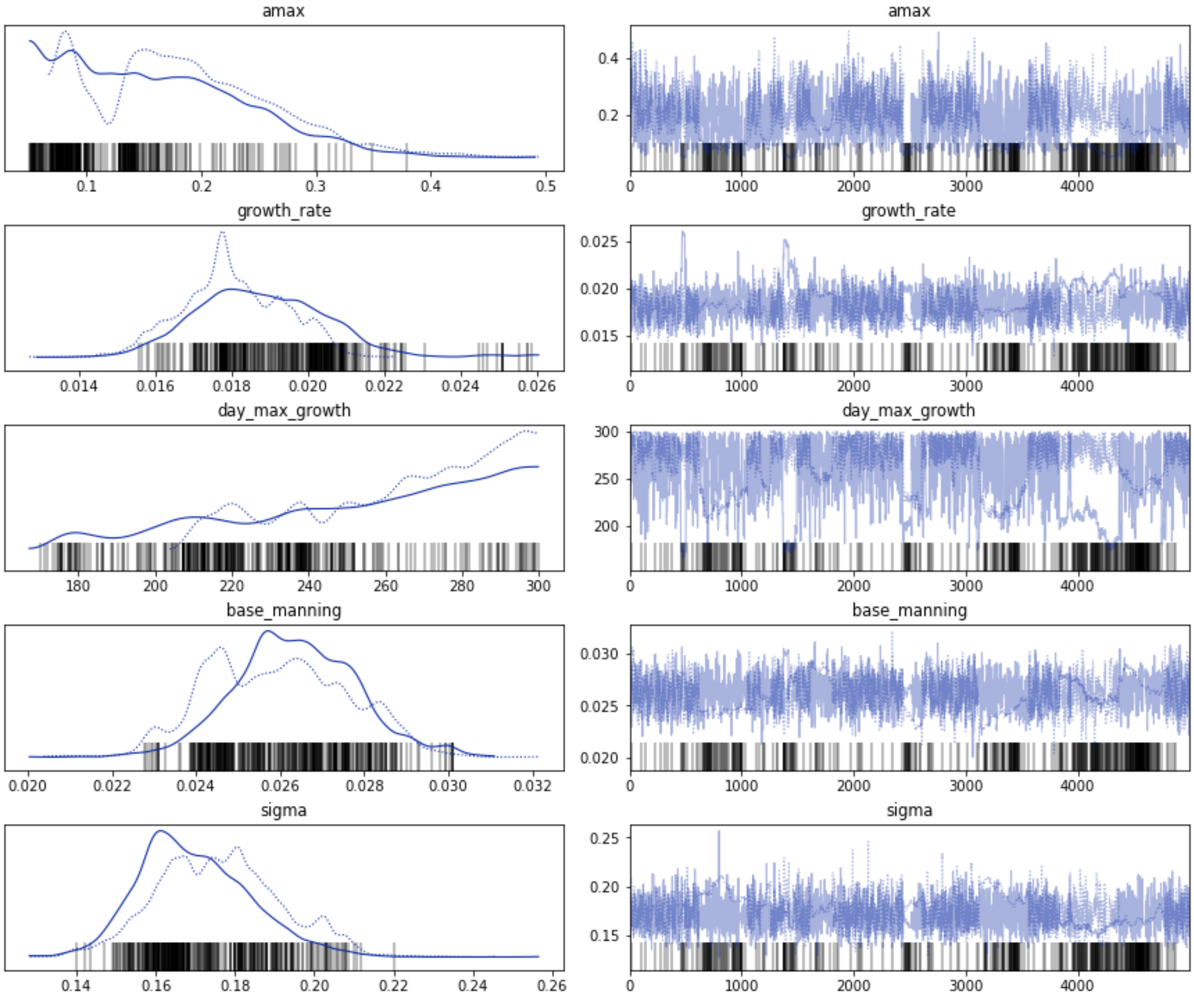
Baakse Beek 2014



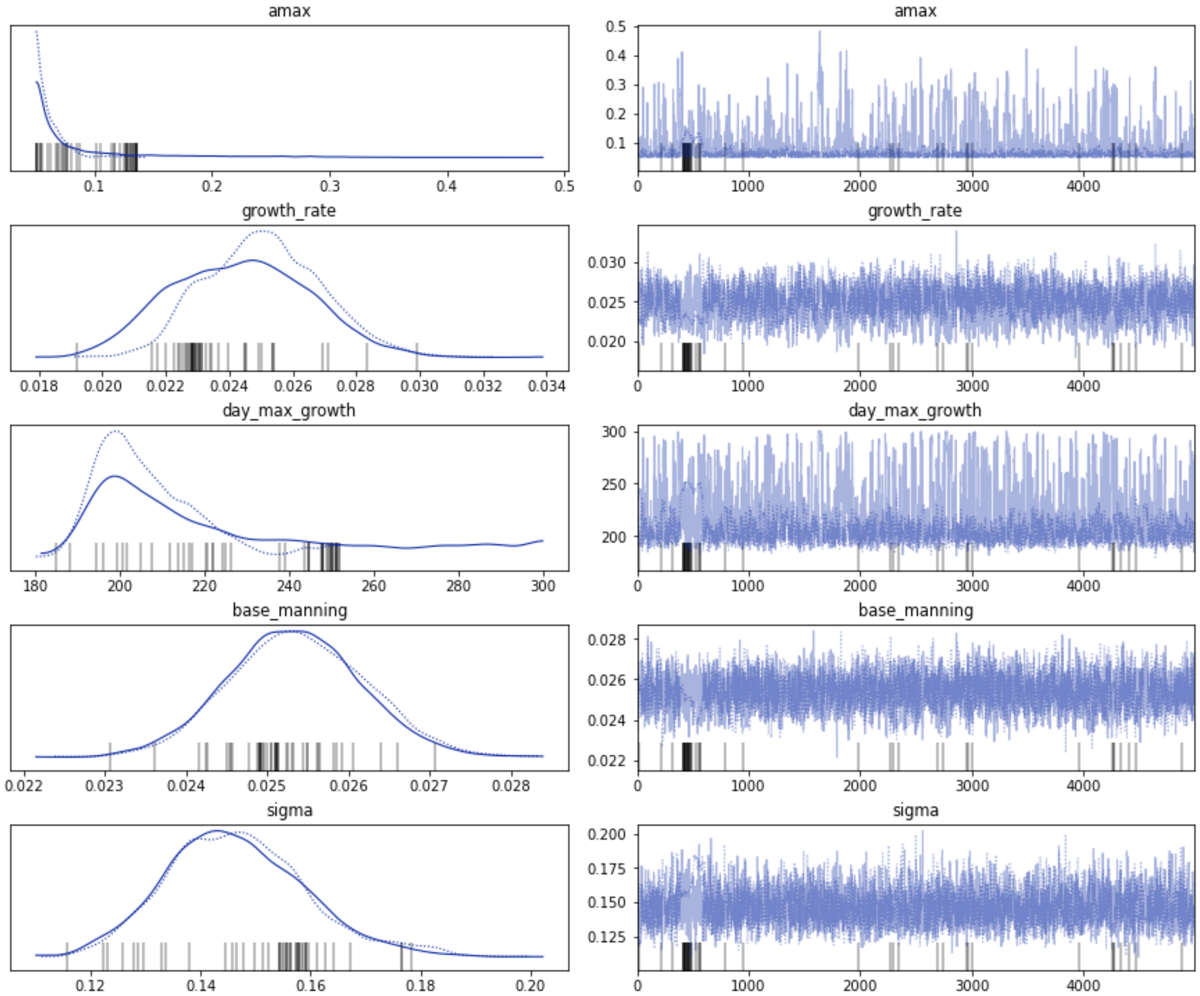
Baakse Beek 2015



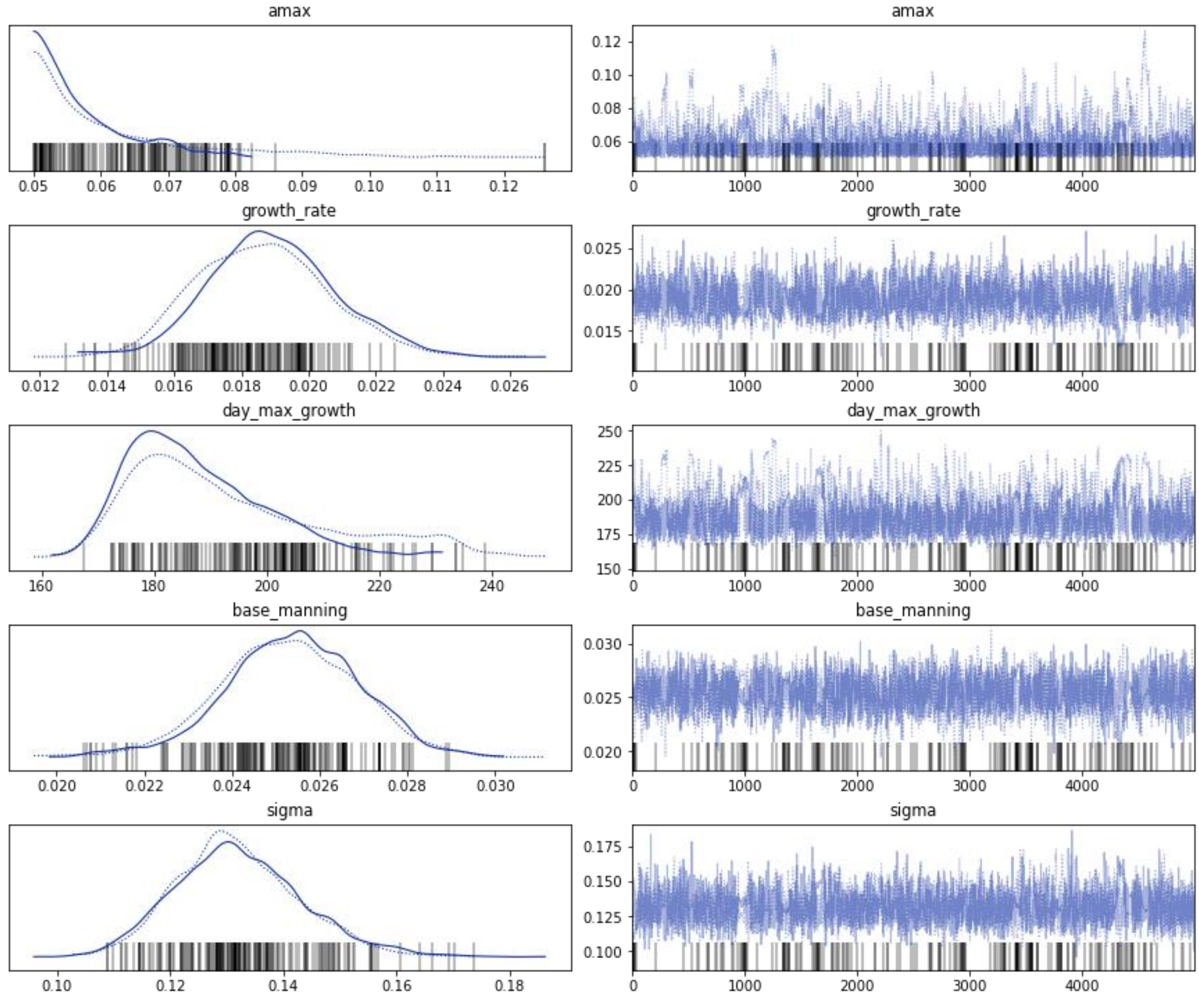
Baakse Beek 2016



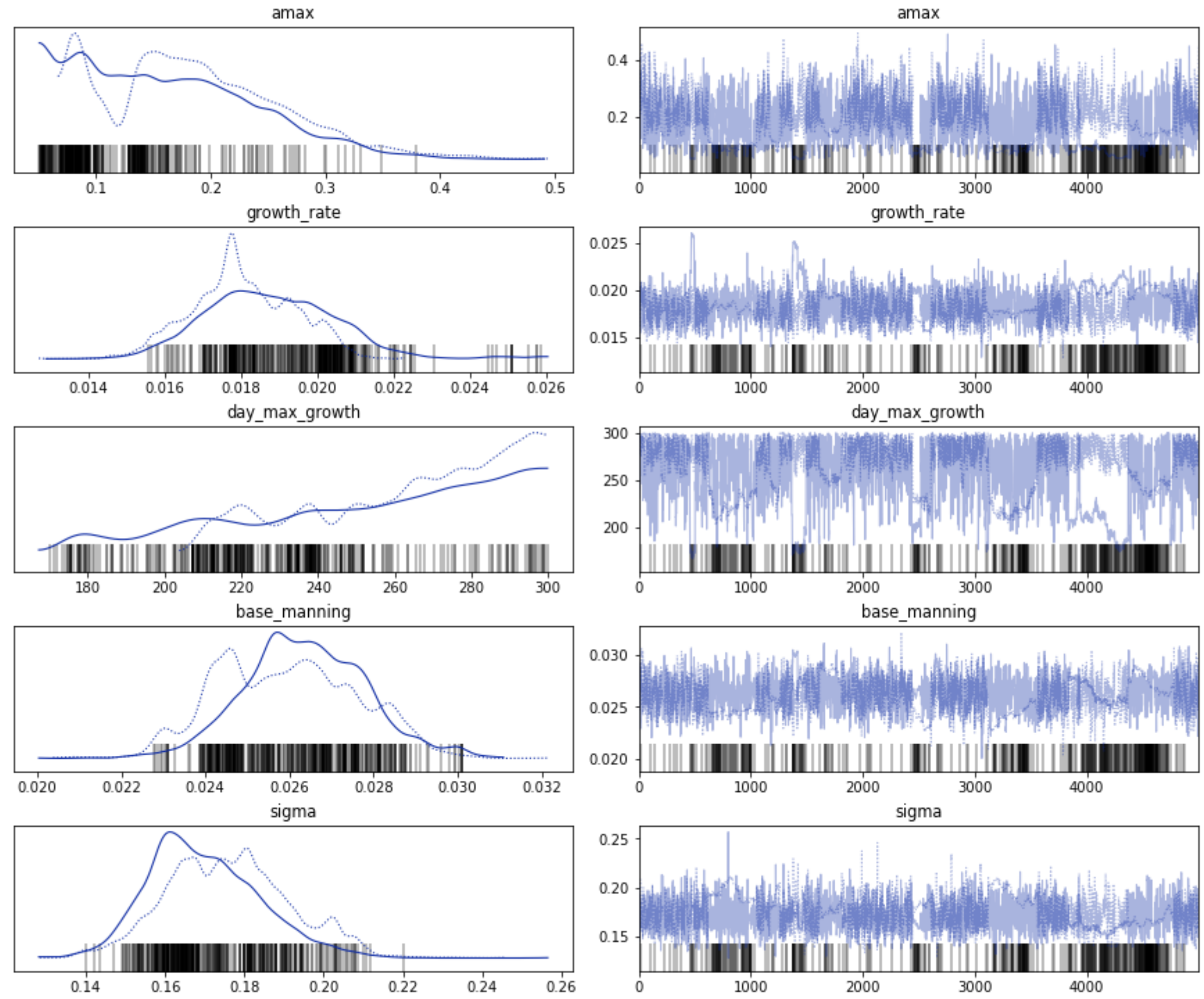
Zwarte Beek 2013



Zwarte Beek 2015



Zwarte Beek 2016



14. Appendix G – Optimalisation script python

```
# %load 00_run_optimisation.py
import re, os
import json
import threading
import subprocess
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
from datetime import datetime, timedelta
from scipy.optimize import minimize
from netCDF4 import Dataset
from pathlib import Path
from multiprocessing import Process, Queue

# ==========================================================================
# Functions
# ==========================================================================

# path to DIMR runner (change to own DIMR runner)
DIMR_exec = r"C:\Program Files (x86)\Deltares\SOBEK
(3.7.21.50810)\plugins\DeltaShell.Dimr\kernels\x64\dimr\scripts\run_dimr.bat"
# regex pattern to recognize parameters in files
# use following conventions:
#   01: upstream discharge (BC)
#   02: downstream water level (BC)
#   03: upstream waterlevel (observation)
#   04: manning coefficient/ roughness (degree of freedom)

pattern = re.compile(r'@\d+')

date_handler = lambda obj: (
   obj.isoformat()
   if isinstance(obj, (datetime.datetime, datetime.date))
   else None
)


def callback(future):
   if future.exception() is not None:
      info ("Exception: {}".format(future.exception()))
   else:
      info ("Process returned: {}".format(future.results()))


def ReplaceParametersInFile(template, destination, values):
   """
   Load bc file from template, change bc's with values
   """
   with open (template, 'r') as FREAD, \
       open (destination, 'w') as FWRITE:
```

```
    for line in FREAD:
      for match in re.findall(pattern, line):
        parameterid = match.split('@')[1]
        line = re.sub('@{}'.format(parameterid),
                '{:.5f}'.format(values[parameterid]),
                line)
      FWRITE.write(line)


def dflow1dOutput(case):
  with Dataset(f'{case}/dflow1d/output/gridpoints.nc', 'r') as f:
    x = f.variables['chainage'][:]
    # last timestep, return waterlevel along river
    sim = f.variables['water_level'][:][-1]
  return x, sim

def RunDFlow1D(param, case, obs, values, xmlfile):
  # Roughness coefficient
  values['04'] = np.abs(param[0])

  ReplaceParametersInFile('{}/template/BoundaryConditions.bc'.format(case),
              '{}/dflow1d/BoundaryConditions.bc'.format(case),
              values)
  ReplaceParametersInFile('{}/template/roughness-Main.ini'.format(case),
              '{}/dflow1d/roughness-Main.ini'.format(case),
              values)

  print ('\n\nNEW ITERATION\n================')
  print ('CURRENT DISCHARGE: {:.2f} m3/s'.format(values['01']))
  print ('CURRENT SLOPE: {:.2f} cm'.format((obs - values['02']) * 100 ))
  print ('CURRENT ROUGHNESS: {:.3f} ({:.0f})'.format(param[0], 1/param[0]))

  #proc = subprocess.Popen('run_opgeknipt.bat', cwd=os.getcwd(), stdout=subprocess.DEVNULL)
  proc = subprocess.Popen(f'{DIMR_exec} {xmlfile}',
              cwd=os.path.join(os.getcwd(), case),
              stdout=subprocess.DEVNULL)
  proc.wait()
  x, sim = dflow1dOutput(case)
  error = np.abs(obs - sim[0])

  print ('CURRENT ERROR: {:.2f} cm'.format(error*100))
  return error


def compute_friction(case, data_files:dict, tstep:int=2, tstart:int=5147, tstop:int=6080,
dimrxml="dflow1d.xml"):
  """
  Args:

    tstep: steps in number of rows in datafile for computing manning.
       If 1, all rows will be used. If 2, every second row will
       be skipped
```

```
    tstart: at which row to start computing roughness
    tstop: at which row to stop computing roughness
"""
time = list()
friction_values = list()
error_values = list()
discharge = list()
values = dict()
upstream_wl = list()
downstream_wl = list()

counter = 0

dateparser = lambda x: datetime.strptime(x, '%d/%m/%Y')
dischargedata = pd.read_csv(data_files.get('discharge'), index_col=0,
                            parse_dates=True,
                            skipinitialspace=True,
                            date_parser=dateparser)
waterlevel = pd.read_csv(data_files.get('waterlevel'), index_col=0,
                            parse_dates=True,
                            skipinitialspace=True,
                            date_parser=dateparser)
datamap = pd.read_csv(data_files.get('bc_map'), index_col=0)

BC_Q = dischargedata[datamap.T[case]['1']]
BC_H = waterlevel[datamap.T[case]['2']]
OBS = waterlevel[datamap.T[case]['3']]

for i in np.arange(tstart, tstop, tstep):
    curtime = dischargedata.index[i].isoformat()
    print (curtime)
    time.append(curtime)

    # Set initial friction
    if (counter > 0) and (friction_values[counter - 1] > 0.001):
        initial_friction = friction_values[counter - 1]
    else:
        initial_friction = 0.03


    values['01'] = BC_Q.iloc[i]
    values['02'] = float(BC_H.iloc[i])
    observation = OBS.iloc[i]
    discharge.append(values['01'])

    if (observation - values['02']) <= 0:
        print ("negative measured slope")
        friction_values.append(np.nan)
        error_values.append('negslope')
    else:
        if ~np.isnan(values['01']) & ~np.isnan(values['02']):
            counter += 1
```

```python
            res = minimize(RunDFlow1D, initial_friction,
                           args=(case, observation, values, dimrxml),
                           method='nelder-mead',
                           options={'fatol':0.1,    # error
                                    'xatol':0.0015}) # manning

            print ('\n++++++++ STEP ENDED ++++++++\n\n')

            upstream_wl.append(observation)
            downstream_wl.append(values['02'])
            friction_values.append(np.abs(res.x[0]))
            error_values.append(res['final_simplex'][1][0])
        else:
            upstream_wl.append(observation)
            downstream_wl.append(values['02'])
            friction_values.append(np.nan)
            error_values.append('naninput')

    OUTPUT = {'time': time, 'discharge': discharge,
              'up': upstream_wl, 'down': downstream_wl,
              'computed_friction': friction_values,
              'residual': error_values}

    jsonout = Path(f'output')
    jsonout.mkdir(parents=True, exist_ok=True)
    with jsonout.joinpath(f'{case}_outputBBERBIJ.json').open('w') as f:
        json.dump(OUTPUT, f, indent=4)
    return OUTPUT

# ============================================================================
# Main script
# adapt locations of csv files
# ============================================================================

if __name__ == "__main__":
    case = 'BB'                 #change name of chase
    data_files = {'discharge': 'Discharge.csv',
                  'waterlevel': 'Waterlevel.csv',
                  'bc_map': 'map_boundary_data.csv'}
    output = compute_friction(case, data_files=data_files, tstart=0, tstop=3046, dimrxml='case.xml')
    with open(f'output/{case}_output.json', 'w') as f:
        json.dump(output, f, indent=4)
```