Validation of neural networks for forecasting water levels at Lobith

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Enabling Delta Life

1 Preface

Right now, you are reading my bachelor thesis. As the final part of the regular programme of the bachelor Civil Engineering, I did an internship at Deltares. After finishing this I will only have to finish my minors to complete the bachelor.

The title of the thesis is: Validation of neural networks for forecasting water levels at Lobith. So obviously the goal was to validate a neural network that forecasts water levels for Lobith. Within the unit Zoet Water Systemen (ZWS), I was able to do my research. The result can be seen in the remainder of this report.

I would like to thank everybody at Deltares for giving me the opportunity to do my bachelor thesis there. In particular, I want to thank Matthijs den Toom and Jaap Kwadijk. Matthijs was my supervisor at Deltares, so he was always nearby and helped a lot with using the required software. Jaap was my supervisor from the university, but also worked at Deltares and was always helpful. Both provided a lot of input and feedback. Without them this thesis would not have been possible.

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Contents

2 Introduction

Water level forecasts are of great importance in the Netherlands. Among other things they are used for all kind of decisions in water management. Decisions for instance about division of water over the different rivers or decisions about measures against high water. So obviously the forecasts should be of high quality.

Making and publishing these forecasts is one of the tasks of Rijkswaterstaat (RWS) [1]. They also make the action plans in case the water levels get too low or too high. The quality of these forecasts is important because the decisions in case of too high or too low water are based on them. In the case of low water levels, the water must be divided and the ships using the rivers need to be informed about the maximum depth they can have. In the case of high-water decisions about the usage of retention areas or evacuation need to be made [2].

To make these forecasts Rijkswaterstaat uses 'RijksWaterstaat samenhangende Operationele Systemen' (RWsOS). This is a program containing multiple models used for forecasting the water levels in the Netherlands. A part of this program focusses on the water levels in the Dutch rivers. One of the rivers for which forecasts are done is the Rhine. To make the forecasts for the Rhine several models are used [3].

The forecasts are split up in two parts. For the forecasts of the first two days LobithW is used and for the forecasts for three and four days ahead HBV and SOBEK are used [4]. LobithW is a multilinear regression model, which means it makes forecasts based on the water level at several locations upstream [5]. The relation between the forecast and the water levels is based on statistical relations between water levels at several locations and the forecasts. For three and four days ahead SOBEK and HBV is used. SOBEK is a modelling suite consisting of different modules. These modules simulate flows and water related processes [6]. The HBV model is a rainfall-runoff model, which simulates hydrological processes at catchment scale [7].

LobithW only uses linear relations between water levels upstream in the Rhine and precipitation in catchments of the Rhine to forecast the water level at Lobith for one and two days ahead. However, with the rise of Artificial Intelligence (AI), Rijkswaterstaat thought better forecasts could be made using the same data. To investigate this a MSc student studying AI, Rick Dijkstra, created the model LobithAI for his thesis [8].

In this report, a neural network that can be used for forecasting water levels at Lobith, called LobithAI will be validated. This is done by doing a sensitivity analysis and an extreme value test. The model and the test will be explained further in the following parts.

2.1 LobithAI

For his MSc-thesis Rick Dijkstra developed LobithAI. This model is developed to investigate the possibilities of Artificial Intelligence (AI) for flow forecasting [8]. It is made as comparison to LobithW; therefore, the models use the same inputs. LobithW is a multiple linear regression model used to forecast water levels at Lobith for one and two days ahead. For more information on LobithW, see the interview report [9].

The goal of his thesis was to investigate the possibilities of AI in water level forecasting, rather than developing a model ready to replace LobithW. LobithAI is a neural network which uses the water levels in several locations upstream of Lobith and Lobith of the day of the forecasts up until four days of recorded data and the forecasted precipitation in several sub catchments up until two days ahead.

LobithAI is a neural network. Neural networks consist of multiple neurons. These neurons receive input(s) in the form of numbers. These inputs are processed by an activation function and thus result in an output. This output is then forwarded to neurons in the next layer. LobithAI is a Deep Neural Network, which means several layers are placed consecutively. This model consists of 8 layers. [8]

LobithW and LobithAI both use water levels and precipitation data of several stations as input. In the calibration of LobithW some stations turned out to have no statistical importance and are thus ignored. These locations are still used in LobithAI along with the other locations LobithW uses. Figure 1 shows all the stations which are used as input for LobithAI. Trier can be seen twice in the figure; this is because both a water level station and a precipitation station are used there.

A difference in input between LobithAI and LobithW is the time used for the stations. LobithW only uses measurements of certain days. For instance, the water level at Andernach one day before the forecast is used. The exact input can be seen in the interview report[9]. For LobithAI the water levels up until four days before the forecast are used for all the stations. For the precipitation data the same difference applies, but instead of four days back, the forecasts for up until 2 days ahead is used. The output of LobithAI is the forecasted water level for 0, 1 and 2 days ahead.

To keep the comparison between LobithW and LobithAI as fair as possible the data used to train LobithAI was like the data used to calibrate LobithW. The data used for the calibration of LobithW was measured between 1982 and 2011[5]. This data was not available when training LobithAI. The data used for training was measured between 2010 and 2018. [8] In the report about the development of LobithAI some testing was done as well. LobithAI was compared to LobithW which showed it performed better for normal water levels[8].

Figure 1: Water level and precipitation stations used by LobithAI

2.2 Goal

The main research question for this thesis is:

How does the LobithAI model behave for flow conditions that are not contained in the training data?

This question will be answered by doing a sensitivity analysis and an extreme data test. Interviews have also been conducted get a better understanding of the model. Because the model is a neural network, it is also a black box. This means it is unclear how the model calculates the forecasts, the impact of the different stations on the forecasts is unclear. A sensitivity analysis can provide some more insight in the black box. Because the users of the forecasting models at Rijkswaterstaat correct the forecasts based on their understanding and experience of the model, it is import for them to have an idea of the functioning of the model.

LobithAI has already been compared to LobithW, but the water levels used in that comparison were not very extreme. For extreme water levels, the forecasts are very important because then choices about the measures against high water must be made. So, in the model is tested with extreme water levels to see if it still behaves as expected. Since no extreme enough measured data has been recorded, it can only be compared to other models. The other model is SOBEK in this case, which is physics based.

3 Interviews about AI in water level forecasting

The report about the interviews about AI in water level forecasting, which is also attached, has been done in Dutch so it can also be useful for Rijkswaterstaat. Still, a small summary about in English will be presented here.

The information for this report was obtained by interviewing Rick Dijkstra, and Eric Sprokkereef and Jasper Stam and by doing literature research. Rick Dijkstra developed LobithAI for his MSc thesis at Rijkswaterstaat. He was interviewed about the technical properties of the model. Eric Stam and Jasper Sprokkereef work at Rijkswaterstaat. Their daily job is to make forecasts for the water levels in Netherlands using RW-sOS, check these forecasts, alter them if necessary and publish the forecasts. They have also been interviewed about other models and their opinion about the use of AI in water level forecasting.

All the interviewees were enthusiastic about LobithAI in general. They think it has a lot more potential than the currently used multi-linear regression model LobithW. But because the quality of the LobithAI is not fully explored yet, the implementation of a model like this will likely still take some time. According to the interviewees the big advantages of AI in water level forecasting are [9]:

- A model based on AI can use all different kinds of input. So also other measurements like temperature or snow height can be used for the forecast.
- A model based on AI can be trained easily, so recalibration or additions of new inputs is easy.
- A model based on AI does not have to consist of several submodels like LobithW, because the sensitivity for the input changes depending on the combination of all the inputs, as can be seen in the sensitivity analysis.
- A model based on AI can use all the available data more efficiently to make forecasts.

Another interesting conclusion from the interviews is about black boxes. A model is a black box if the internal structure or working is not known or understood. Sometimes a model is a black box on purpose, for instance when the model is confidential. However, in the case of flow forecasting, a black box not desirable. In this case the model is a black box because there is no physical base for the model, so its behaviour is hard to understand or predict. The forecasts are checked and usually also corrected. This can be done because of the experience of the forecasters and through understanding of the model. This is harder in the case of a black box.

More details can be seen in the report about the interviews and literature study, which is also attached.

4 Sensitivity analysis

In this chapter the sensitivity analysis of LobithAI will be discussed. This is done to see which input determines the result the most and whether this is different for different combinations of inputs. Also, it shows if the any potential unrealistic output of the model.

4.1 Method

The sensitivity analysis was done in following way: First a reference dataset is made for the particular analysis. These sets will be discussed more extensively later. In the beginning the model makes forecasts with this dataset. Then the water level or precipitation values for a single location are changed in small steps. These steps were taken within physically realistic bounds. By comparing these forecasts at Lobith, the impact of this change on the forecasts can be determined. For every location this is done 100 times with different changes relative to the first run. The minimal and maximal values are chosen in a way that they are still possible.

For the water level stations, the lowest water level used is set just below the lowest water level ever measured at that station. The highest water level used is a little more than the highest water level ever measured there. This way the most extreme cases that have happened are also covered. For the weather stations, the lower bound is obviously zero and the upper bound at 200 mm, which is about the highest recorded rainfall in Germany[10]. When combining these points, a line can be made to visualize the impact. This process can be repeated for all the locations and all the different datasets. This results in figures like those seen below.

$$normalized\ water\ level = \frac{water\ level - \mu}{\sigma} \tag{1}$$

As said before, there are different datasets used. Within these datasets the locations are changed one by one. Because the impact of changing the water level at a certain location also depends on the other inputs, different datasets are used. These datasets are like the reference values from which the water levels at the locations are changed. The inputs of LobithAI should be normalized before being used. This means that

#	**Water levels**	**Precipitation**	**Water levels deviation**	**Precipitation deviation**	**Range**
1	Extreme low	None	-2	-0.5	Normal
2	Low	None	-1	-0.5	Normal
3	Average	Average	0	0	Normal
4	Increased	Increased	1	1	Normal
5	High	High	2	2	Normal
6	Very high	Very high	4	3	Normal
7	Extreme high	Extreme high	8	5	Normal
8	Average	Average	0	0	Large
9	Extreme low	High	-2	2	Normal

Table 1: Different reference for the sensitivity analysis

not the actual water level is the input, but it must be converted with Equation 1. μ means the average water level at that location and σ is the standard deviation for that location. The same equation applies to the precipitation. The averages and standard deviations can be seen in Appendix A.1. Because normalized values are used, the table also shows the normalised values.

The situations in the table are not realistic but are still used because they cover the most extreme values. As said before, the limits for changing the water level or precipitation at a certain location is based on the most extreme recorded values. This is also the case for the situations used. The water levels do not go below -2 deviations and above 8 deviations. The precipitation does not go below -0.5 deviations and above 5 deviations.

4.2 Results

In Figure 2 an example of a graph as output of the sensitivity analysis can be seen. This graph shows three different lines. The impact of a change in water level on the forecast for the same day, one day ahead and two days ahead. The blue line the is impact on the forecast for the same day, this is almost zero. For a change in water level at Kaub the forecast for the current day changes 0.8 mm, which is negligible. This is as expected because this forecast should just be a copy of the water level at Lobith at that day.

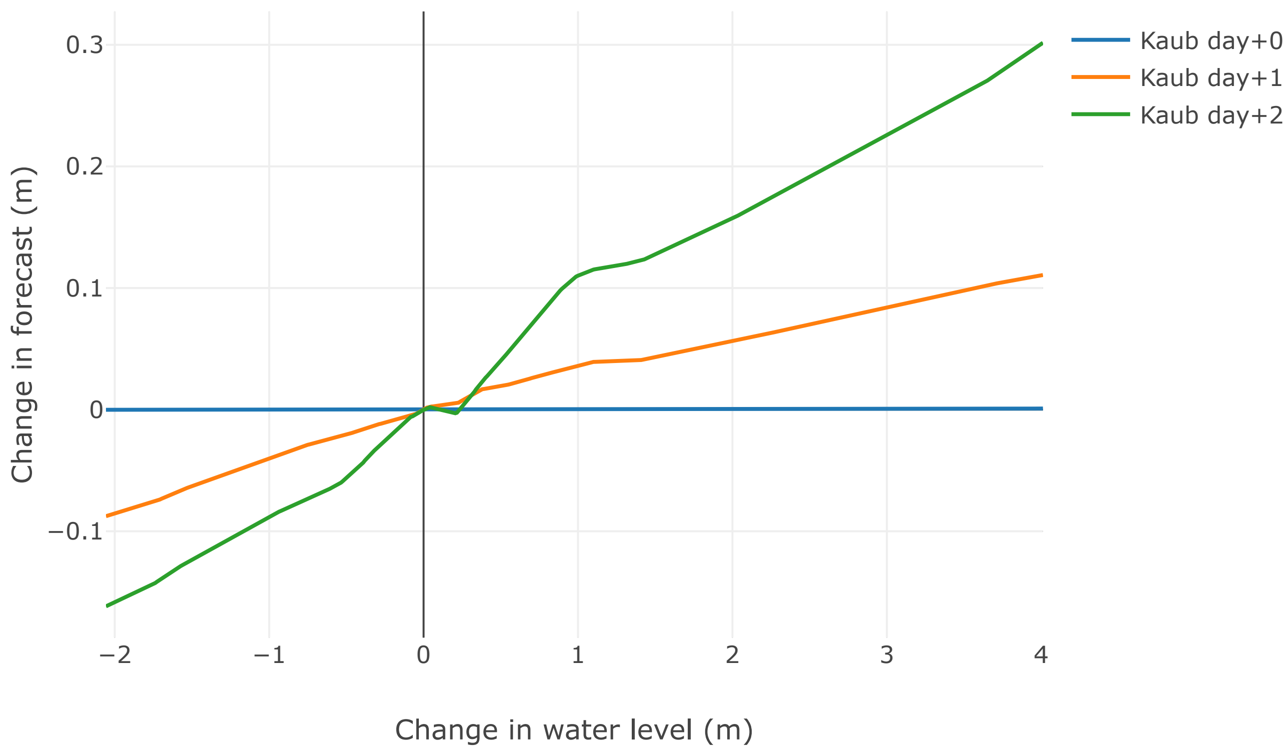

Figure 2: Sensitivity analysis for Kaub with average water levels and average precipitation

The orange line shows the impact of a change in water level at Kaub in on the forecast at Lobith for one day ahead. As can be seen here, the forecast gets higher for a higher water level at Kaub. This is as expected because the water flows from Kaub to Lobith.

The green line is showing the impact on the forecast for two days ahead. This impact is about double the impact on the forecast for two days ahead. This is also logical, because it takes the water about two days to get from Kaub to Lobith.

Between -2 and +4 m relative to the original water level the model made 100 forecasts. This means every 6 cm a new test was run, so very little interpolation was done. This graph shows that an increase of 4 meters at Kaub only changes the forecast for two days ahead with 30 cm. This might seem insignificant, but, in reality the water level does not only change at Kaub. It also changes at other stations which also contribute to the forecast. Together they can change the forecast at Lobith much more. This is just an example, graphs like this have also been made for all the other locations and all other reference datasets.

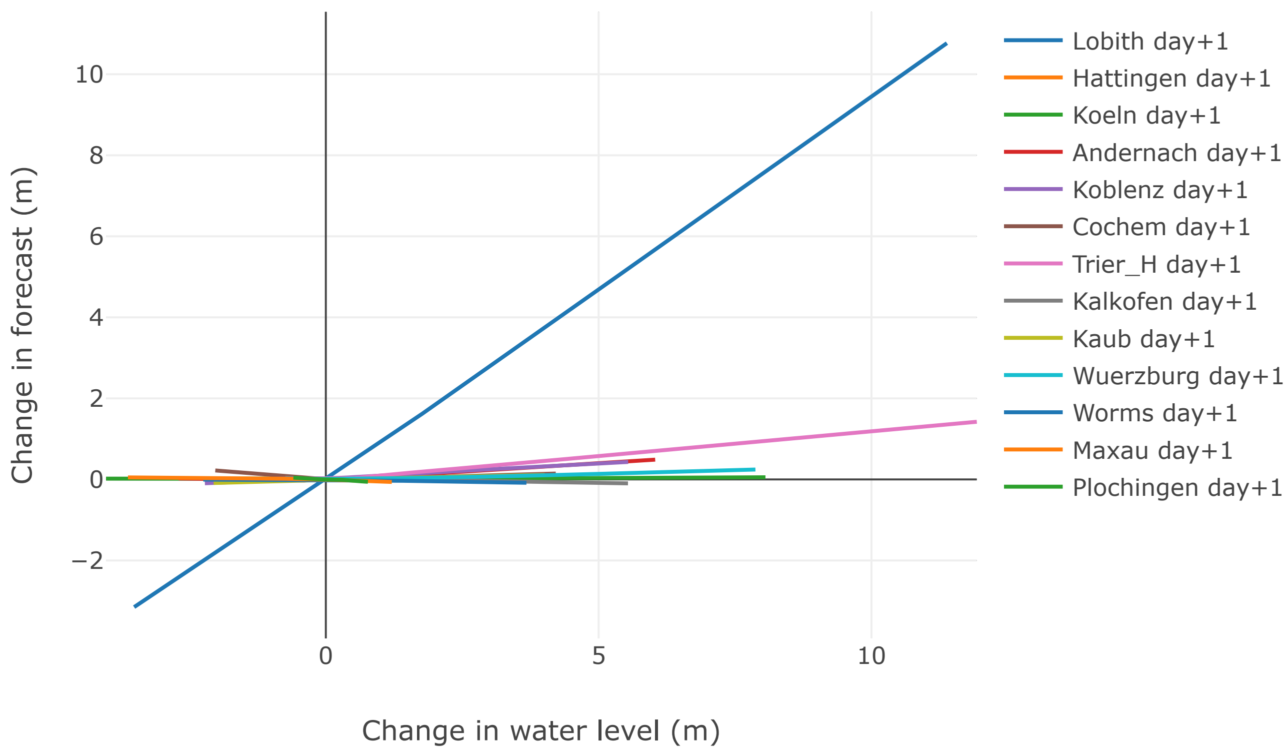

Figure 3: Sensitivity analysis for Water levels (day+1) with average water levels and average precipitation.

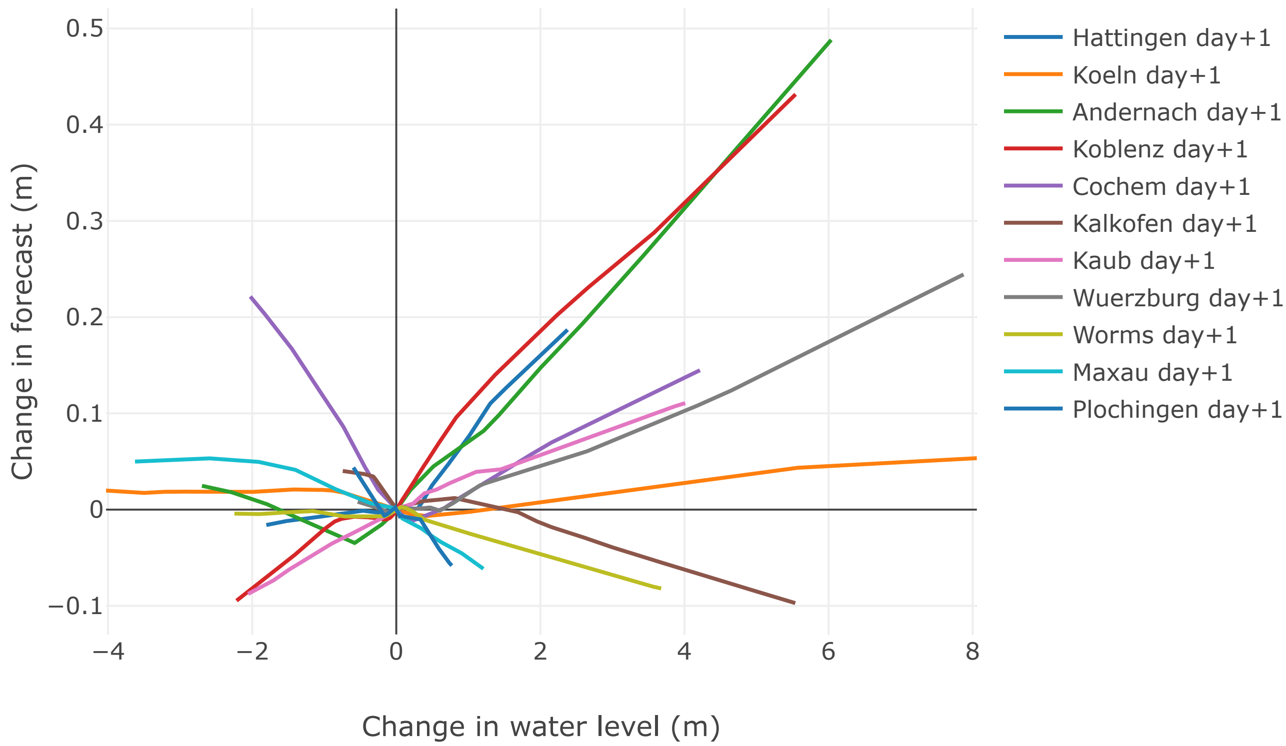

Figure 4: Sensitivity analysis for Water levels (day+1) with average water levels and average precipitation without Lobith and Trier.

Figure 3 combines all the lines for the forecast for one day of one dataset. It clearly shows that the water level at Lobith is the dominant factor. Because of the scale of it the other lines are not clearly visible. To show the other lines better the Figure 4 shows the same lines but without Lobith and Trier.
Because the model is a neural network, the relations for the different stations differ depending on the reference conditions. So only one graph can never cover the complete analysis. To tackle this problem, the analysis has been done for a lot of different reference situations. This way a better overview is found. The sensitivity analysis is done for the cases seen in Table 1.

In the list above, there is only one case where the deviation of the water levels and the precipitation are not the same. This is because there is a very high correlation between the precipitation and the water levels. The case where this is not the case is included to see how the model behaves for unexpected values.

Changing the water levels and precipitation at all the locations at the same time was also tested. The change relative to the deviation was the same for every location, not the change in water level. This can be seen in Figure 5. As can be seen there, the forecasts change linearly.

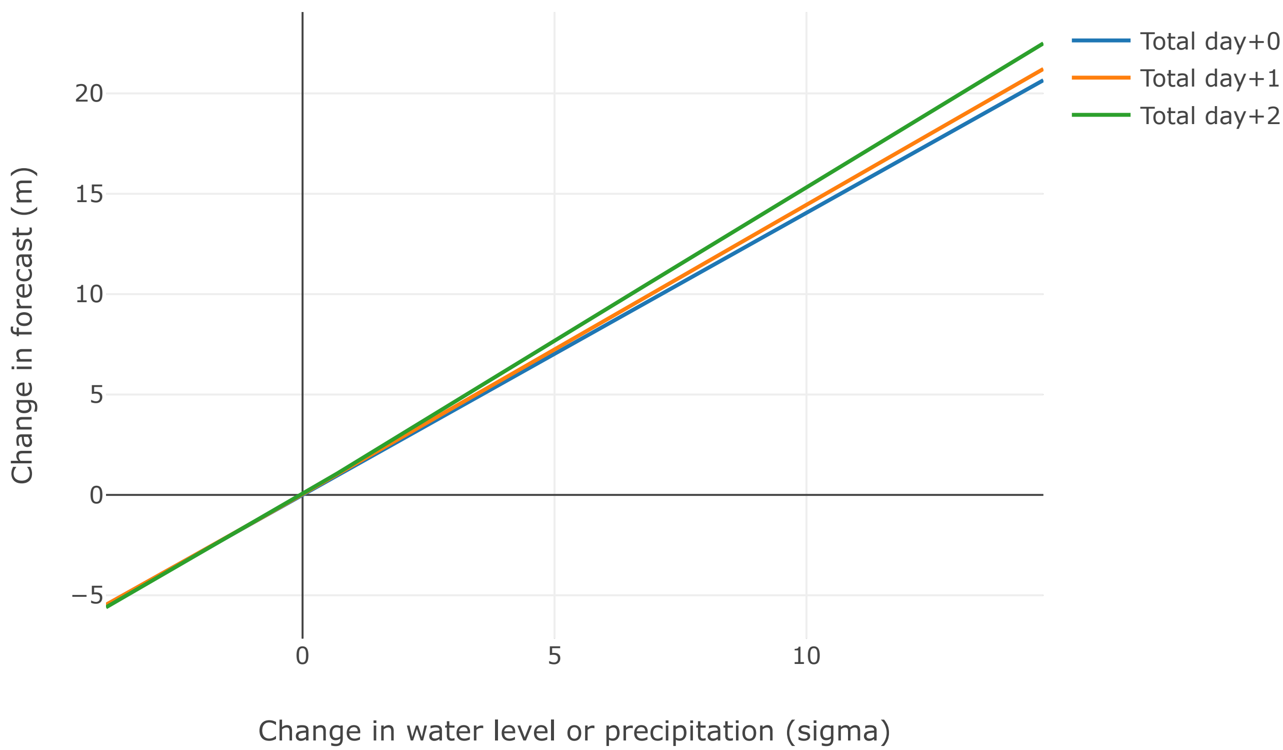

Figure 5: Sensitivity analysis for all the water levels and precipitation at the same time

The graphs in the appendices and shown above show a lot of information about the operation of the model. The most important points are noted here:

- The water level at Lobith has by far the most impact on the forecasts for 0, 1 and 2 days ahead. The further ahead, the smaller the impact of Lobith is.
- For some reason, the model also outputs the forecast for day+0. This should just be the water level at Lobith for that day. However, that is not completely the case. It is (almost) not influenced by anything other than the water level at Lobith.
- The forecast is always linearly related to the water level at Lobith, while the relation with other stations is not linear.
- The more extreme the initial conditions the more linear the influence of changing a station is on the forecasts. This is most likely because the trainings data did not include a lot of similar data, so only linear relations were found.
- If all the stations change equally at the same time the forecasts also change linearly.

5 Extreme data test

Here the extreme data test will be discussed. This is done to test the quality of the model.

5.1 Method

Because the quality of the model has not been tested for very extreme conditions this is done in this part of the report. The sensitivity analysis used extreme values, but those cases were not realistic, and the performance of the model was not tested there. To get data as extreme as possible, fictional data has been used. To keep the data realistic the data is obtained from "Deining and Doorbraak". This is a fictional scenario consisting of precipitation values simulating very extreme conditions. In Delft-FEWS the water levels and discharges are calculated using SOBEK and HBV models. This means a "realistic" high water scenario is simulated. LobithAI will be compared to SOBEK here.

The input for both LobithAI and LobithW must be converted to water levels. For some of the stations the simulation generated discharges. These discharges can be converted to water levels. To this there are rating curves, these curves show the corresponding water levels for certain discharges. However, for these extreme discharges, the rating curves sometimes did not contain the simulated discharges. This means the discharges could not be converted to water levels correctly. To fix this the rating curves have been extrapolated, but this might not be completely accurate. In the discussion this is explained more extensive.

So, after using Delft-FEWS, the water level and precipitation data was available for multiple days. This means LobithAI could make forecasts based on this data. These forecasts were compared to the values simulated by FEWS for the next days. This resulted in the graphs as seen below. So, the values are generated and not recorded. However, these values are assumed as reality to check LobithAI.

5.2 Results

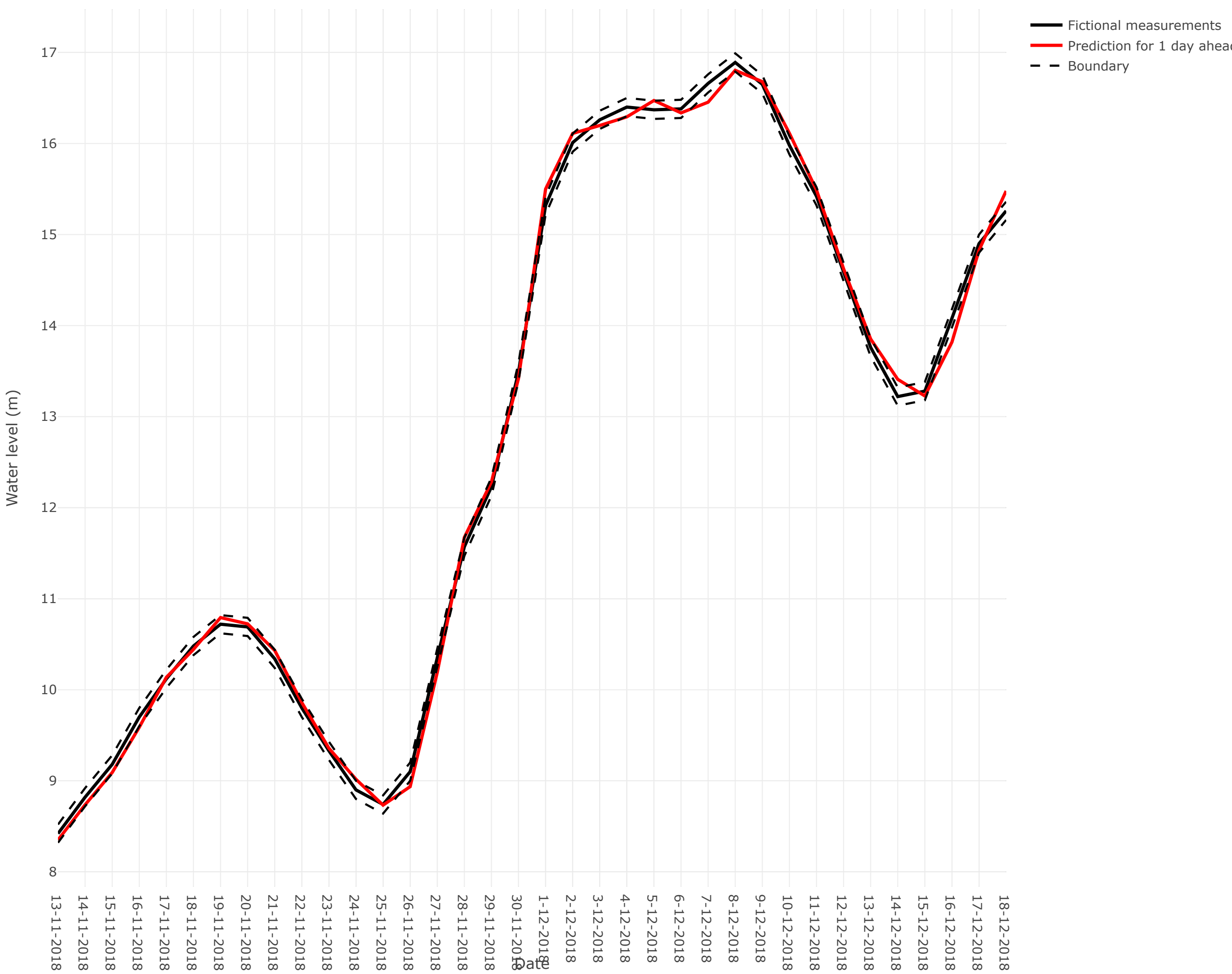

Figure 6: Forecast for one day with the generated values

Figure 7: Forecast for one day with the generated values

Figure 6 and 7 show the water levels with the corresponding forecasts. The black lines show the simulated water levels, the dashed black lines show the desired threshold as set by Rijkswaterstaat. The threshold for one day ahead is 10 cm and for two days ahead 20 cm. In Figure 8 the error for both forecasts can be seen.

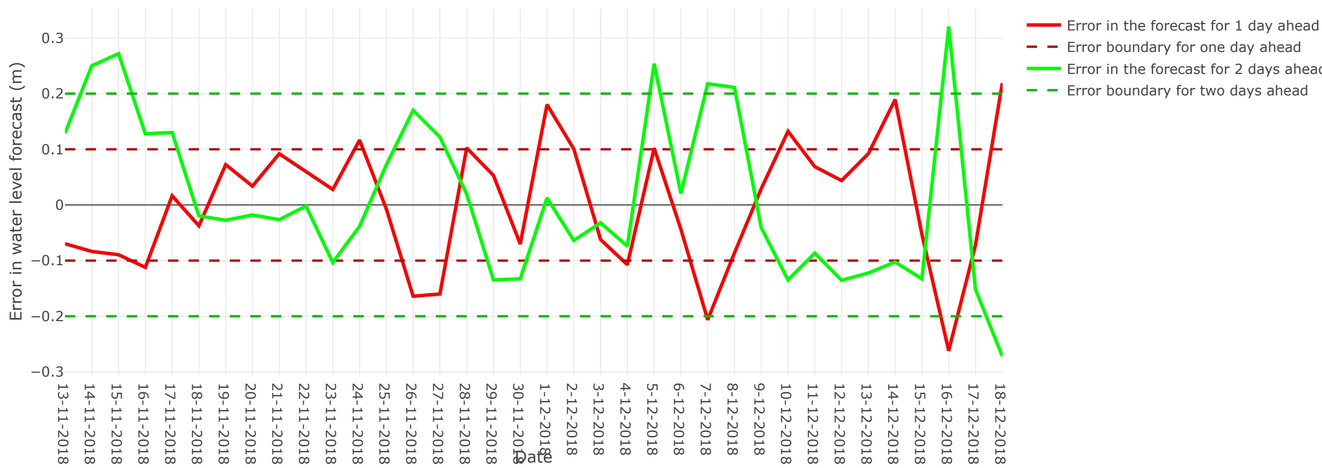

Figure 8: Forecast for one day with the generated values

These figures show that the forecasts are quite close to the simulated water levels. This means that LobithAI functions quite like the physical based model SOBEK. This is suprising because LobithAI only uses statistical ralations.

6 Discussion

As can be seen in the other chapters LobithAI functions quite well, but there are some things to consider. For the sensitivity analysis only, a few cases have been considered, these cases were different and cover the complete range of inputs, but there many more combinations of input possible, which might result in a slightly different sensitivity. Since the sensitivity analysis is only performed to get a picture of the sensitivity of the model and this is achieved, this is not a problem.

For the extreme value test, it is a problem that only one case is considered. In this case the model functions reasonable but not perfect. But since only one case is considered, things could be very different for other cases. The actual quality of the model cannot be determined for this case.

6.1 Possible improvements

More training data could improve the functioning of the model, but it is not necessary for good functioning. If more data is available when training a model, it is advised to use this data. The interviews suggest that more inputs could improve the model. Especially new kind of inputs like temperature, snow height or water levels in lakes in the Switzerland.

As seen in the extreme value test, some of the rating curves were not enough. Table 2 shows the extreme recorded values for the discharge and the extreme values in the rating curves can be seen. Some values are bolt, this means that the lowest or highest recorded discharge value is not contained in the rating curve. The rating curves show the relation between the water levels and the discharge. However, these rating curves were too small for some of the water level stations. For the stations in Worms, Würzburg, Trier, Cochem, Köln and Lobith the smallest discharge ever recorded was smaller than the lowest discharge in the rating curve. For Cochem the highest recorded discharge was also not in the rating curve. Because of this LobithAI could not forecast for those extreme values. This is not only a problem for LobithAI, also LobithW cannot functions if the discharges enter these very extreme values.

So, to conclude this section, the following changes should be made to let LobithAI function better:

- The training data should contain more extreme values, to prevent extrapolation.
- The rating curves should be extended for both the extremely high and extremely low discharges.
- The model should have more kinds of inputs, like temperature or snow height, to function better.

Location	**Riverbranche**	**Lowest recorded discharge (m3/s)**	**Highest recorded discharge (m3/s)**	**Lowest discharge in rating curve (m3/s)**	**Highest discharge in rating curve (m3/s)**
Maxau	Rhine	340	4340	275	6414
Plochingen	Neckar	-	-	3.7	810
Worms	Rhine	415	5400	**448**	6000
Würzburg	Main	12	2080	**50**	2130
Kaub	Rhine	482	7160	478	7540
Kalkofen	Lahn	3	840	0	856
Trier	Mosel	21	3840	**50**	4990
Cochem	Mosel	10	4020	**58**	**3822**
Koblenz	Rhine	-	-	-	-
Andernach	Rhine	560	10400	545	11037
Köln	Rhine	401	10900	**583**	12131
Hattingen	Ruhr	8.42	974	1.13	1473
Lobith	Rhine	575	12300	**630**	16284

Table 2: Extreme values for the rating curves and extreme recorded values

7 Conclusion

To answer the research question:

How does the LobithAI model behave for flow conditions that are not contained in the training data?

The extreme value test showed that the model also functions good for flow conditions beyond the training data. The functioning of LobithAI was close to the physical based model SOBEK. The sensitivity analysis showed that the model is consistent. So, combining these, the results are very positive for LobithAI. With some more testing and possibly some improvements, it might be able to run alongside LobithW soon.

In the end this research shows that water level forecasting can be done with neural networks, even if some flow conditions are not contained in the training data.

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A Sensitivity analysis

A.1 Averages and standard deviations

Location	Average (m)	std (m)
Maxau	4.96	0.93
Plochingen	1.65	0.22
Worms	1.98	1.02
Würzburg	1.67	0.54
Kaub	2.12	1.03
Kalkofen	2.24	0.68
Trier	3.03	1.04
Cochem	2.72	0.81
Koblenz	2.19	1.11
Andernach	2.61	1.28
Köln (Koeln)	3.64	1.61
Hattingen	1.79	0.82
Lobith	9.13	1.41

Table 3: Averages and standard deviations for water level stations

Location	Average (mm)	std (mm)
Borken	22.5	45.9
Dusseldorf	20.8	41.6
Frankfurt	17.3	40.5
Giessen	16.4	38.6
Nancy	21.8	46.8
Strasbourg	16.5	38.7
Stuttgart	19.2	44.2
Trier	20.7	43.2

Table 4: Averages and standard deviations for precipitation stations

A.2 Average water levels and average precipitation

As said before, for the sensitivity analysis using normal water levels and normal precipitation all the graphs will be shown here. For every combination of inputs there are different kind of graphs. The first kind of graphs are the location specific graphs. These graphs contain three lines. These three lines show the impact of a change in water level or precipitation at that locations to the forecasts for +0, +1 and +2 days. Figures 9 - 21 show the impact of a change in water level on the forecasts. Figures 22 - 29 show the impact of a change in precipitation of the forecast. The figures 30, 31 and 32, figures 33, 34 and 35 do the same, but for the precipitation. The last figure for normal precipitation and normal is Figure 36, it shows the change in forecast when all the locations, for both water levels and precipitation, change equally in terms of deviation.

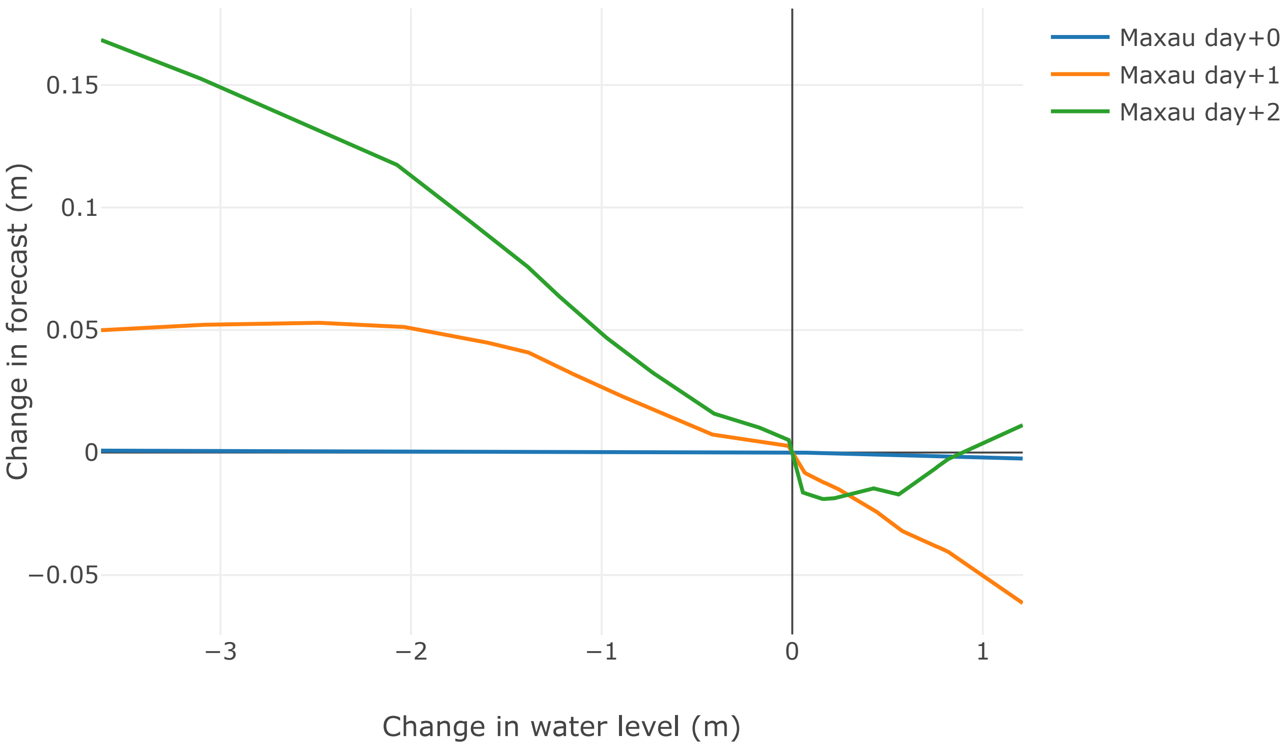

Figure 9: Sensitivity analysis for Maxau with average water levels and average precipitation

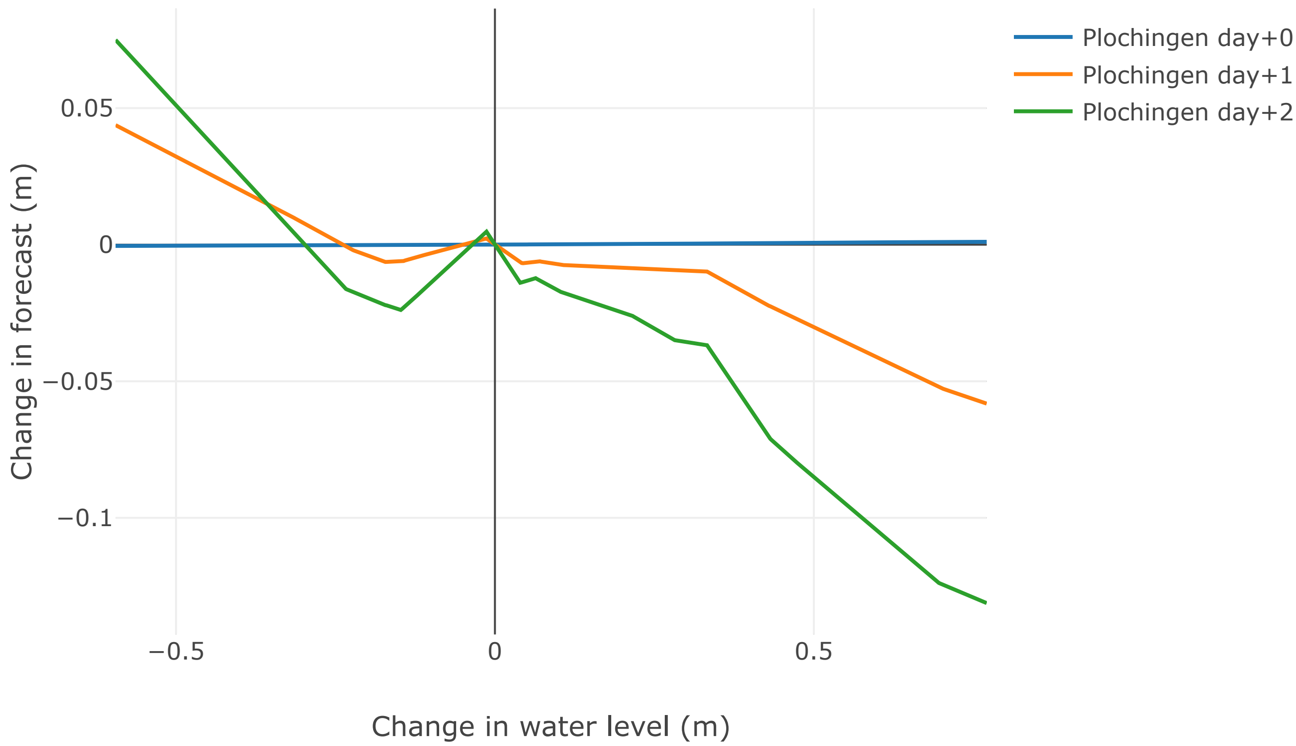

Figure 10: Sensitivity analysis for Plochingen with average water levels and average precipitation

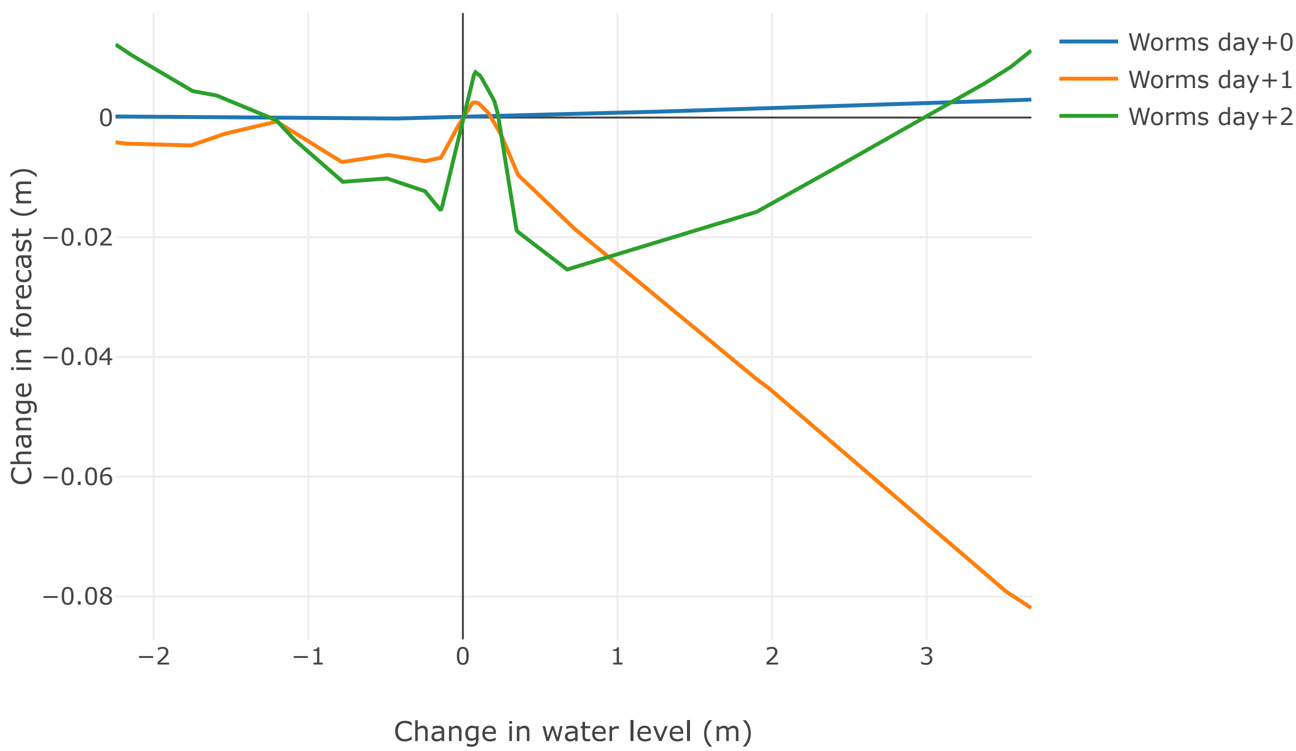

Figure 11: Sensitivity analysis for Worms with average water levels and average precipitation

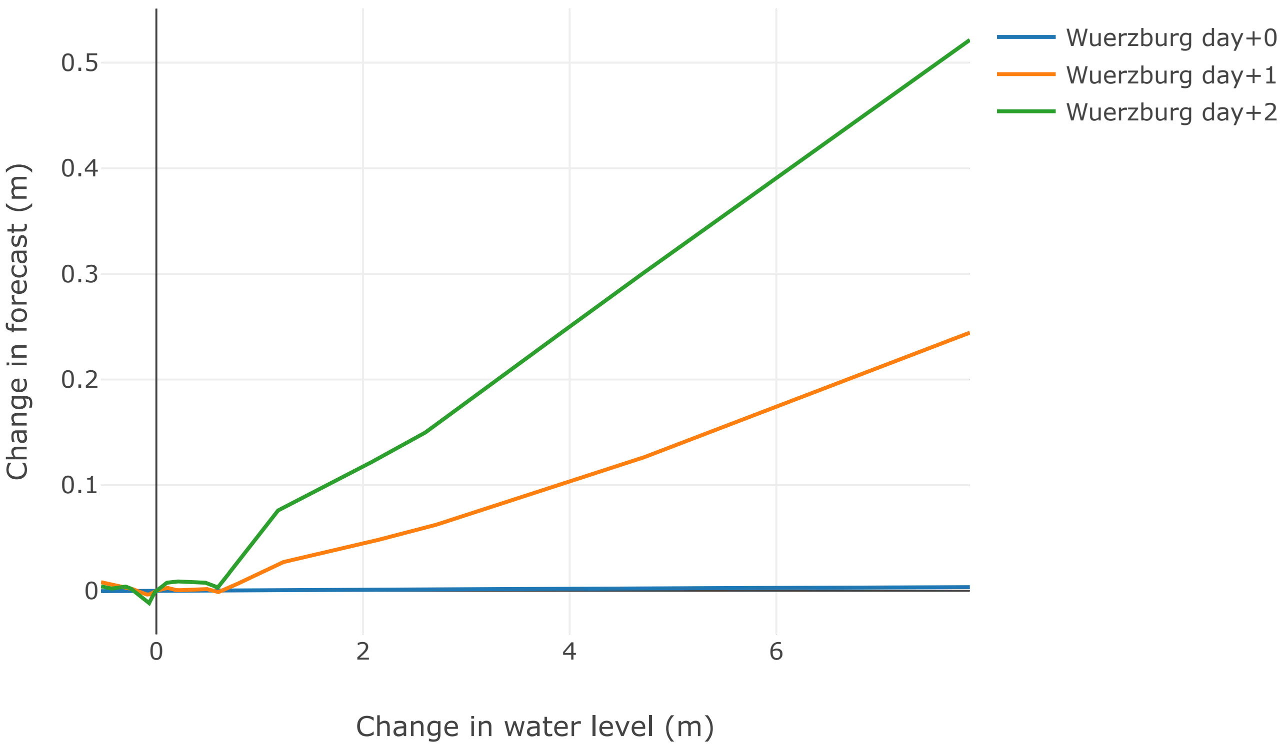

Figure 12: Sensitivity analysis for Würzburg with average water levels and average precipitation

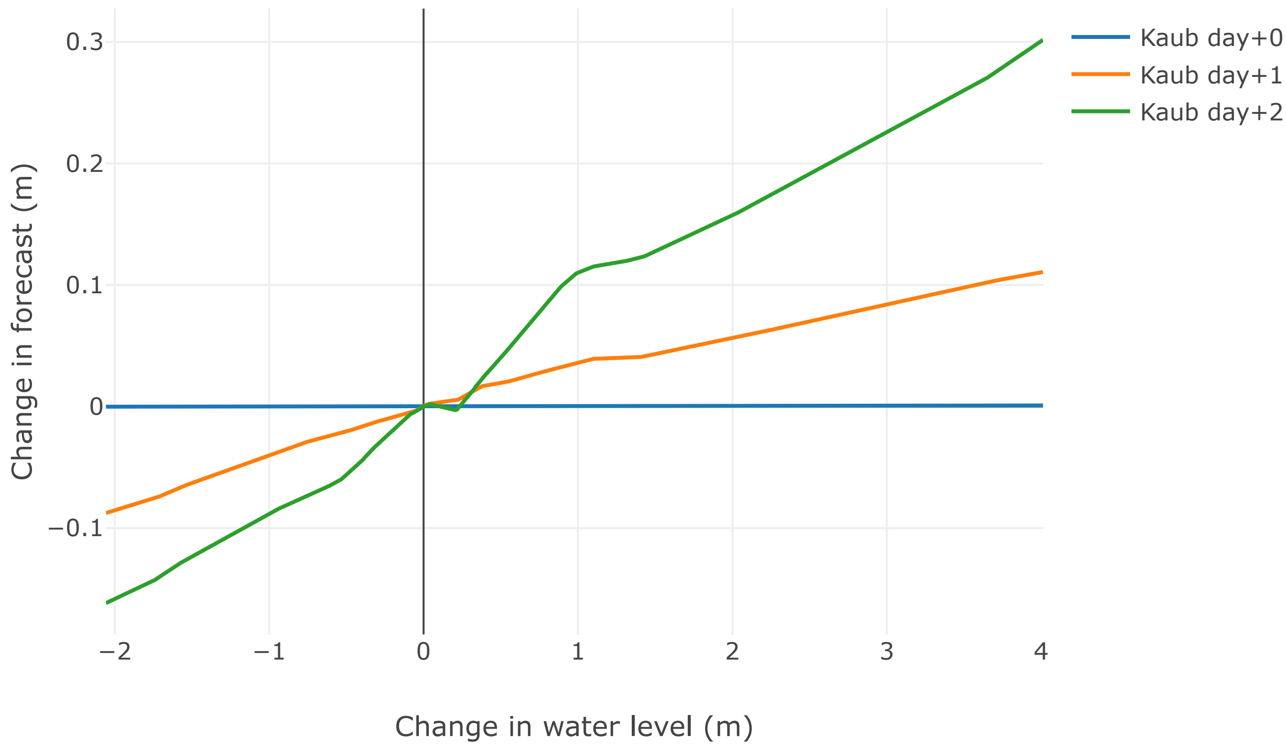

Figure 13: Sensitivity analysis for Kaub with average water levels and average precipitation

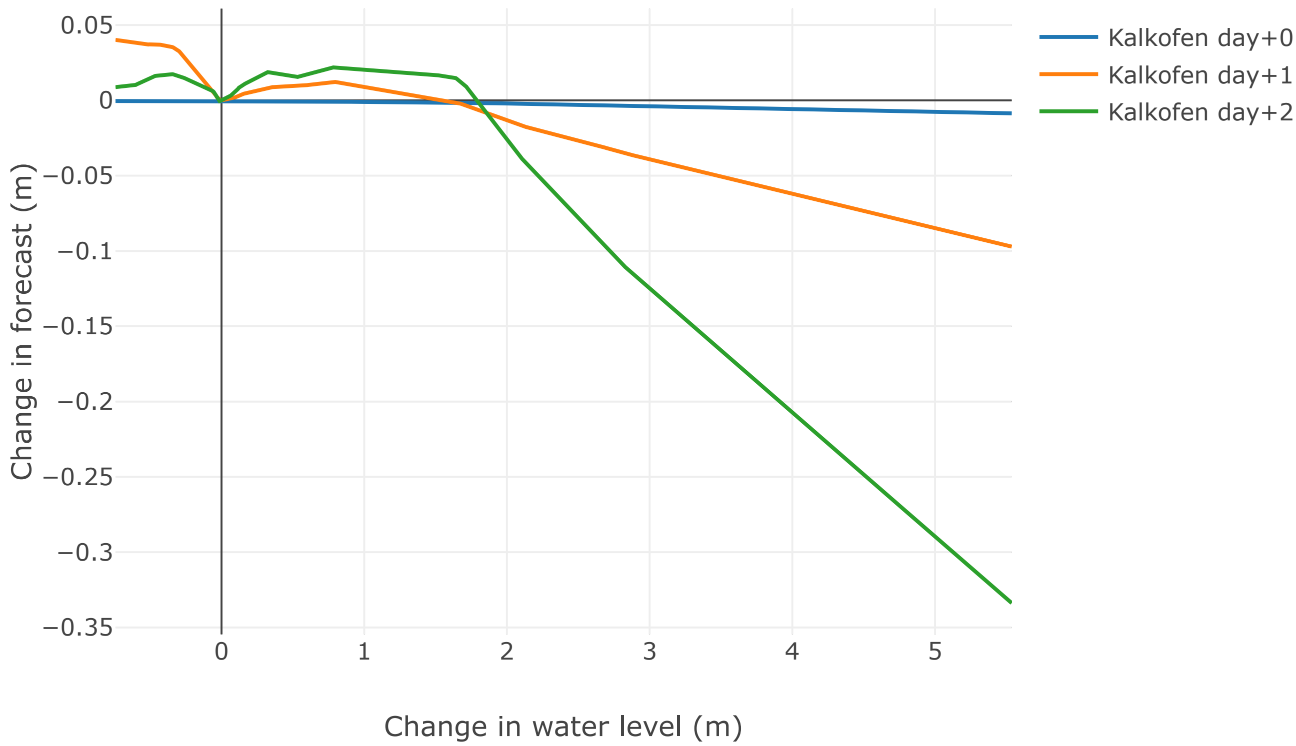

Figure 14: Sensitivity analysis for Kalkofen with average water levels and average precipitation

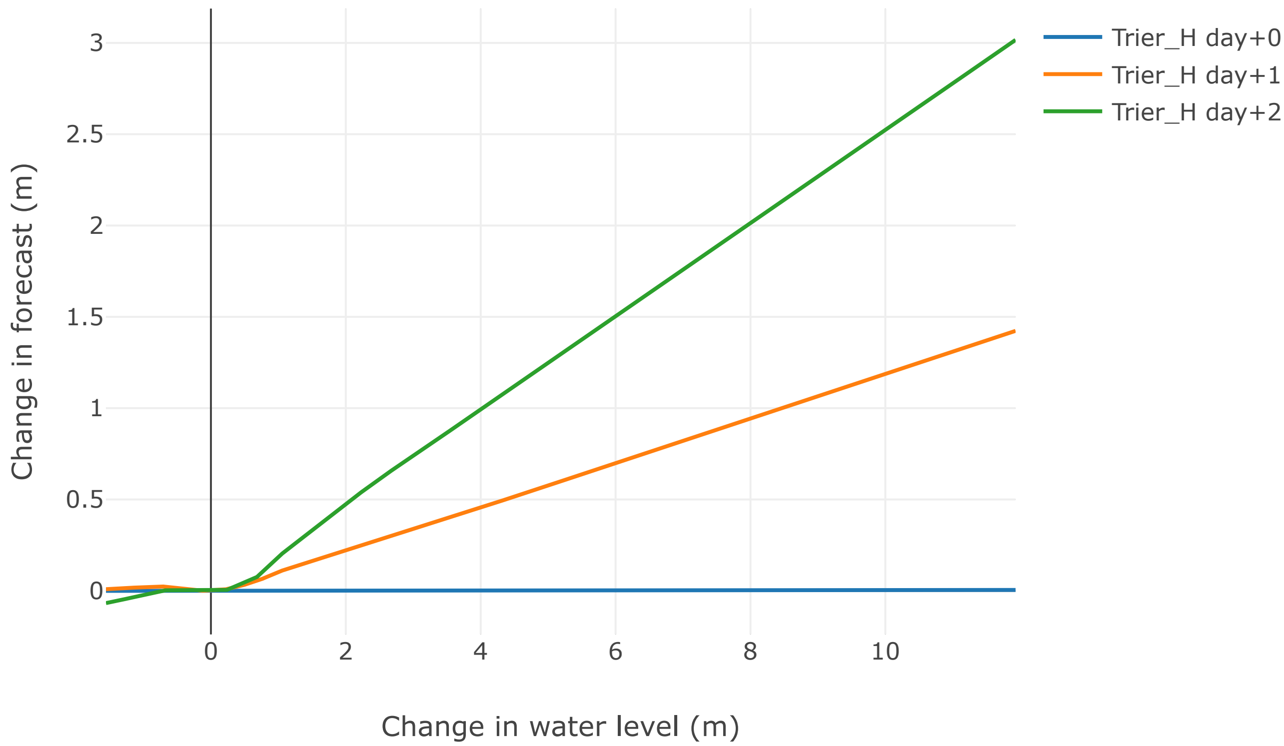

Figure 15: Sensitivity analysis for Trier (Water levels) with average water levels and average precipitation

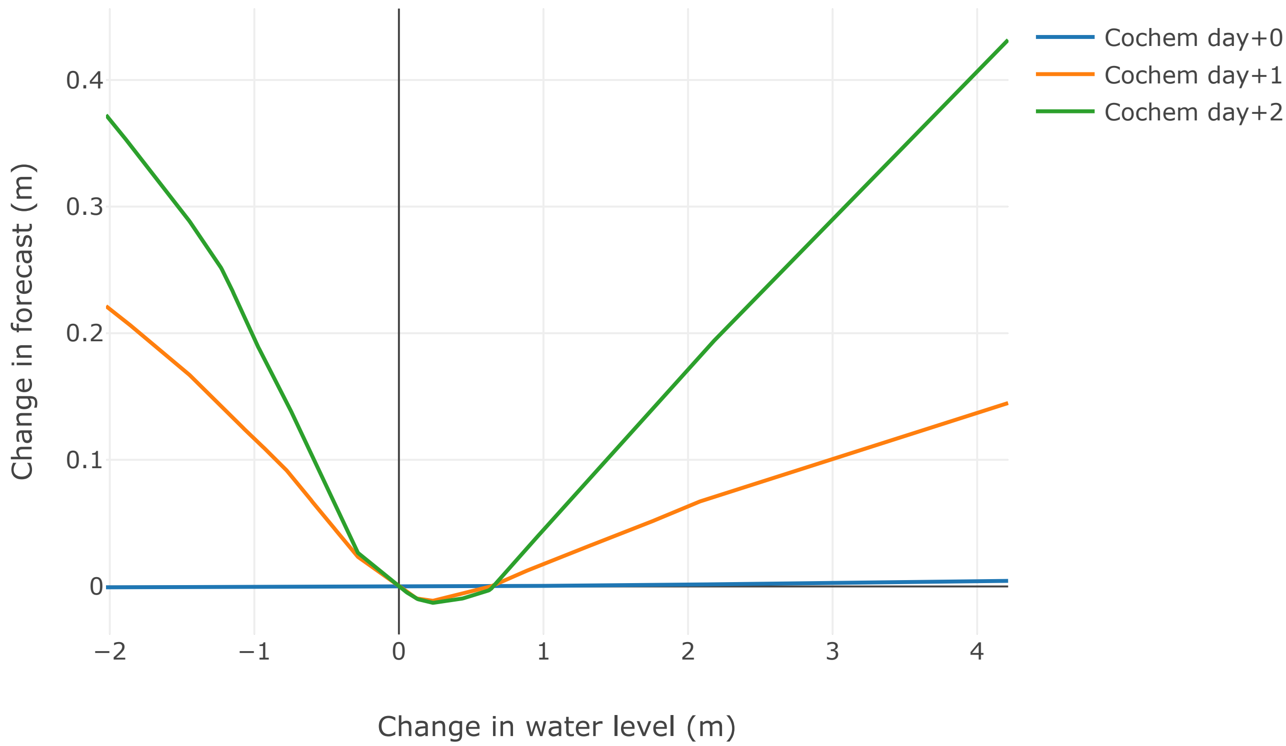

Figure 16: Sensitivity analysis for Cochem with average water levels and average precipitation

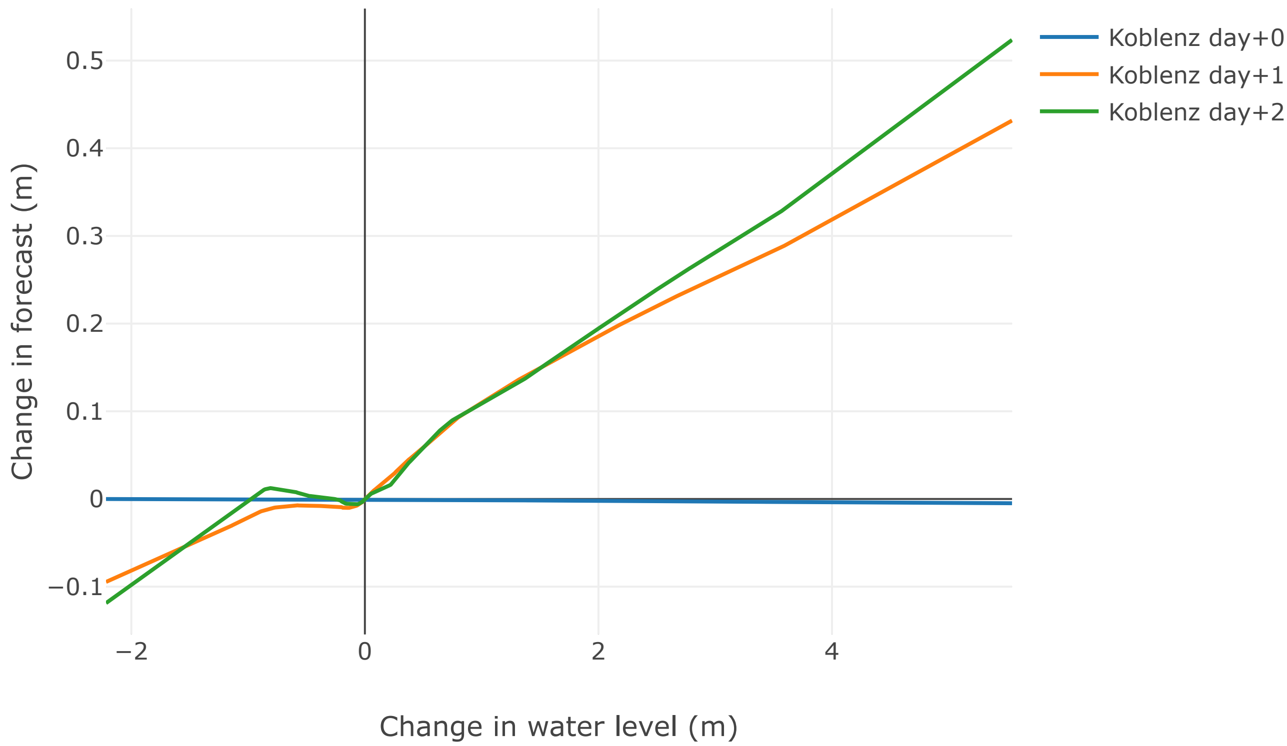

Figure 17: Sensitivity analysis for Koblenz with average water levels and average precipitation

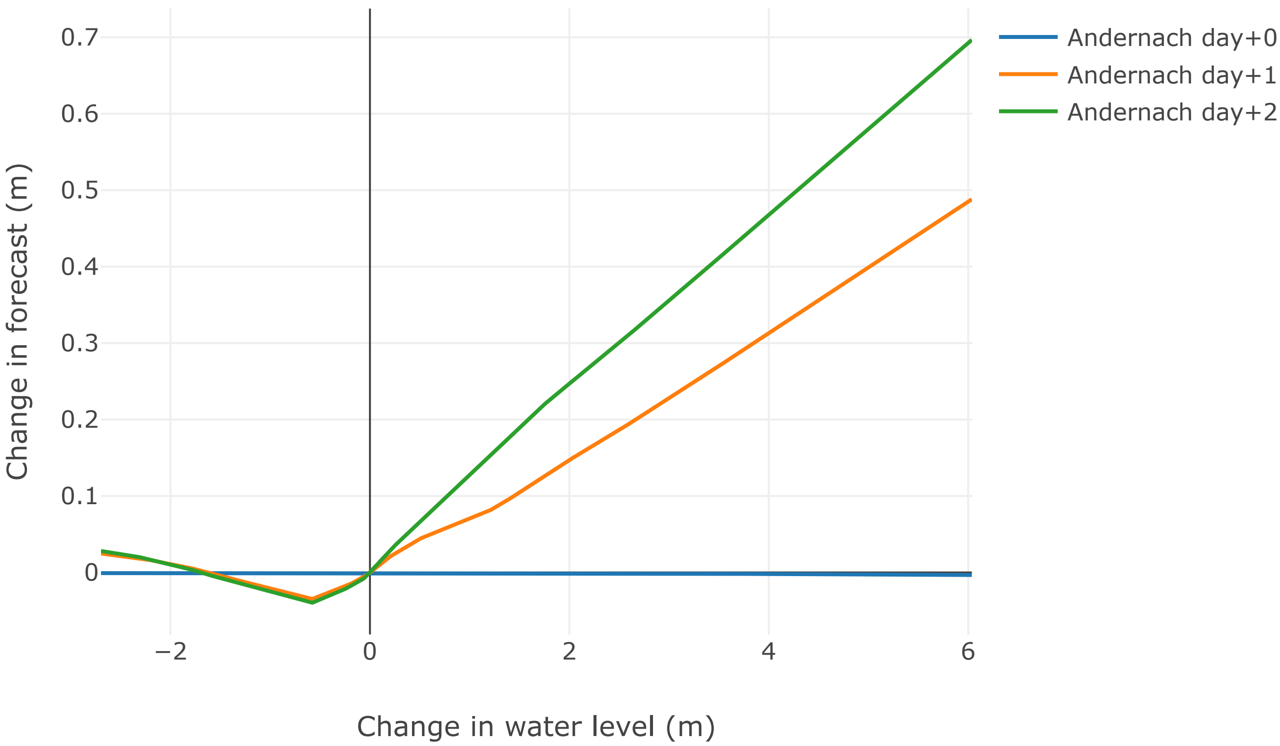

Figure 18: Sensitivity analysis for Andernach with average water levels and average precipitation

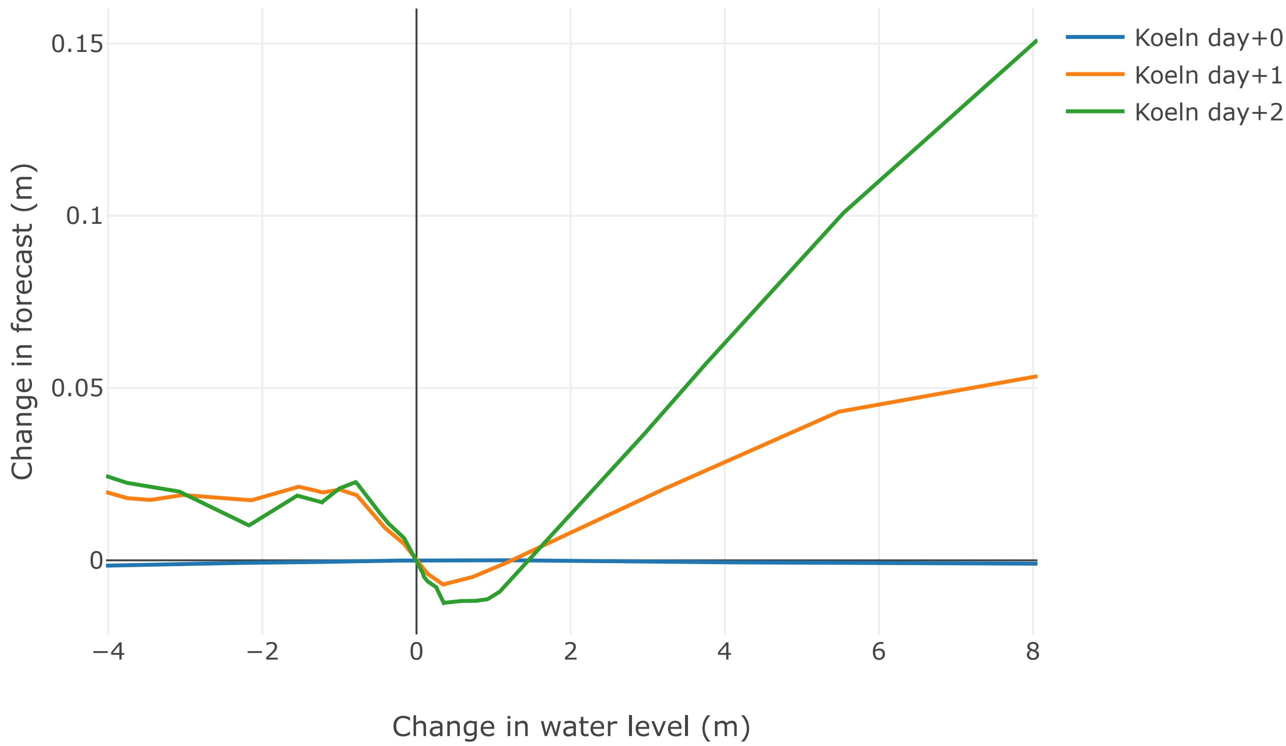

Figure 19: Sensitivity analysis for Köln with average water levels and average precipitation

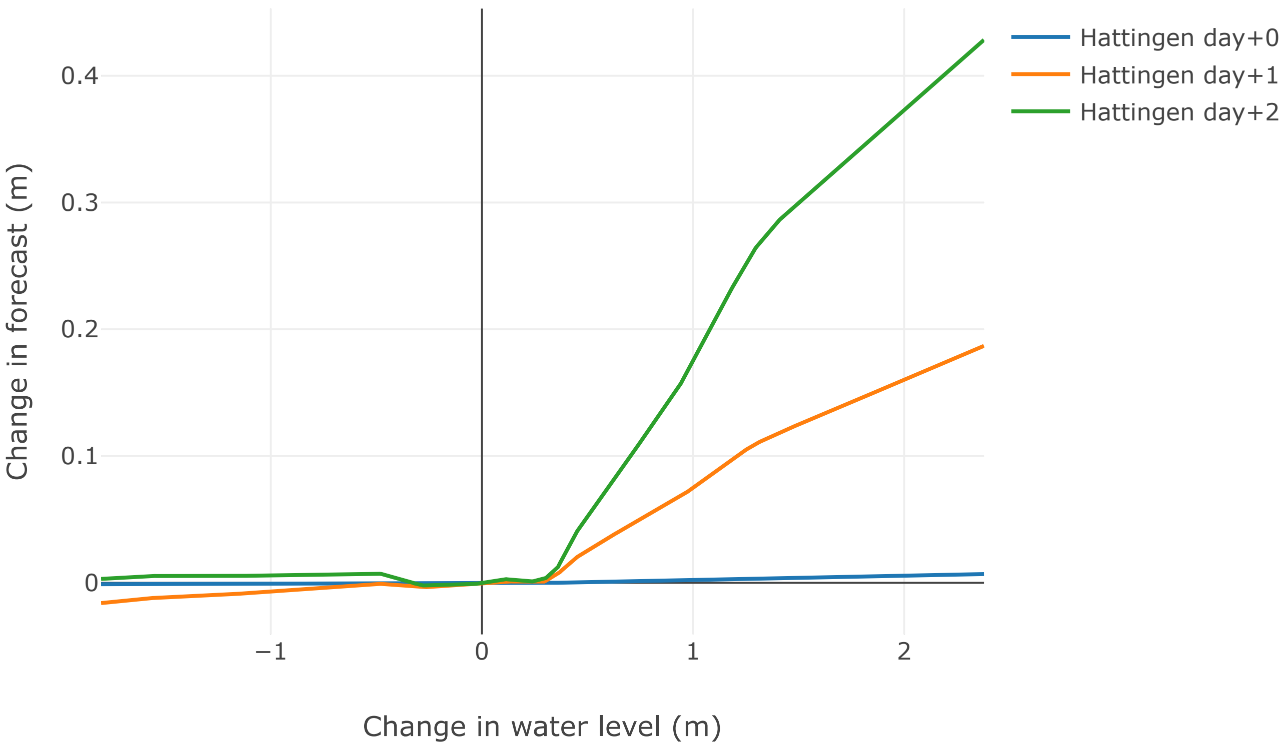

Figure 20: Sensitivity analysis for Hattingen with average water levels and average precipitation

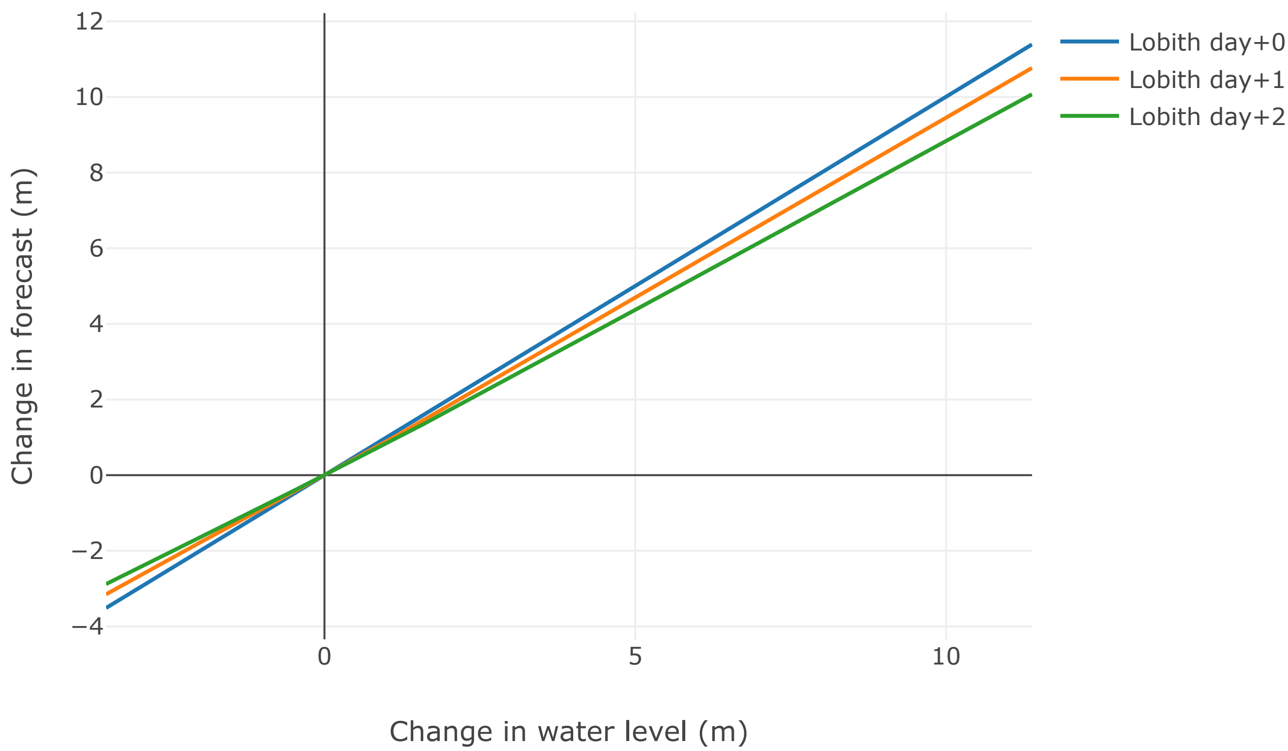

Figure 21: Sensitivity analysis for Lobith with average water levels and average precipitation

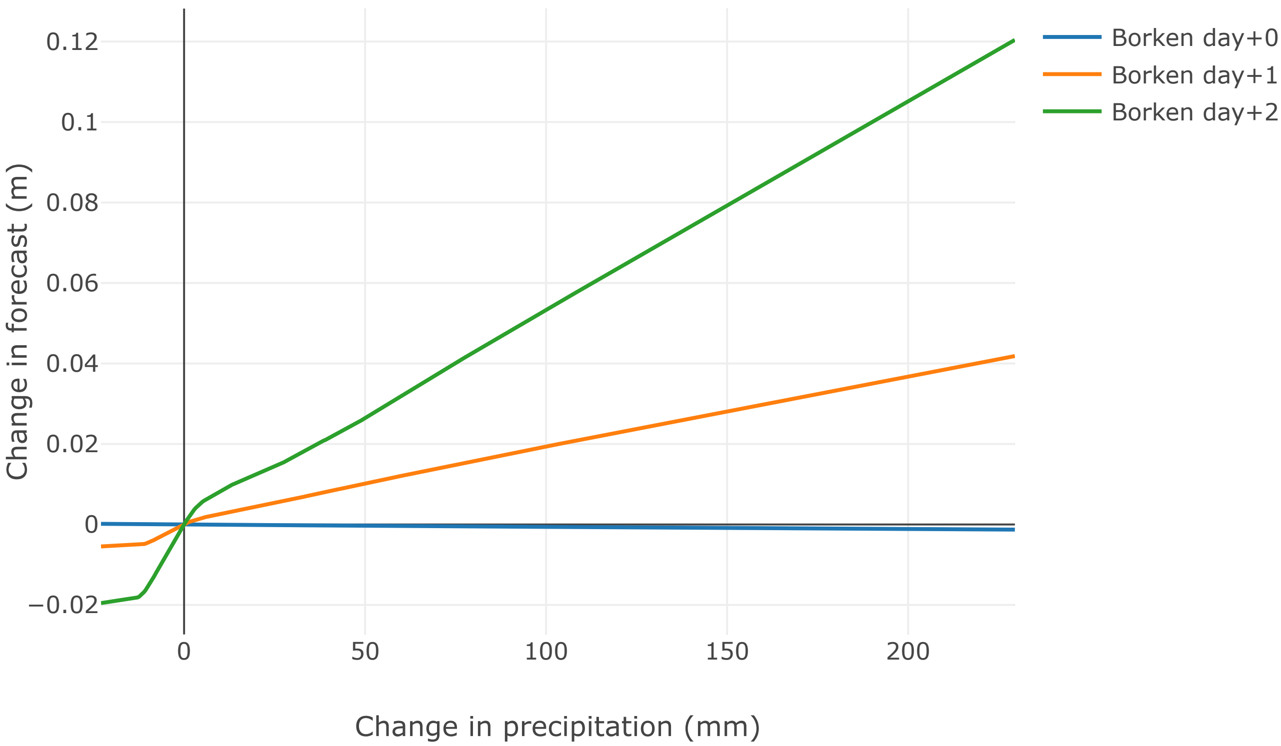

Figure 22: Sensitivity analysis for Borken with average water levels and average precipitation

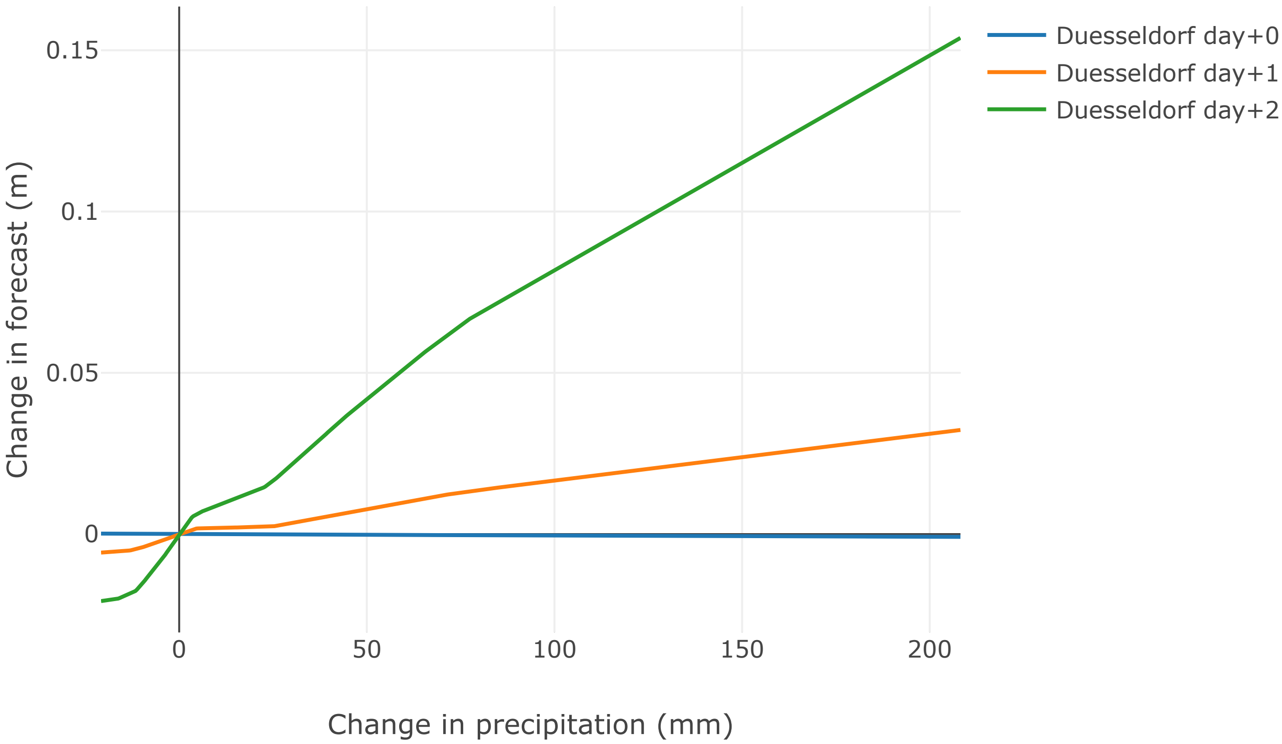

Figure 23: Sensitivity analysis for Düsseldorf with average water levels and average precipitation

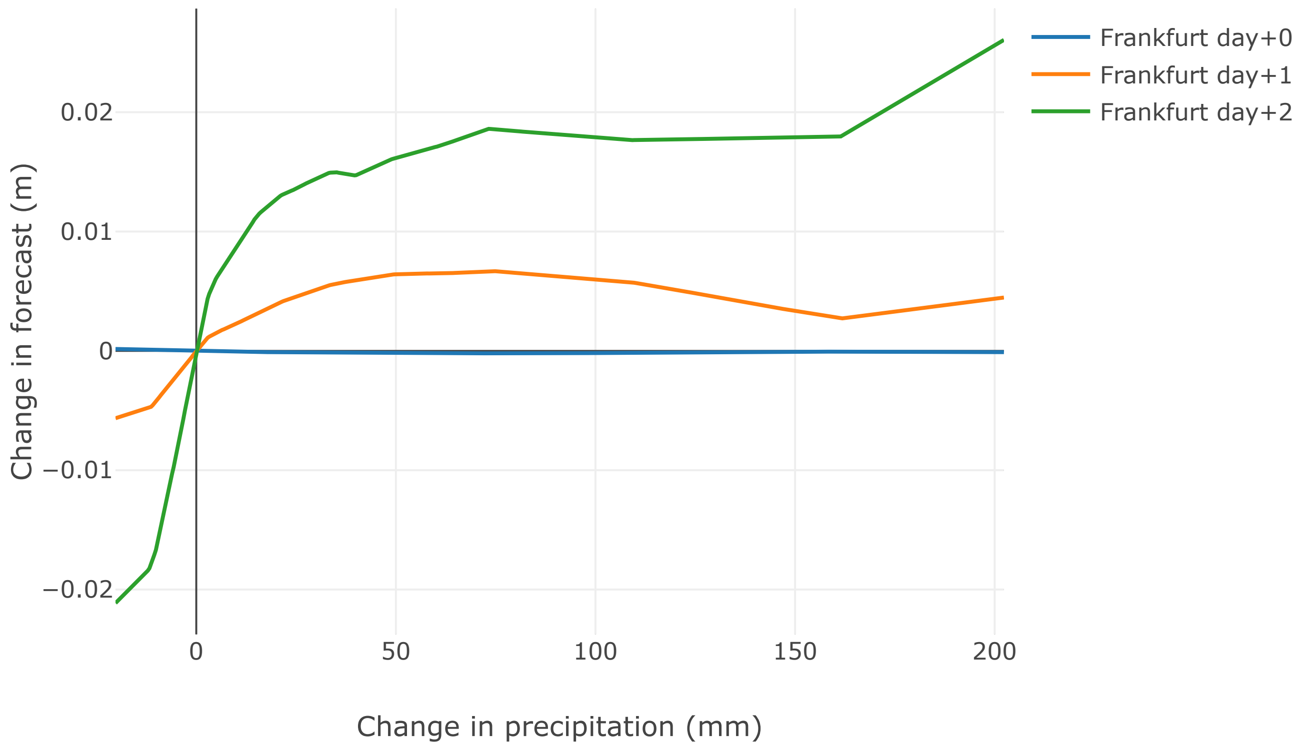

Figure 24: Sensitivity analysis for Frankfurt with average water levels and average precipitation

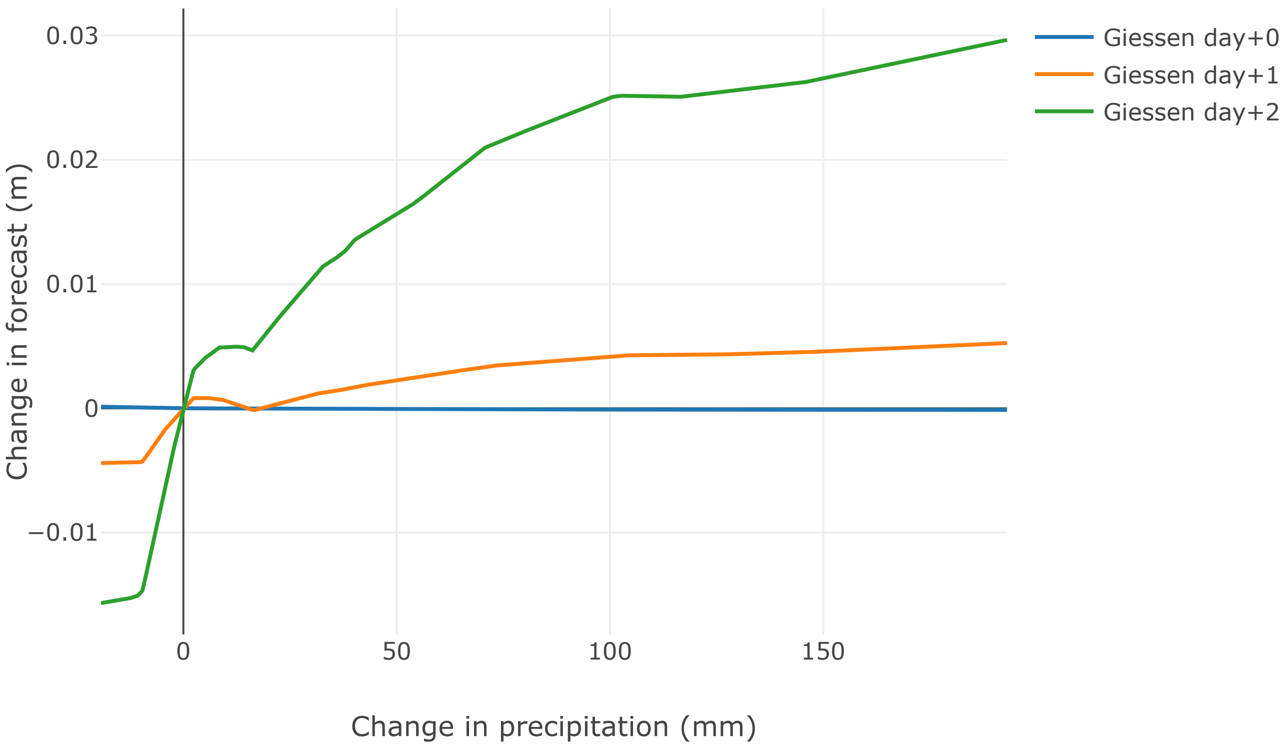

Figure 25: Sensitivity analysis for Giessen with average water levels and average precipitation

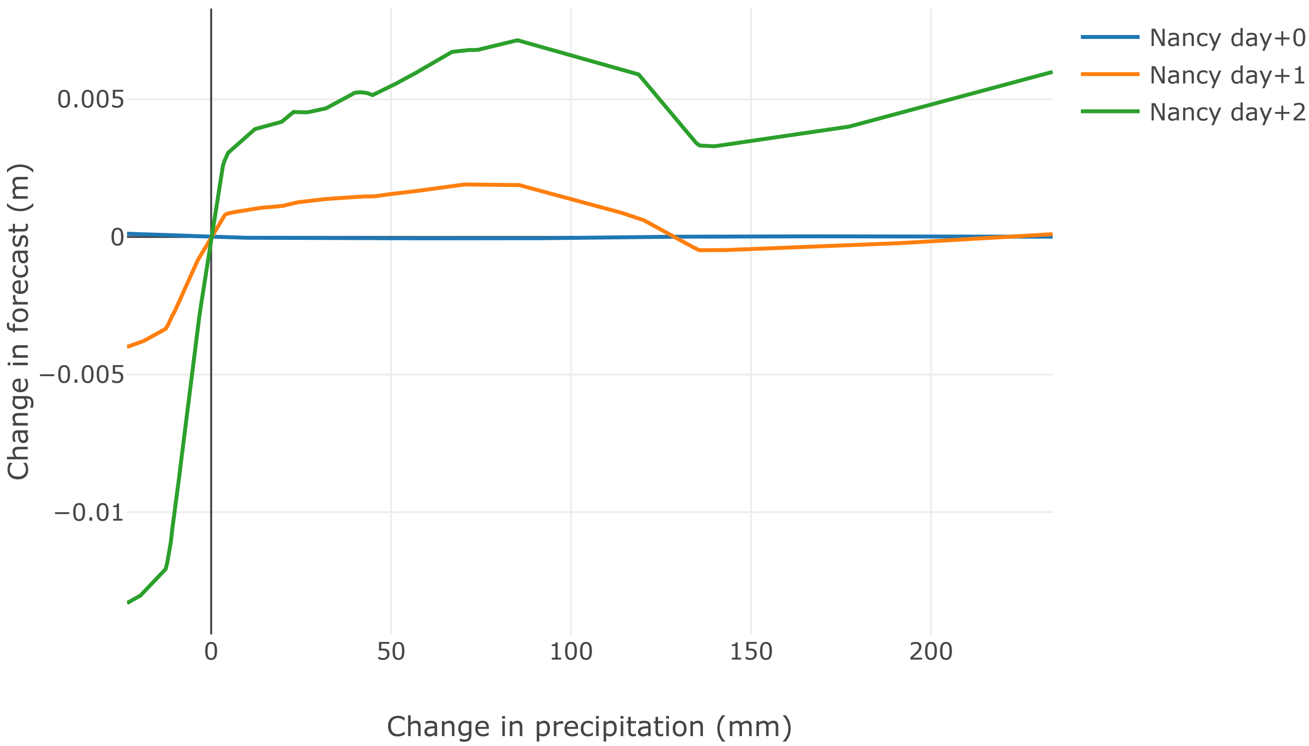

Figure 26: Sensitivity analysis for Nancy with average water levels and average precipitation

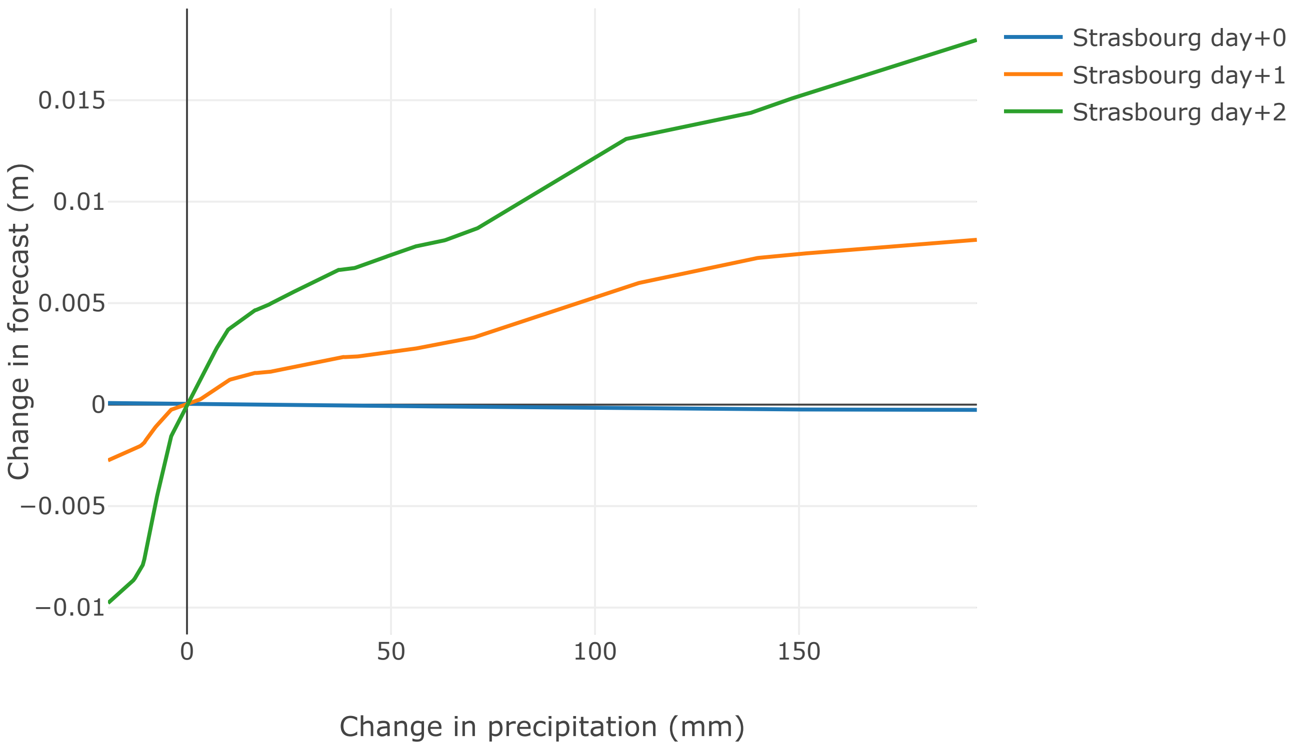

Figure 27: Sensitivity analysis for Strasbourg with average water levels and average precipitation

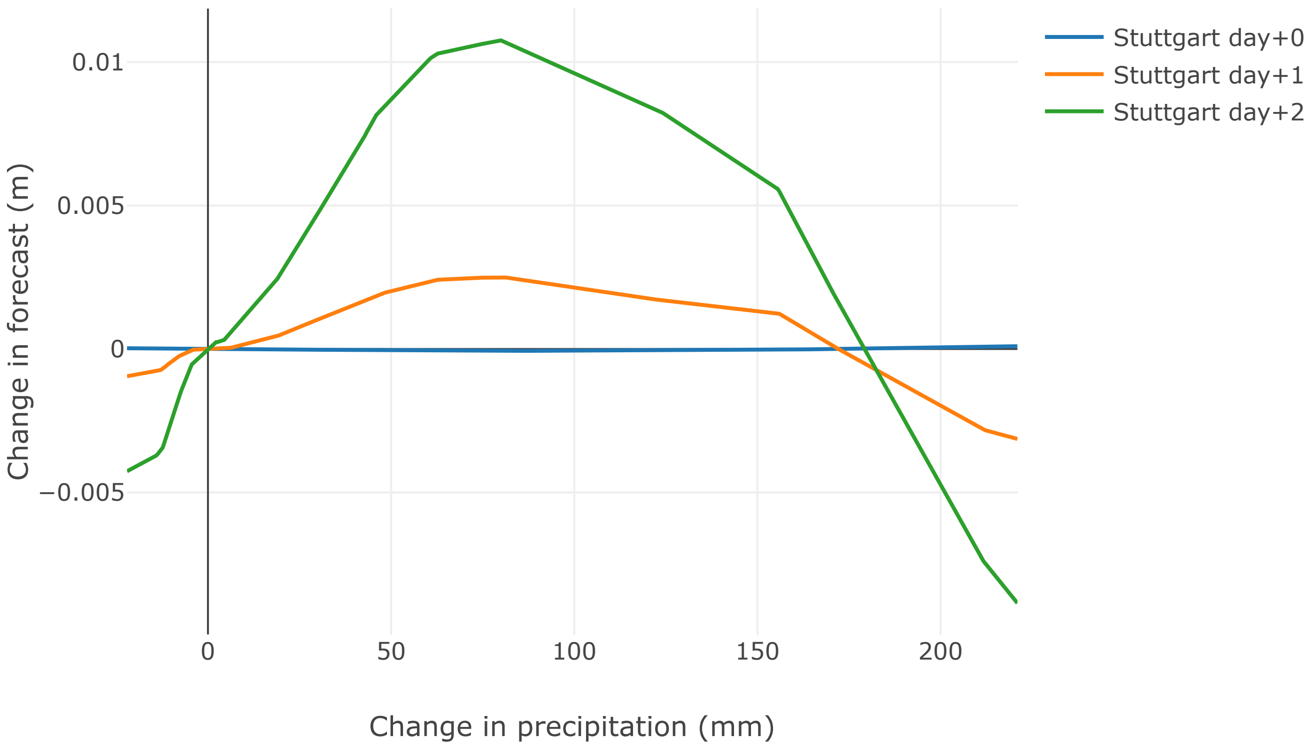

Figure 28: Sensitivity analysis for Stuttgart with average water levels and average precipitation

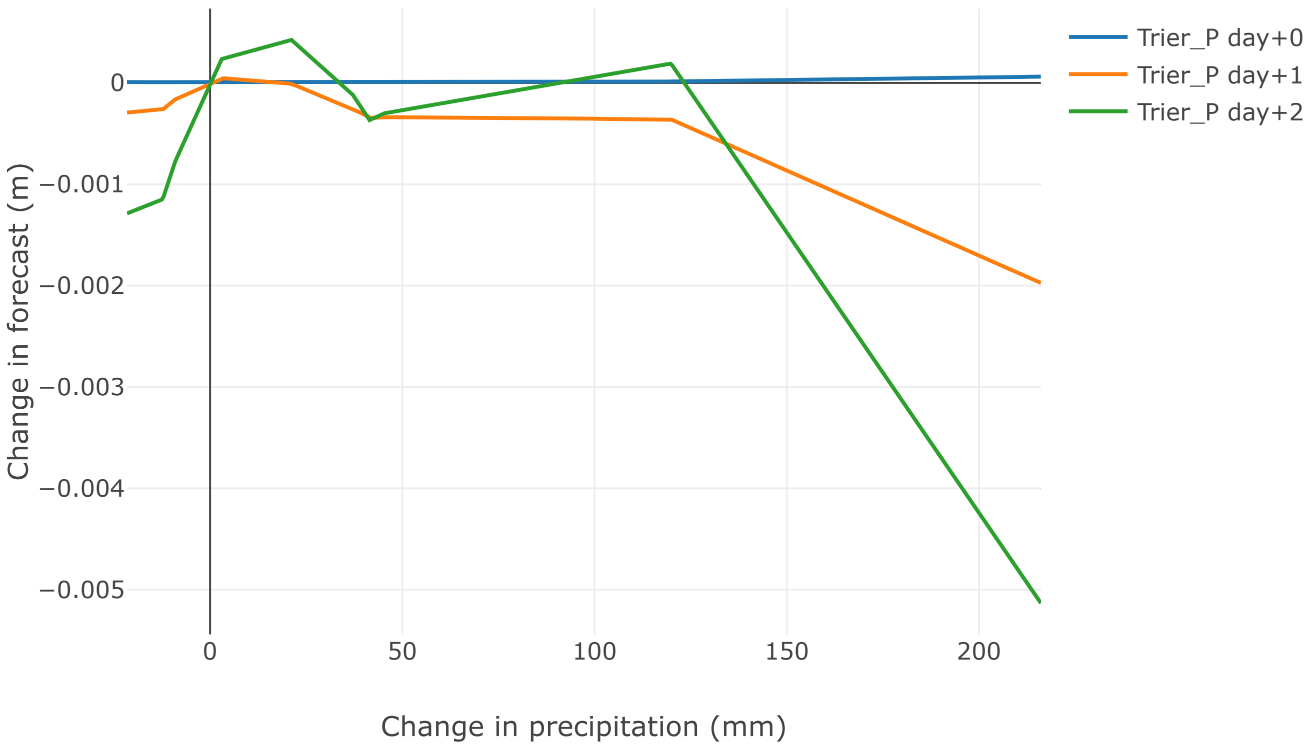

Figure 29: Sensitivity analysis for Trier (Precipitation) with average water levels and average precipitation

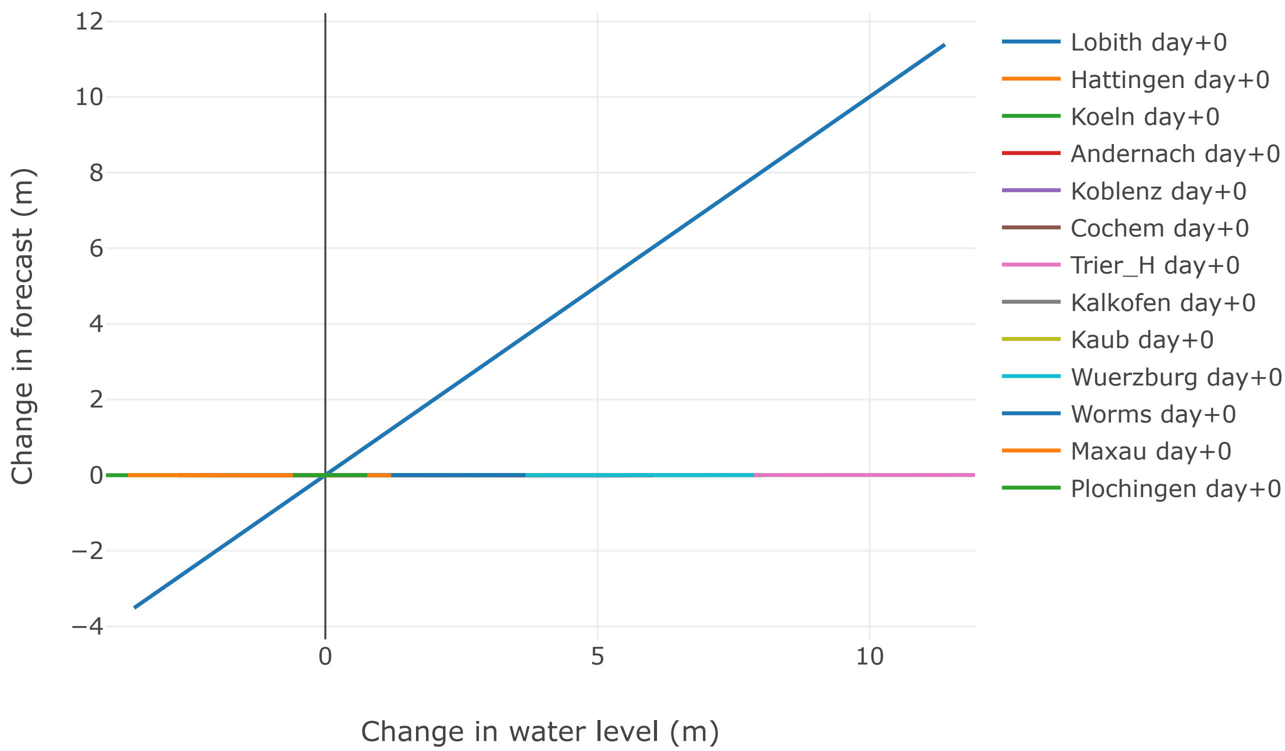

Figure 30: Sensitivity analysis for Water levels (day+0) with average water levels and average precipitation

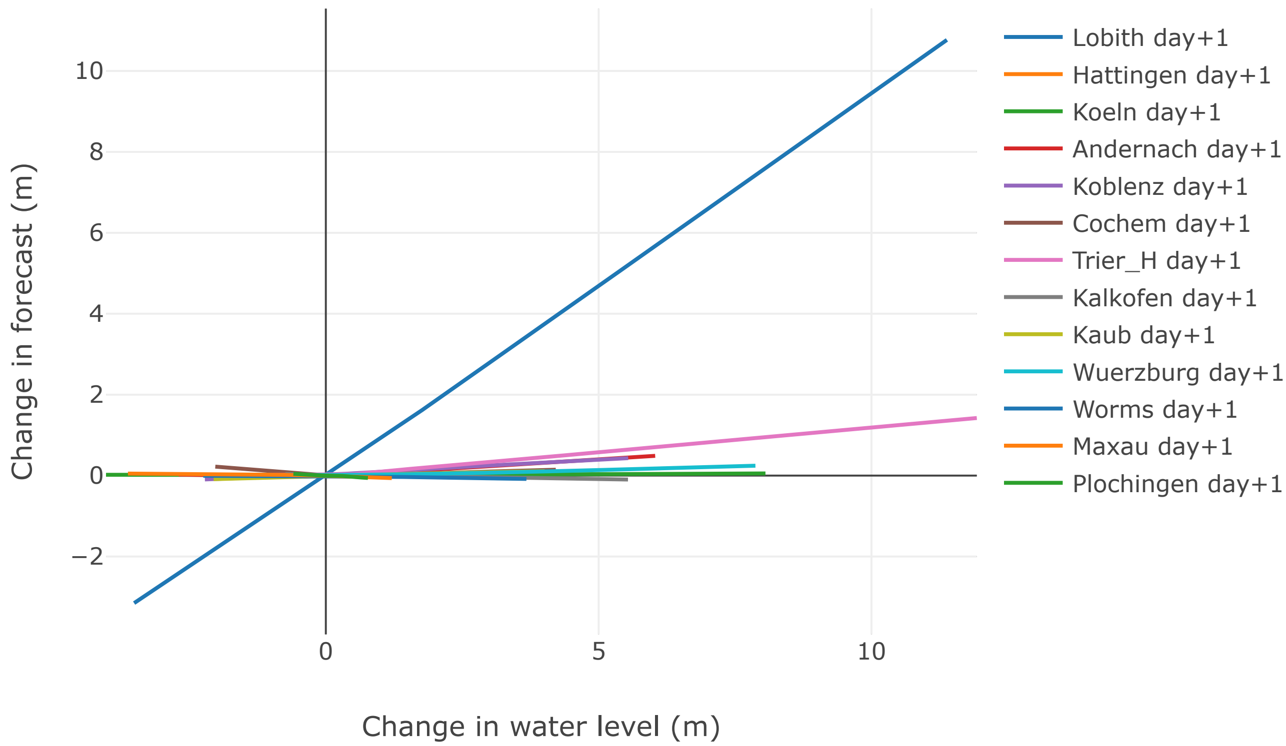

Figure 31: Sensitivity analysis for Water levels (day+1) with average water levels and average precipitation

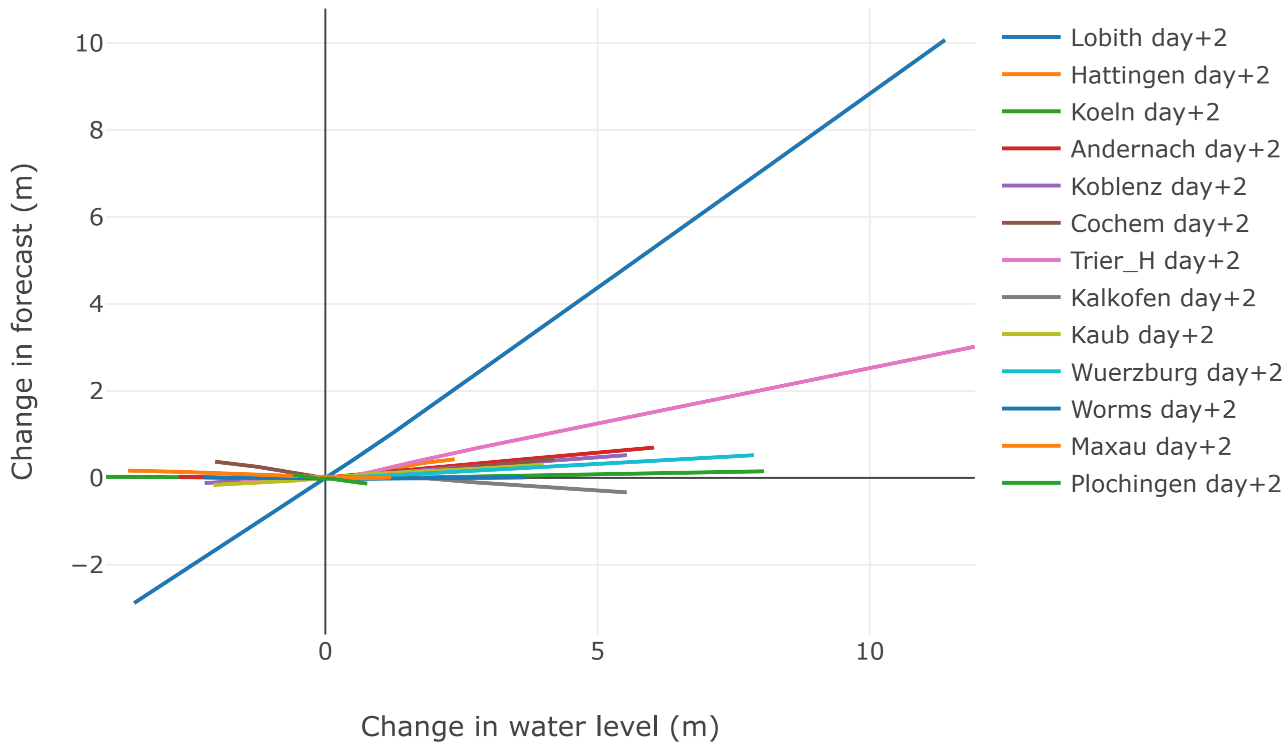

Figure 32: Sensitivity analysis for Water levels (day+2) with average water levels and average precipitation

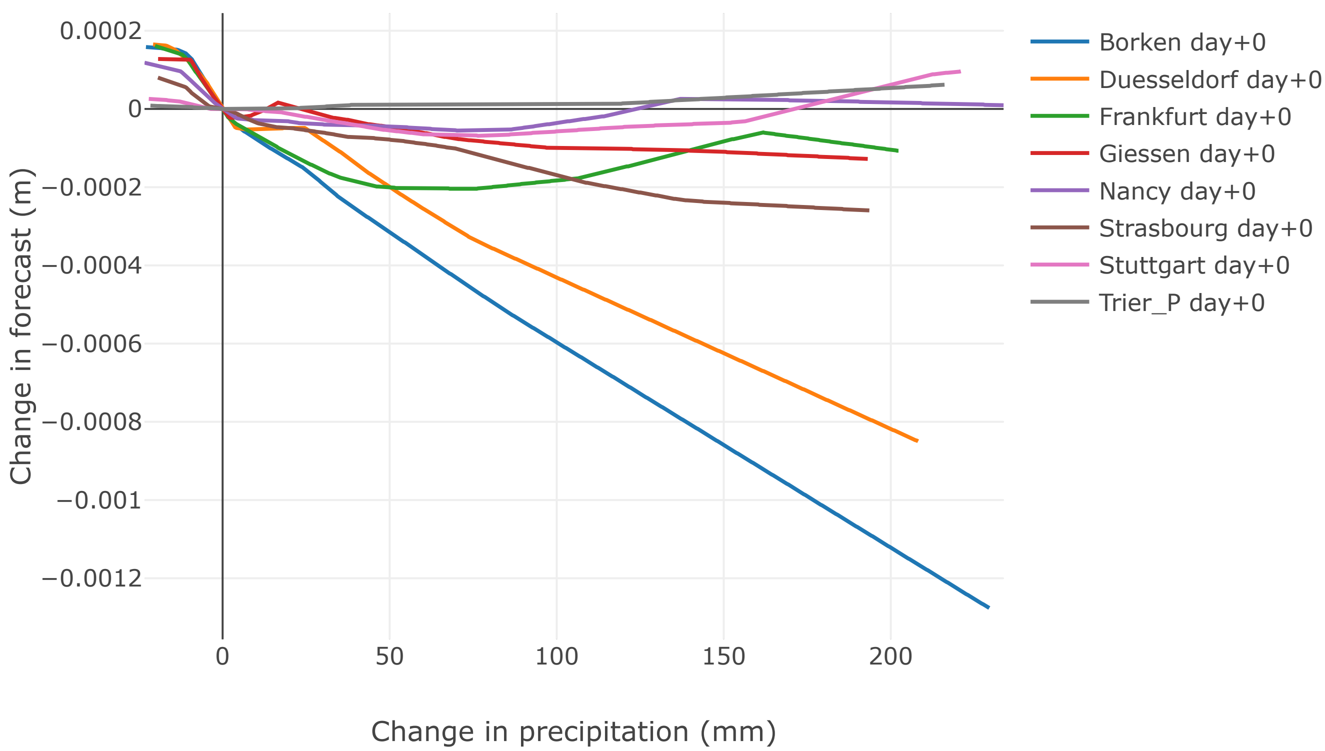

Figure 33: Sensitivity analysis for Precipitation (day+0) with average water levels and average precipitation

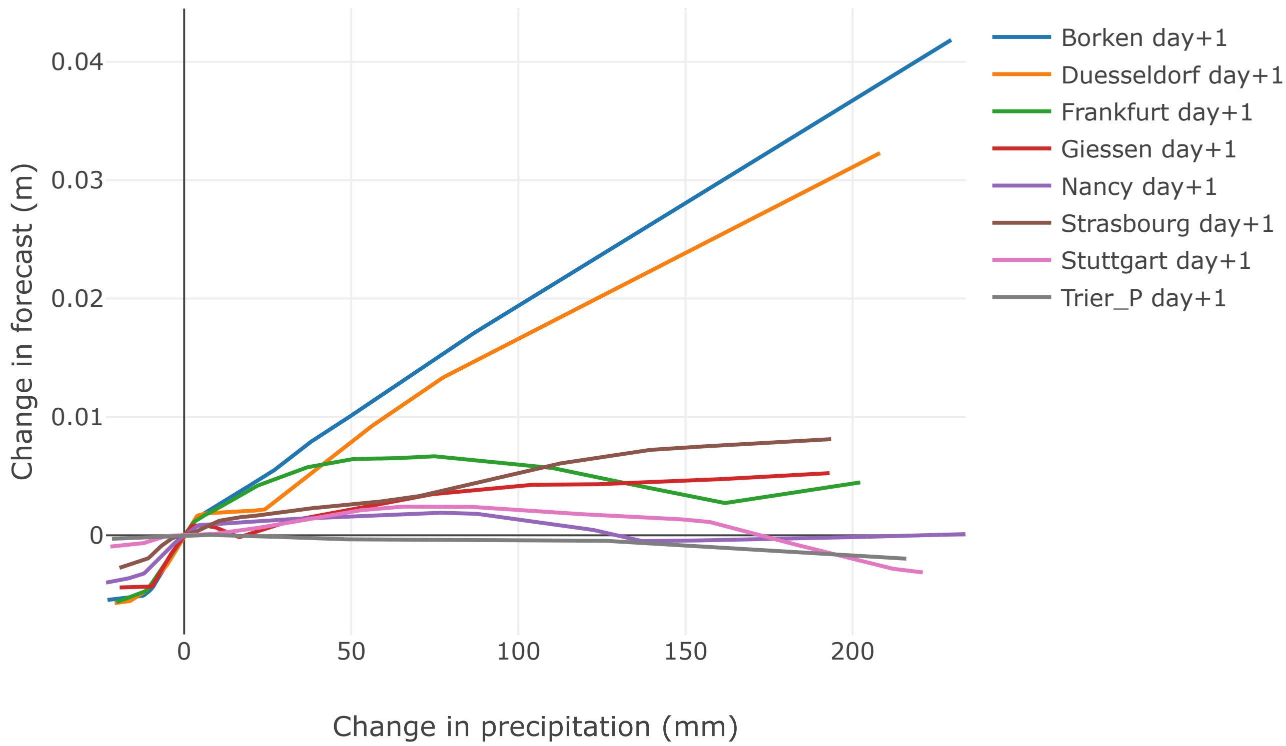

Figure 34: Sensitivity analysis for Precipitation (day+1) with average water levels and average precipitation

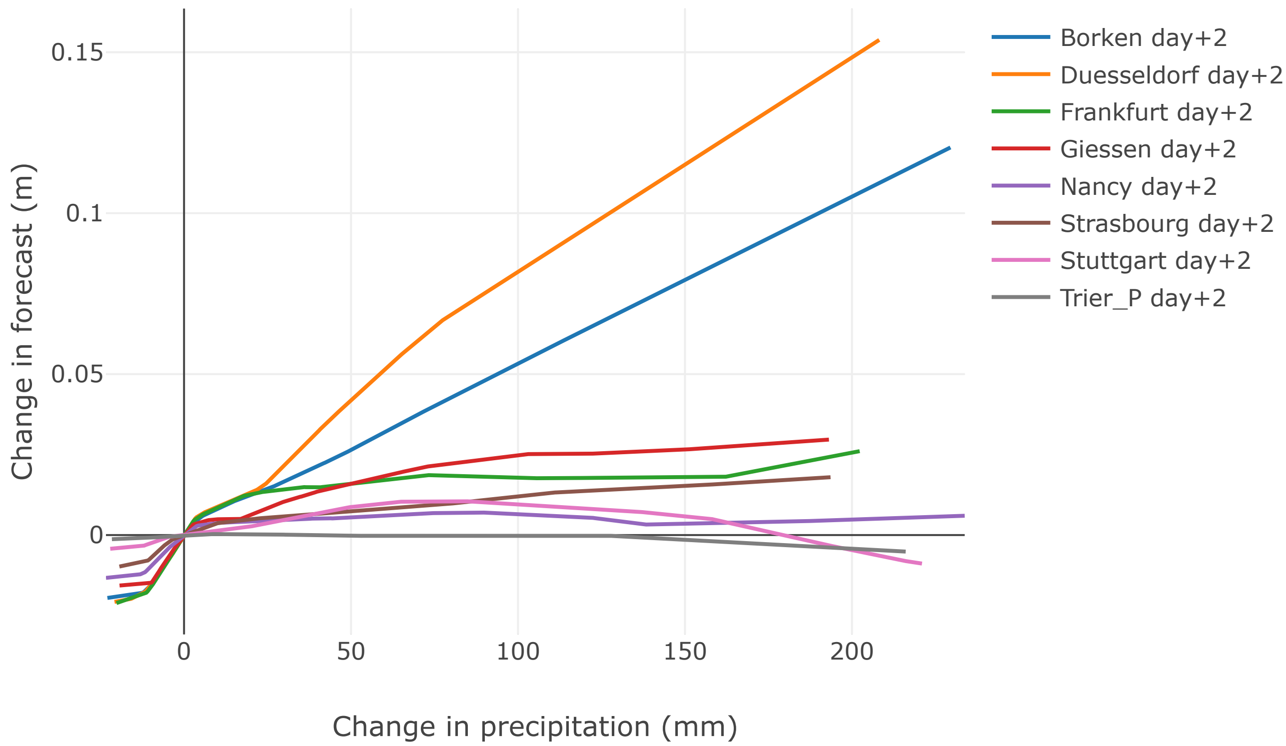

Figure 35: Sensitivity analysis for Precipitation (day+2) with average water levels and average precipitation

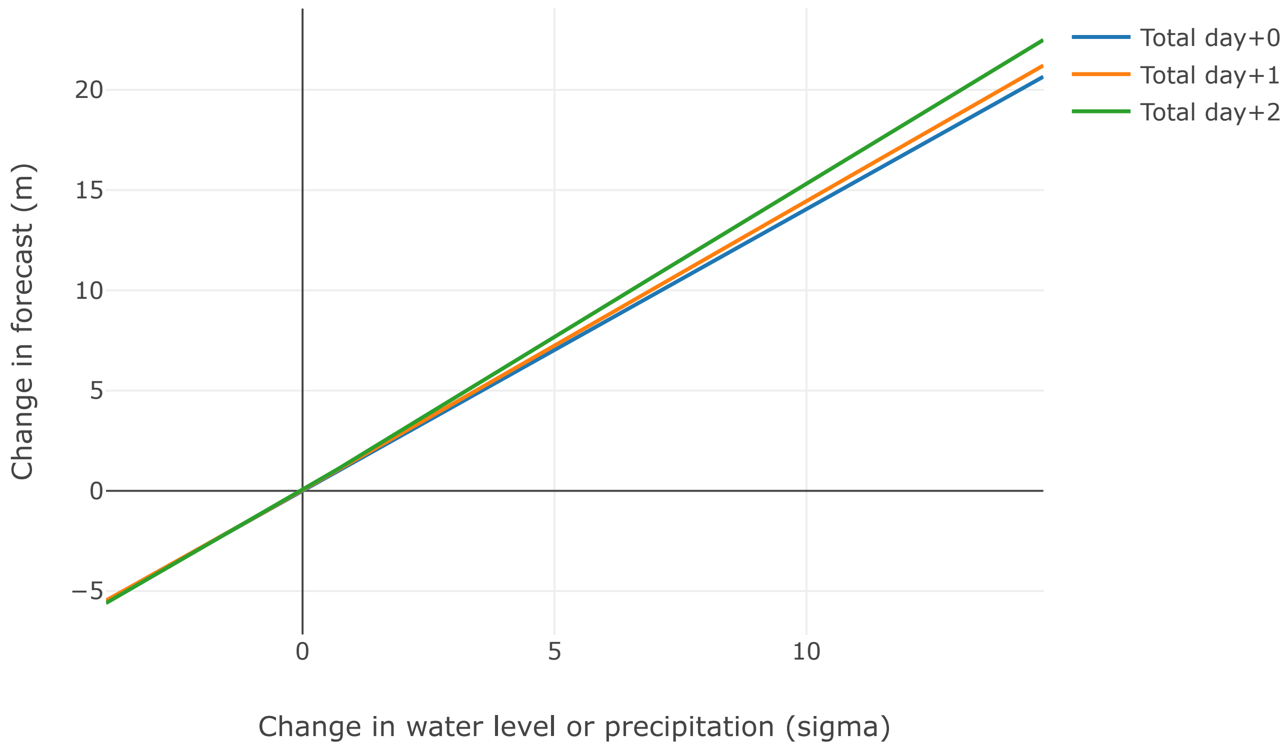

Figure 36: Sensitivity analysis for Total with average water levels and average precipitation

A.3 Extremely low water levels and no precipitation

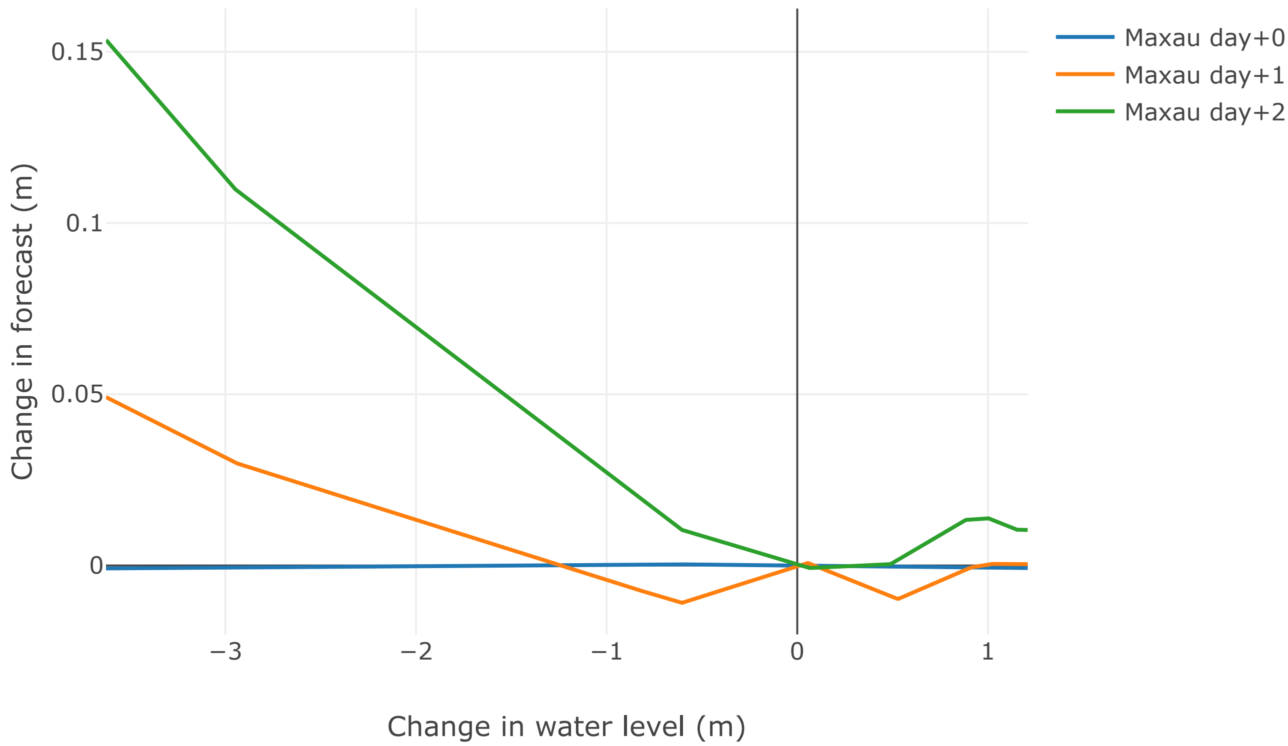

Figure 37: Sensitivity analysis for Maxau with extremely low water levels and no precipitation

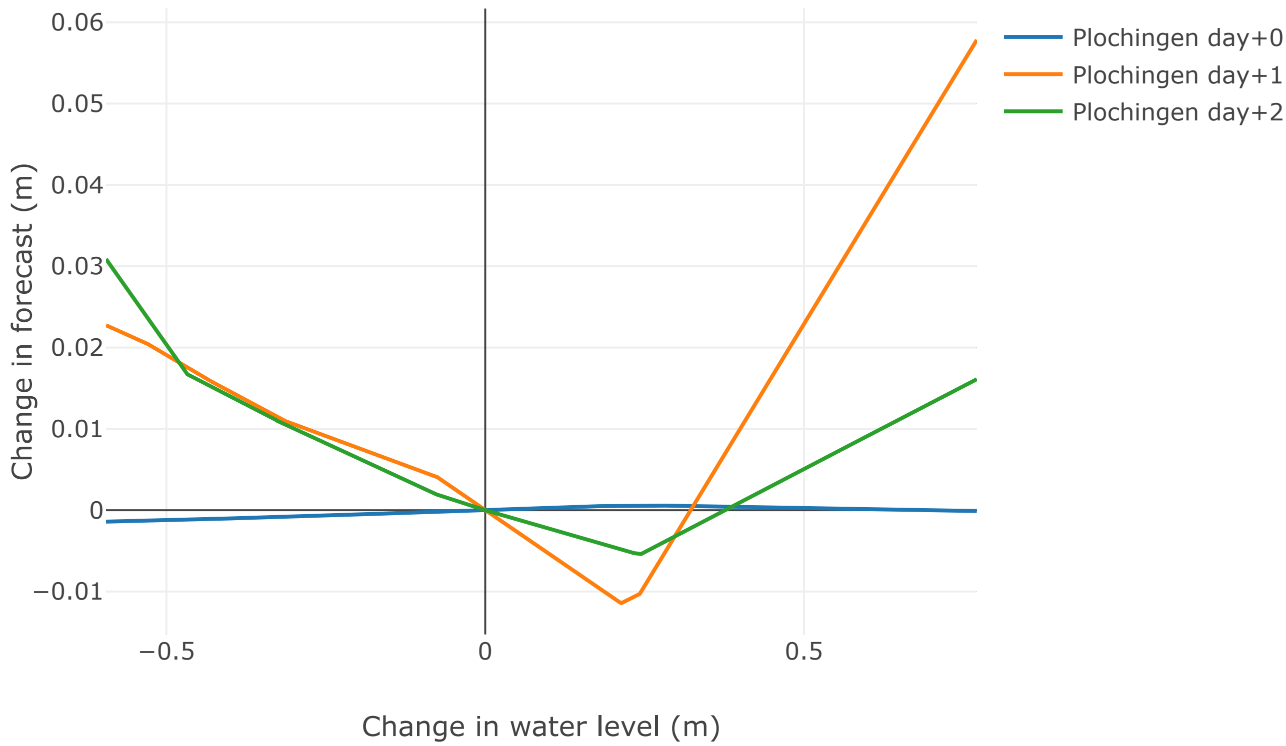

Figure 38: Sensitivity analysis for Plochingen with extremely low water levels and no precipitation

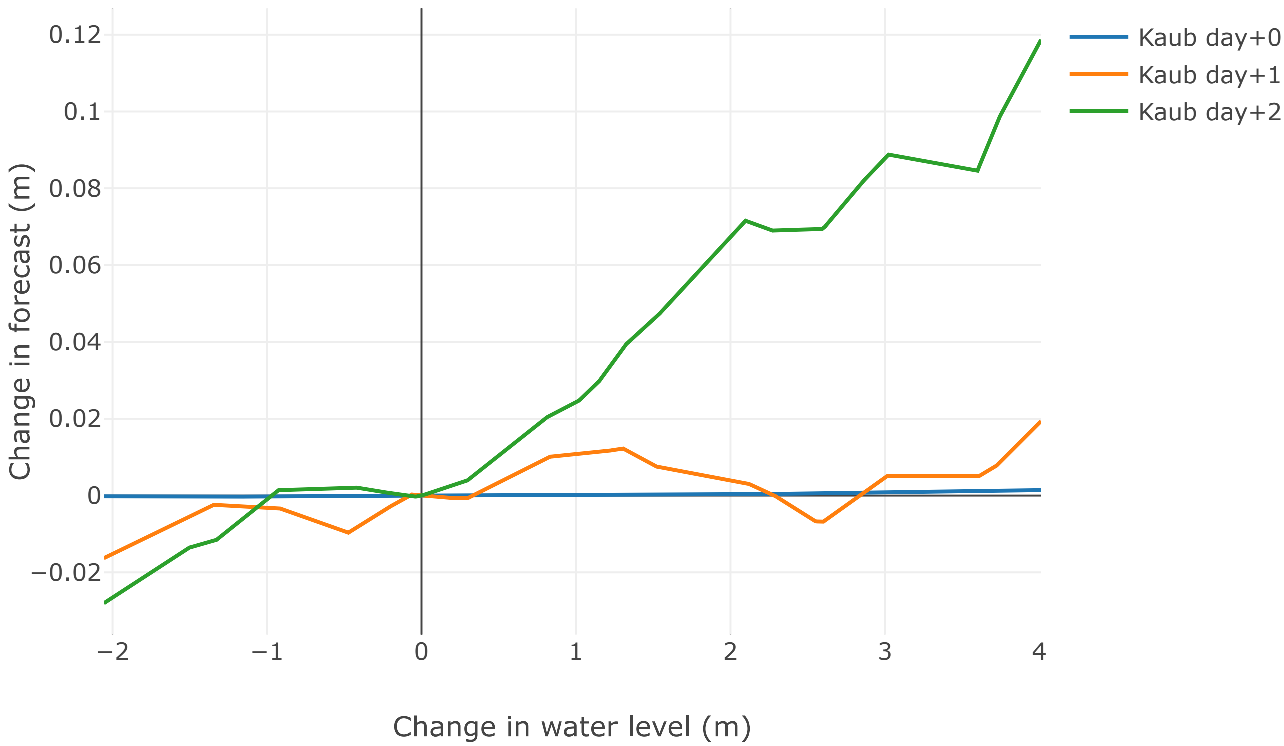

Figure 39: Sensitivity analysis for Kaub with extremely low water levels and no precipitation

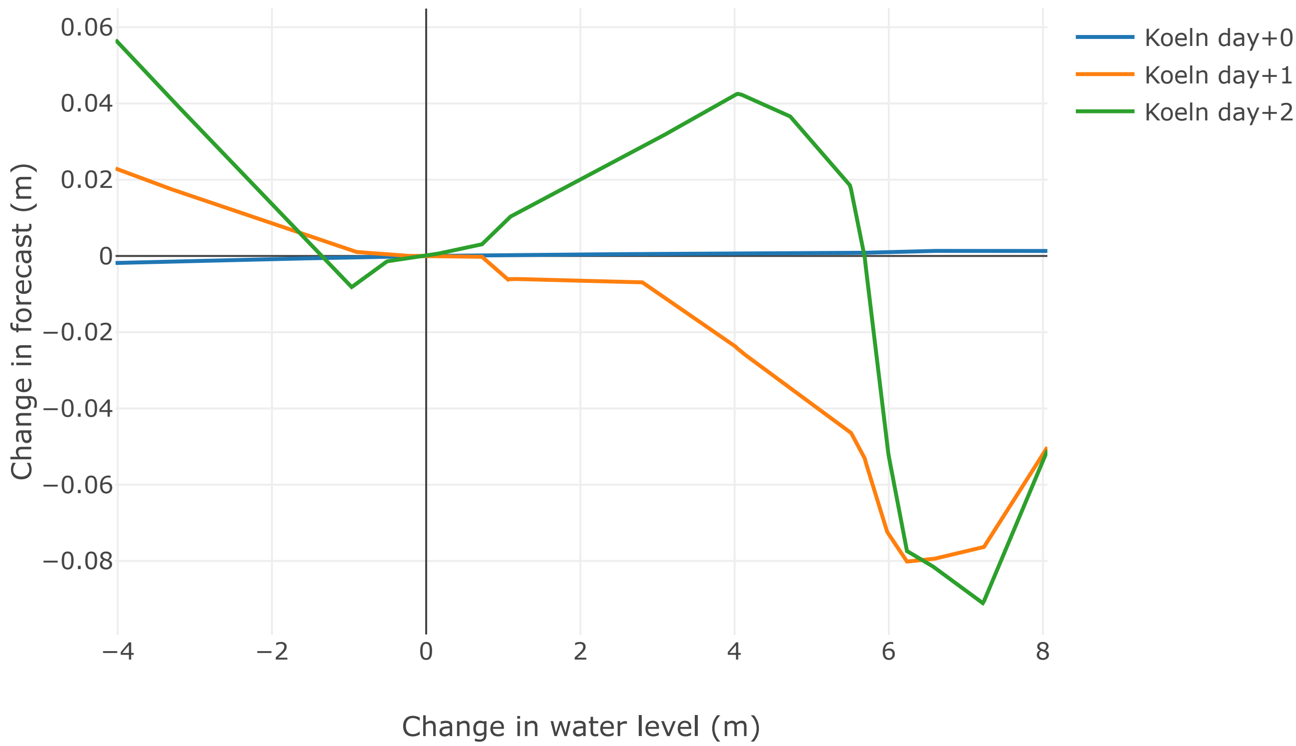

Figure 40: Sensitivity analysis for Köln with extremely low water levels and no precipitation

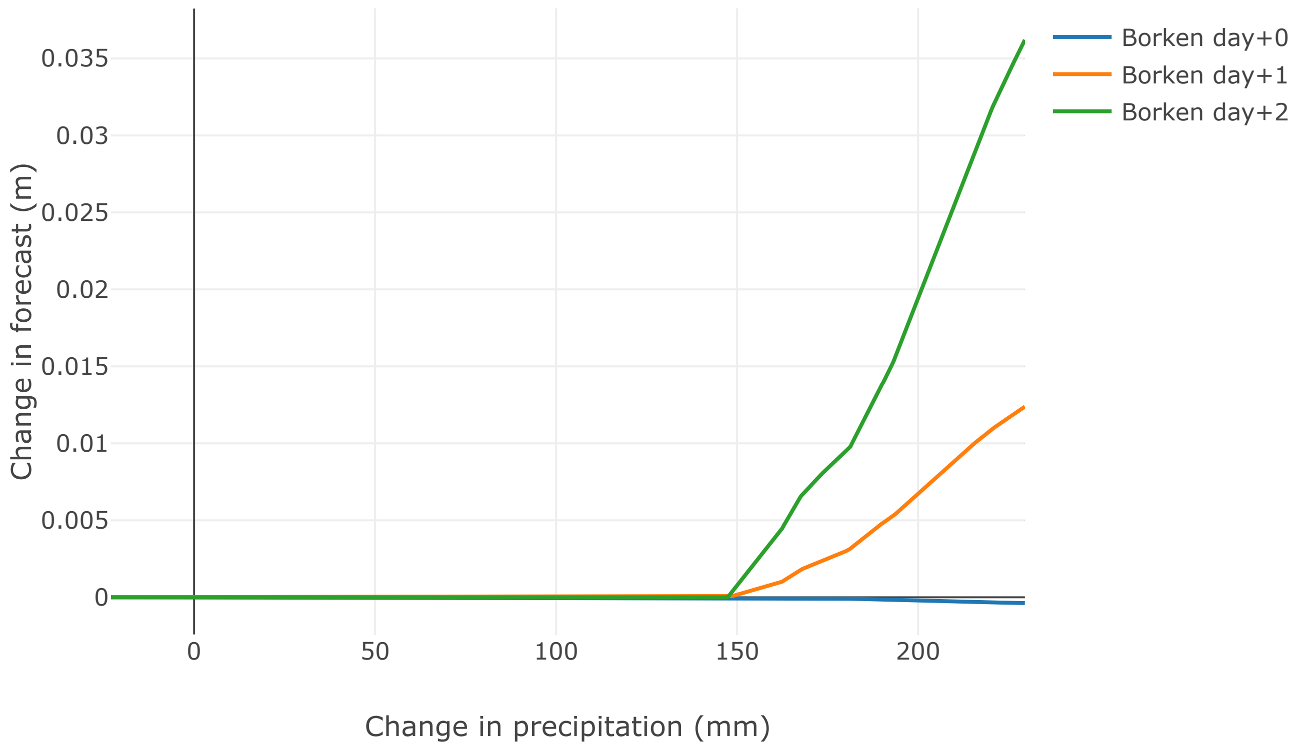

Figure 41: Sensitivity analysis for Borken with extremely low water levels and no precipitation

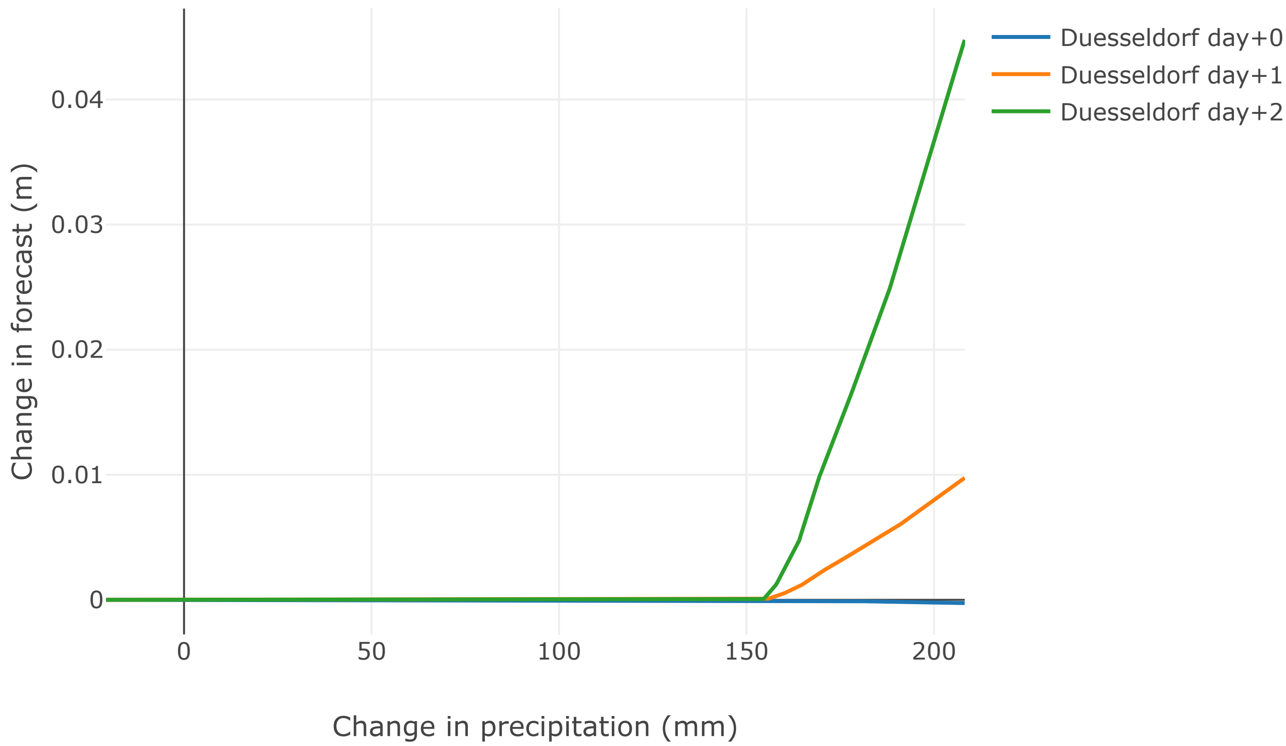

Figure 42: Sensitivity analysis for Düsseldorf with extremely low water levels and no precipitation

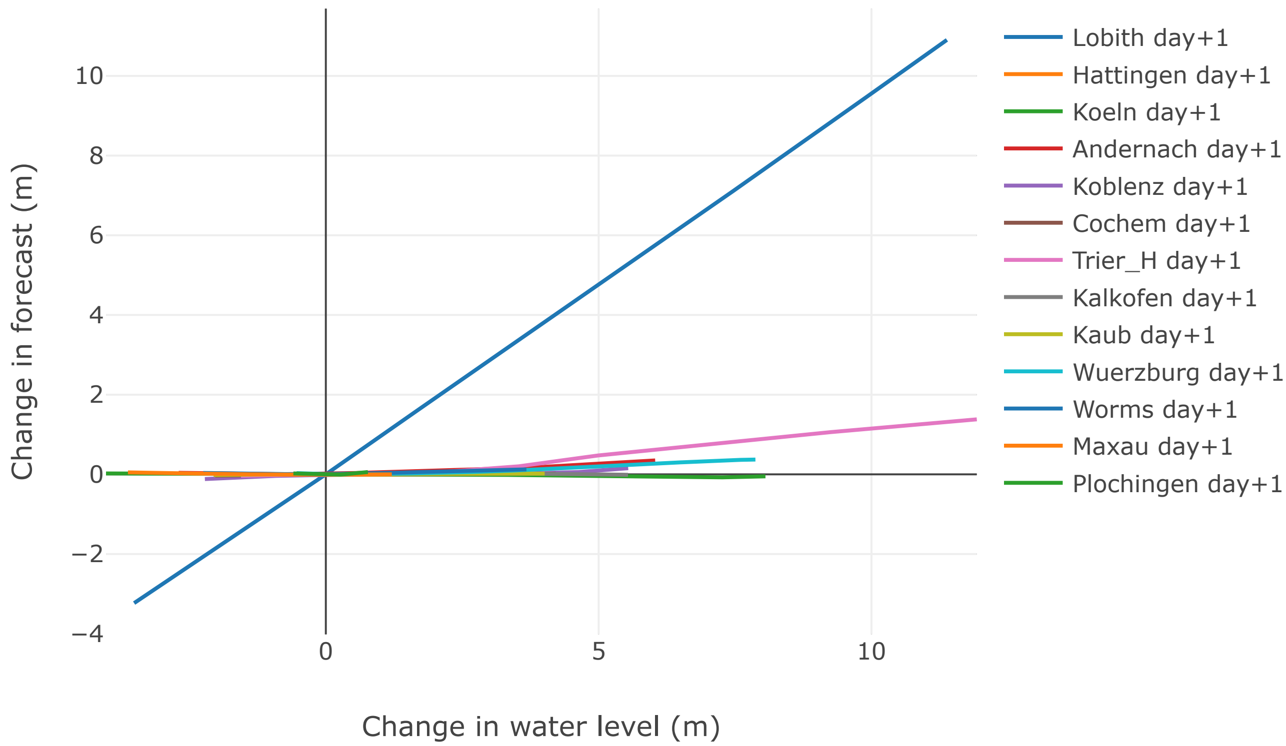

Figure 43: Sensitivity analysis for Water levels (day+1) with extremely low water levels and no precipitation

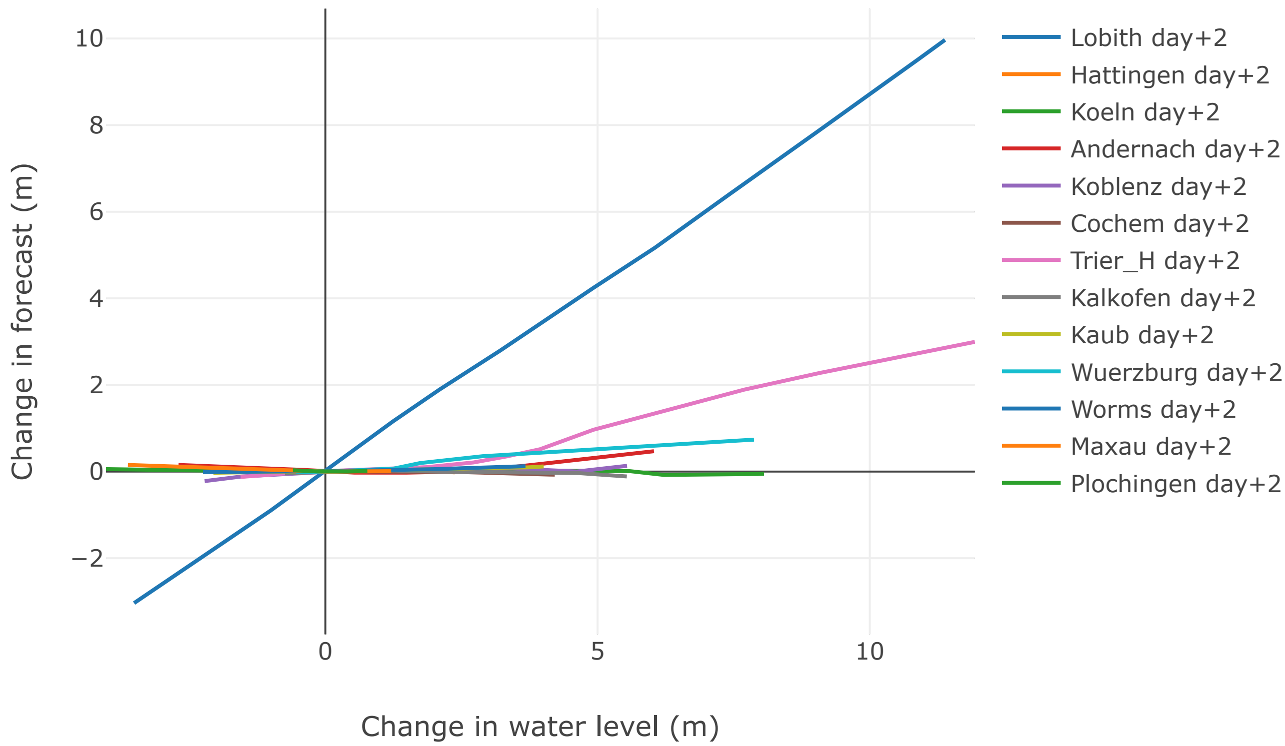

Figure 44: Sensitivity analysis for Water levels (day+2) with extremely low water levels and no precipitation

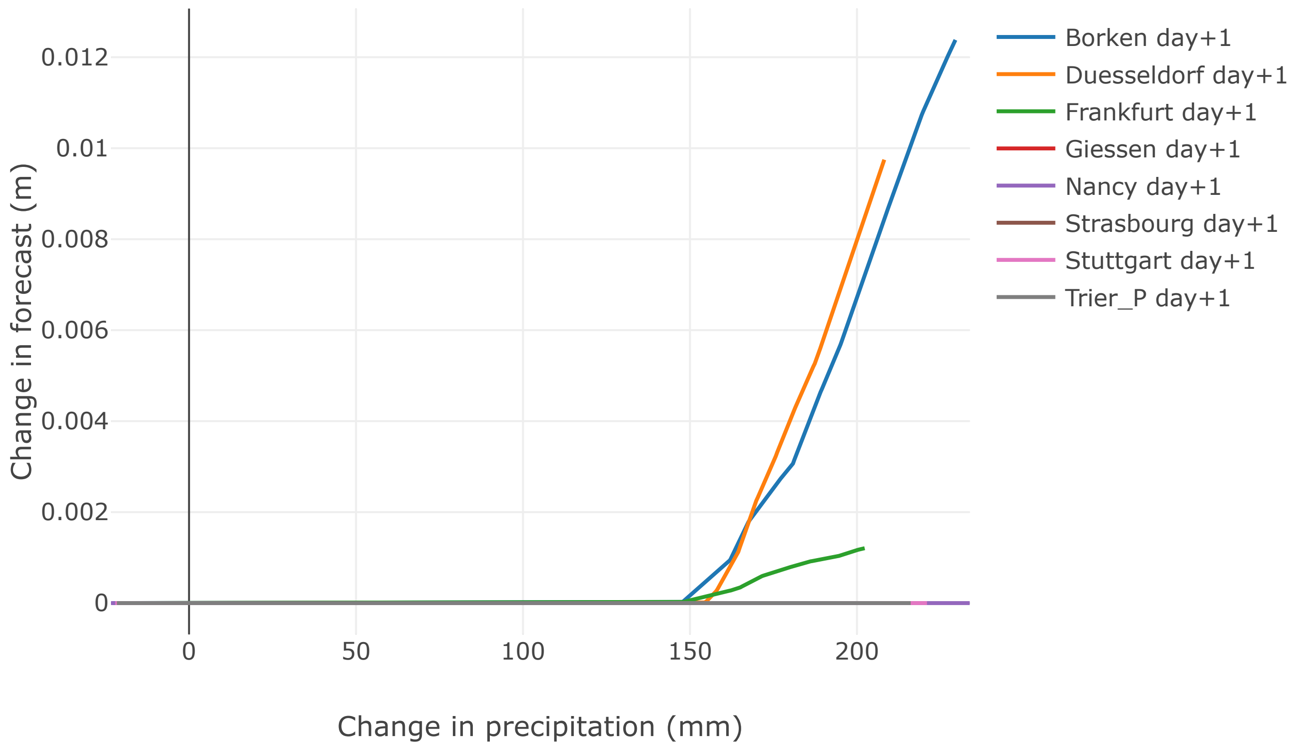

Figure 45: Sensitivity analysis for Precipitation (day+1) with extremely low water levels and no precipitation

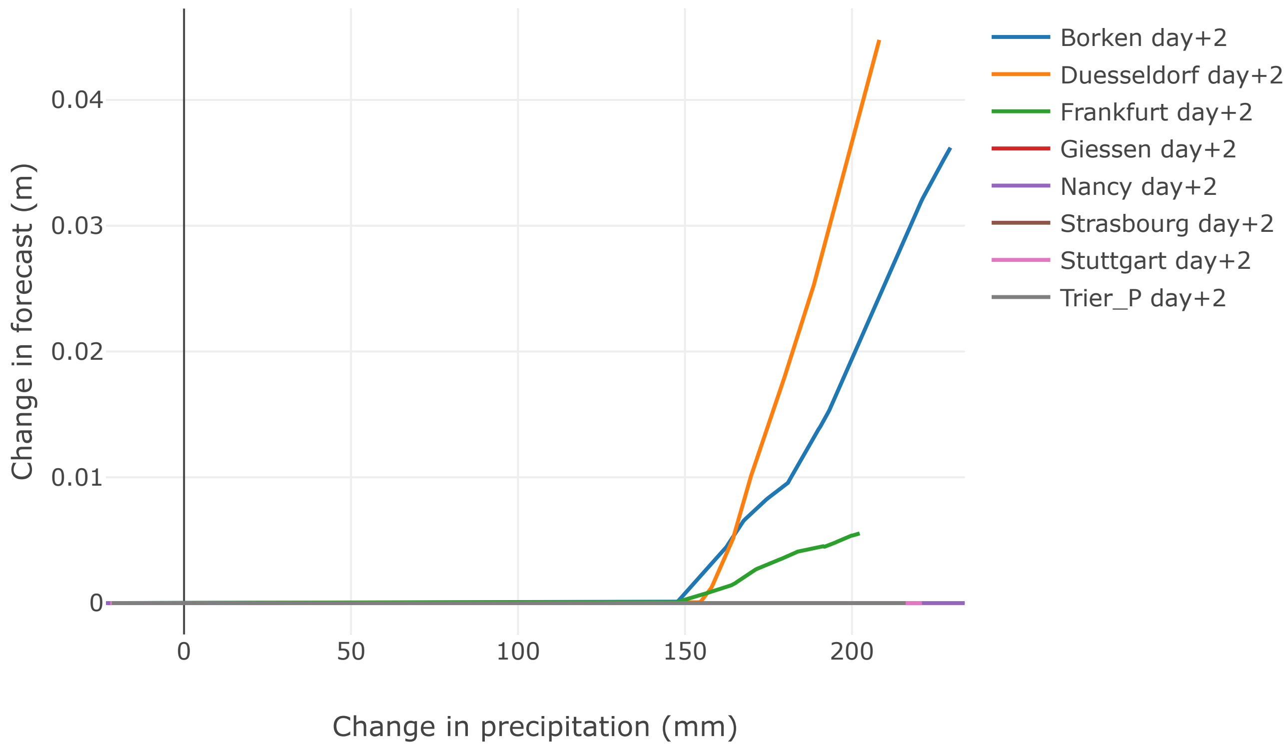

Figure 46: Sensitivity analysis for Precipitation (day+2) with extremely low water levels and no precipitation

A.4 Low water levels and no precipitation

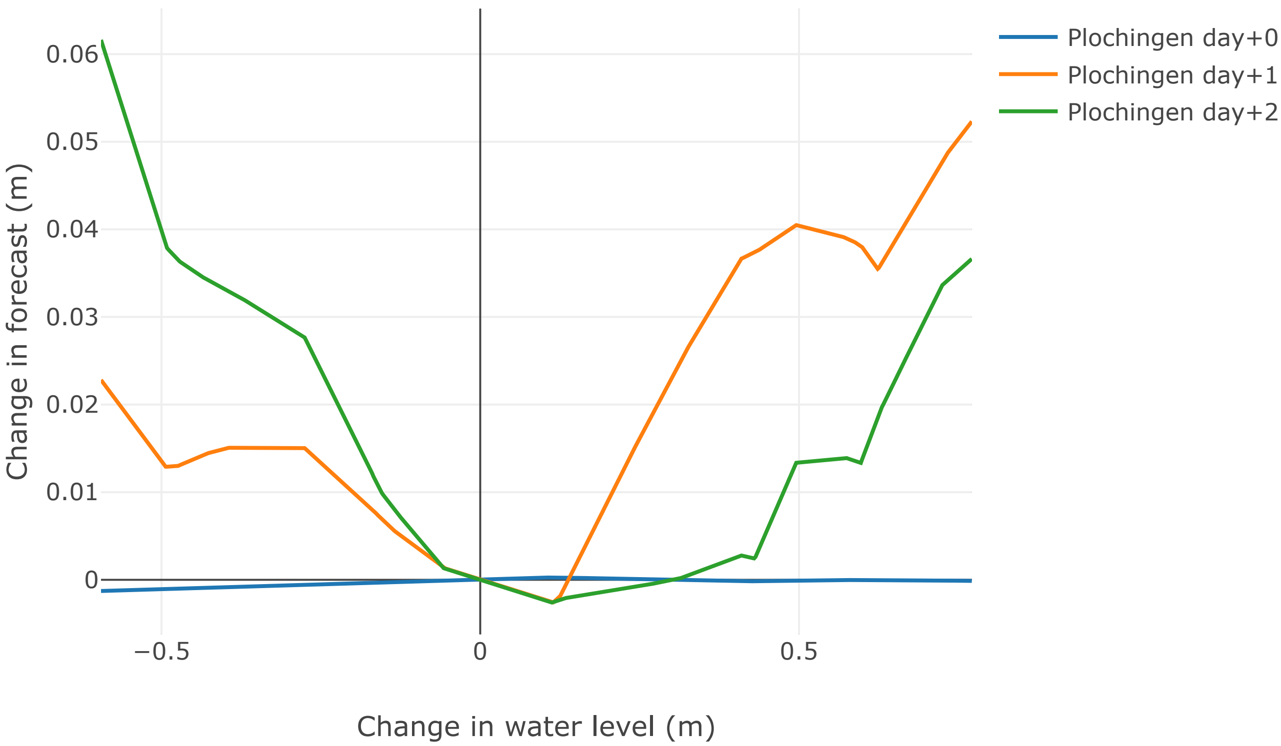

Figure 47: Sensitivity analysis for Plochingen with low water levels and no precipitation

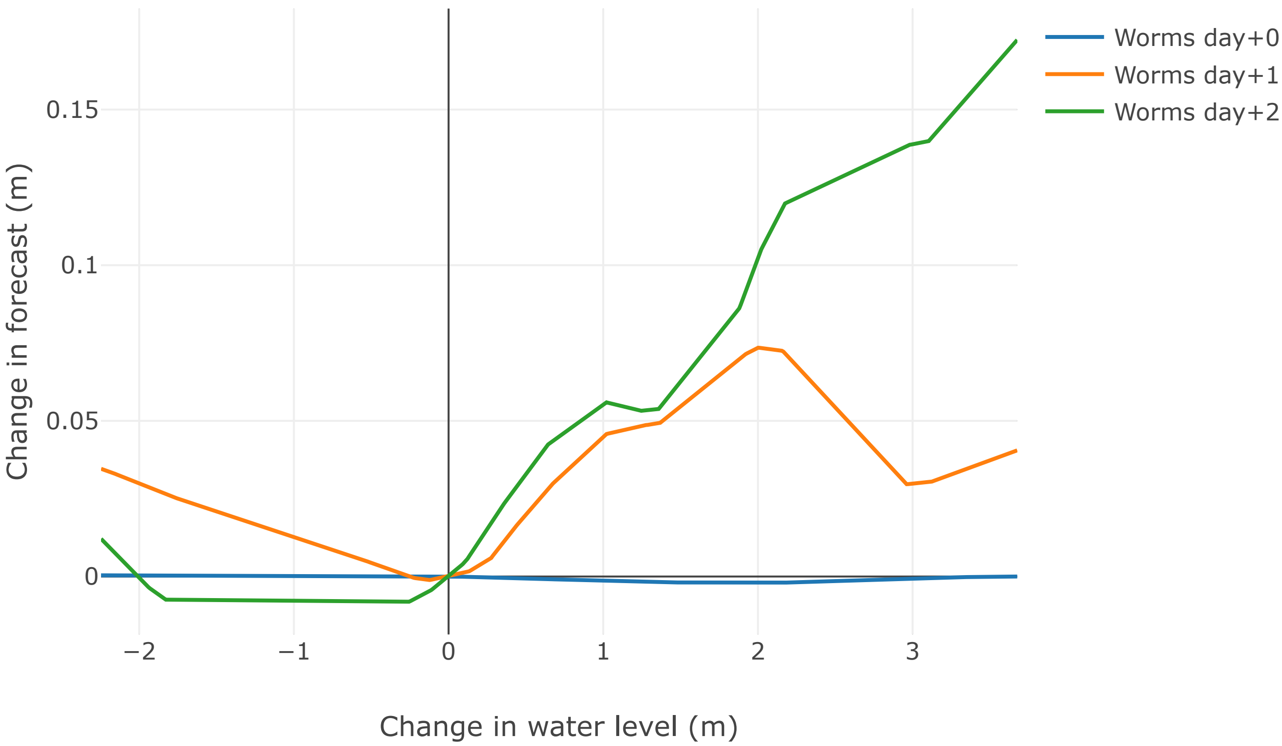

Figure 48: Sensitivity analysis for Worms with low water levels and no precipitation

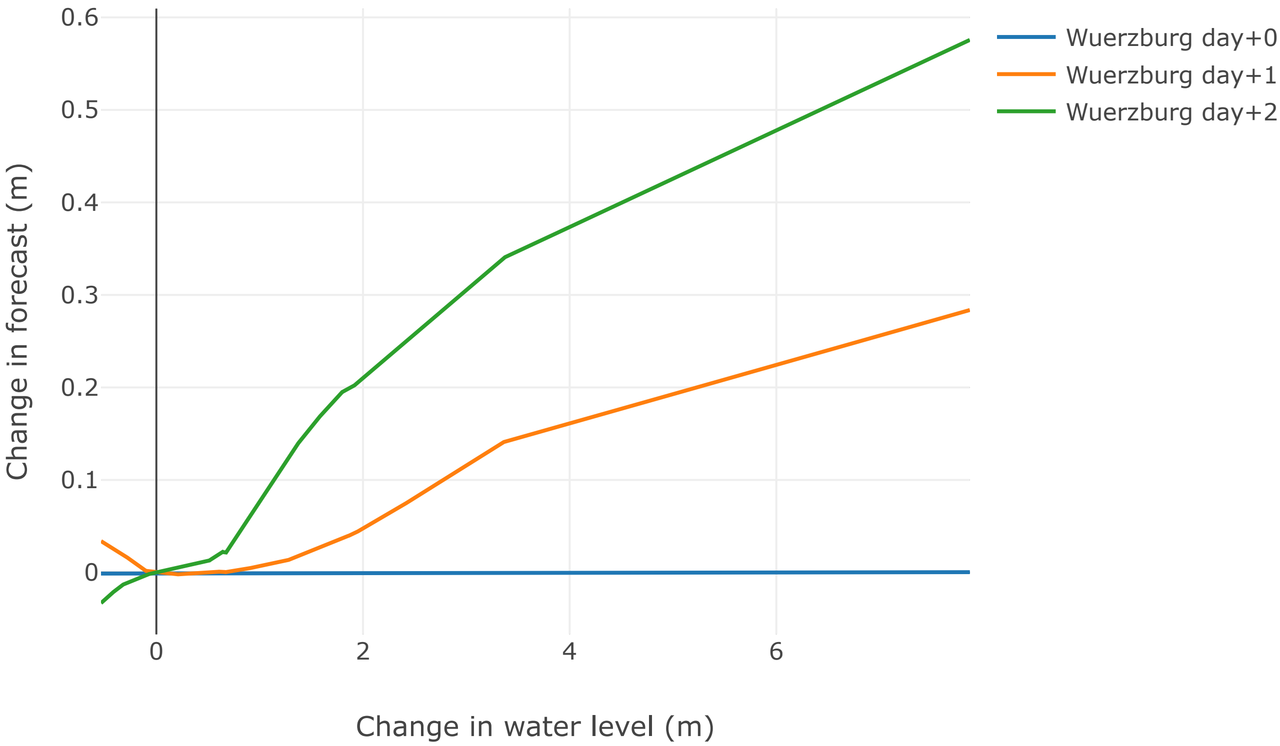

Figure 49: Sensitivity analysis for Würzburg with low water levels and no precipitation

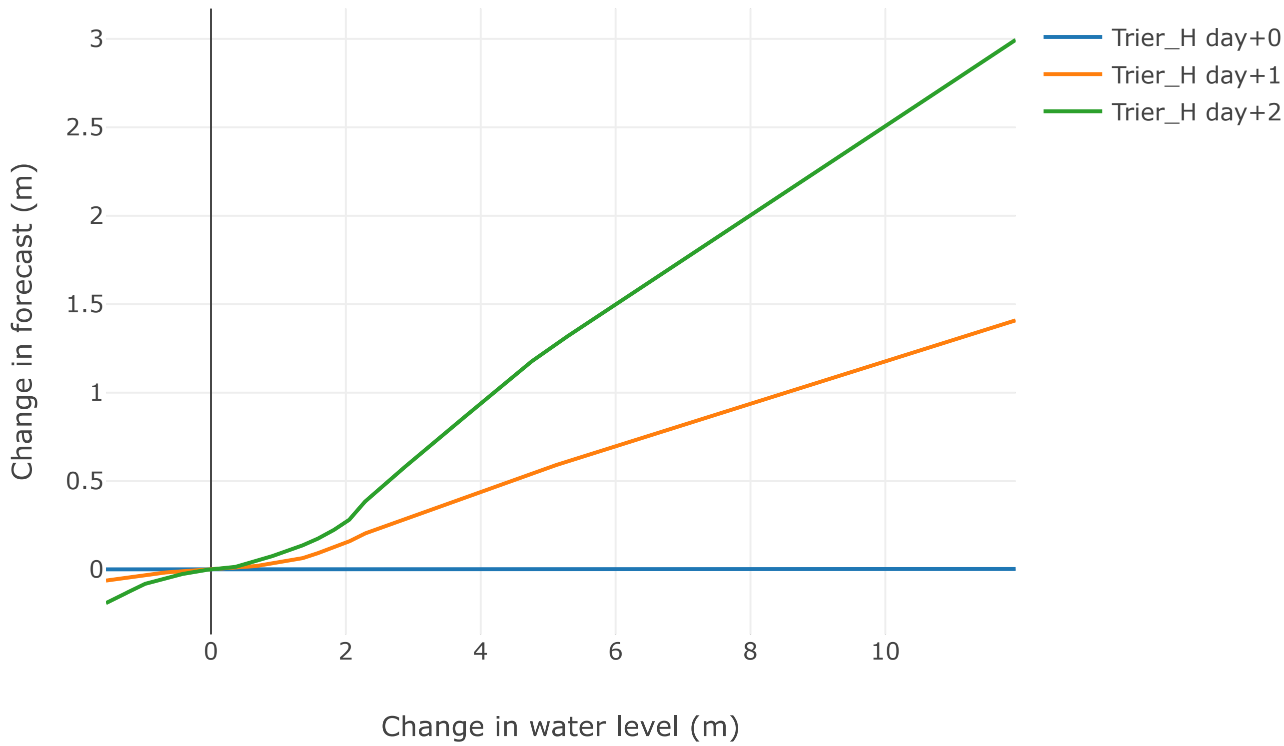

Figure 50: Sensitivity analysis for Trier (Water levels) with low water levels and no precipitation

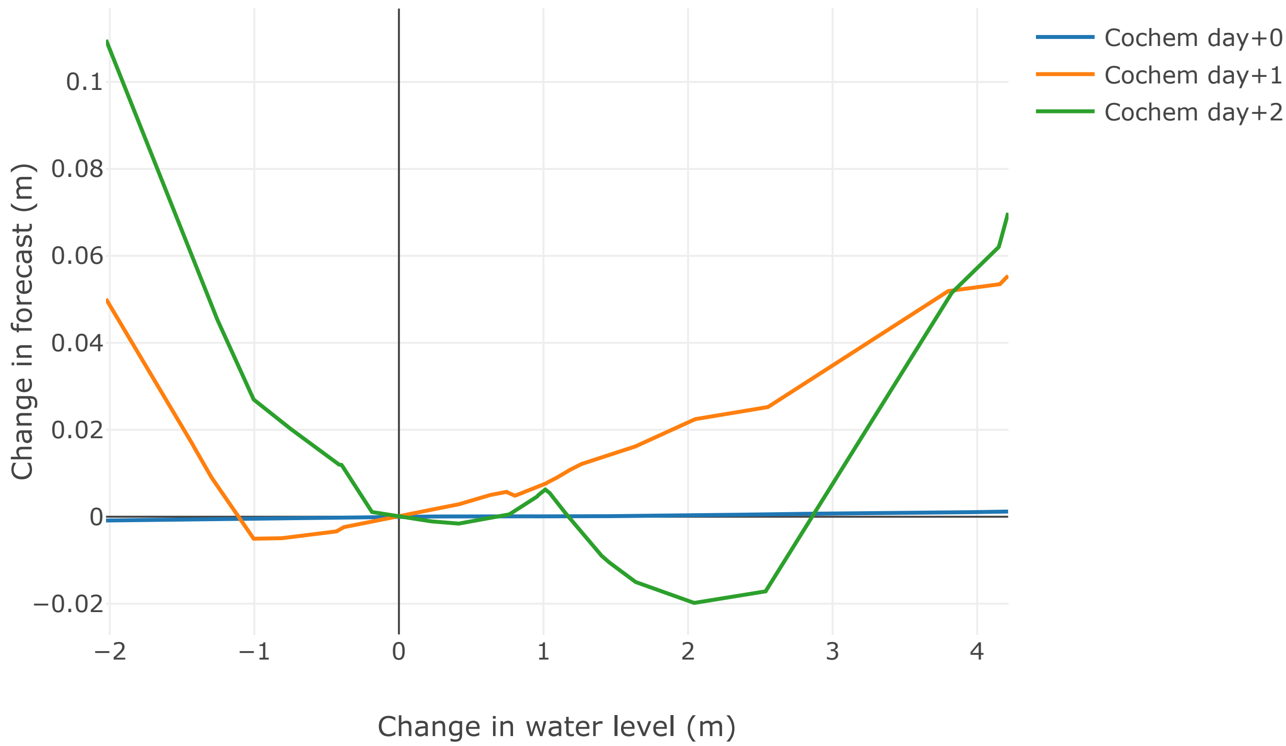

Figure 51: Sensitivity analysis for Cochem with low water levels and no precipitation

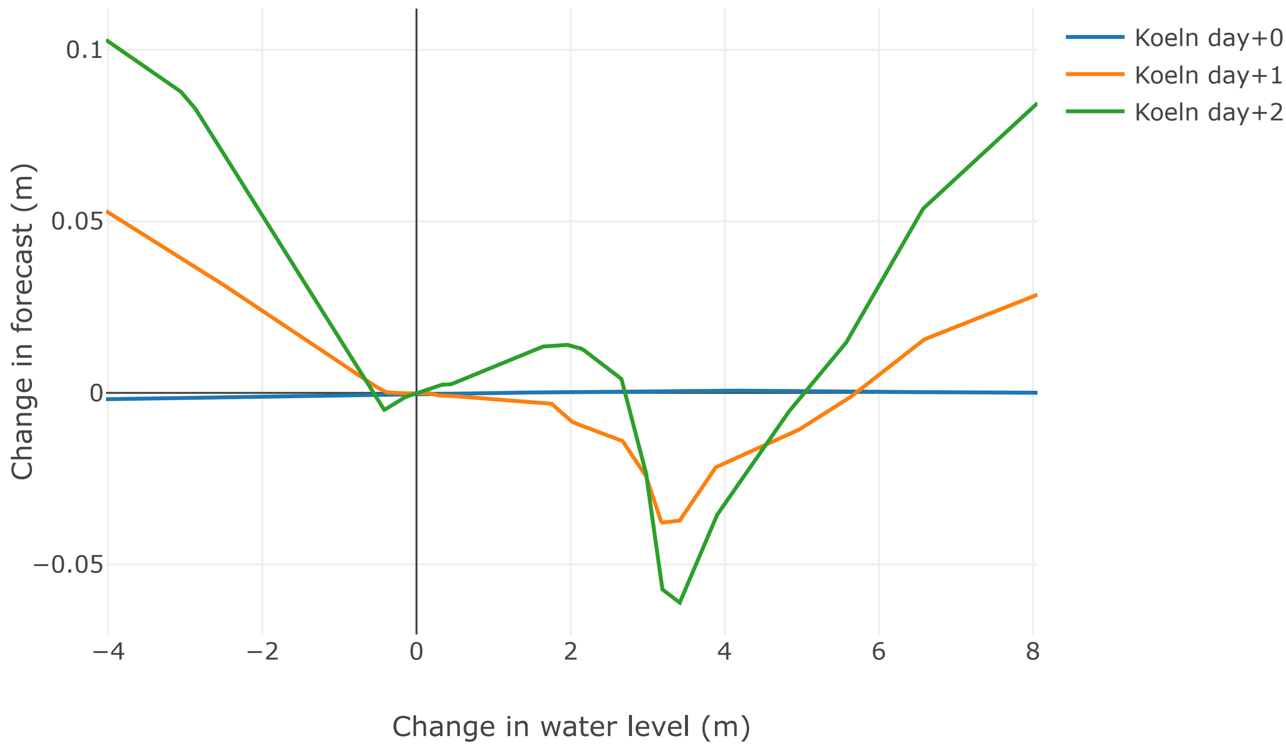

Figure 52: Sensitivity analysis for Köln with low water levels and no precipitation

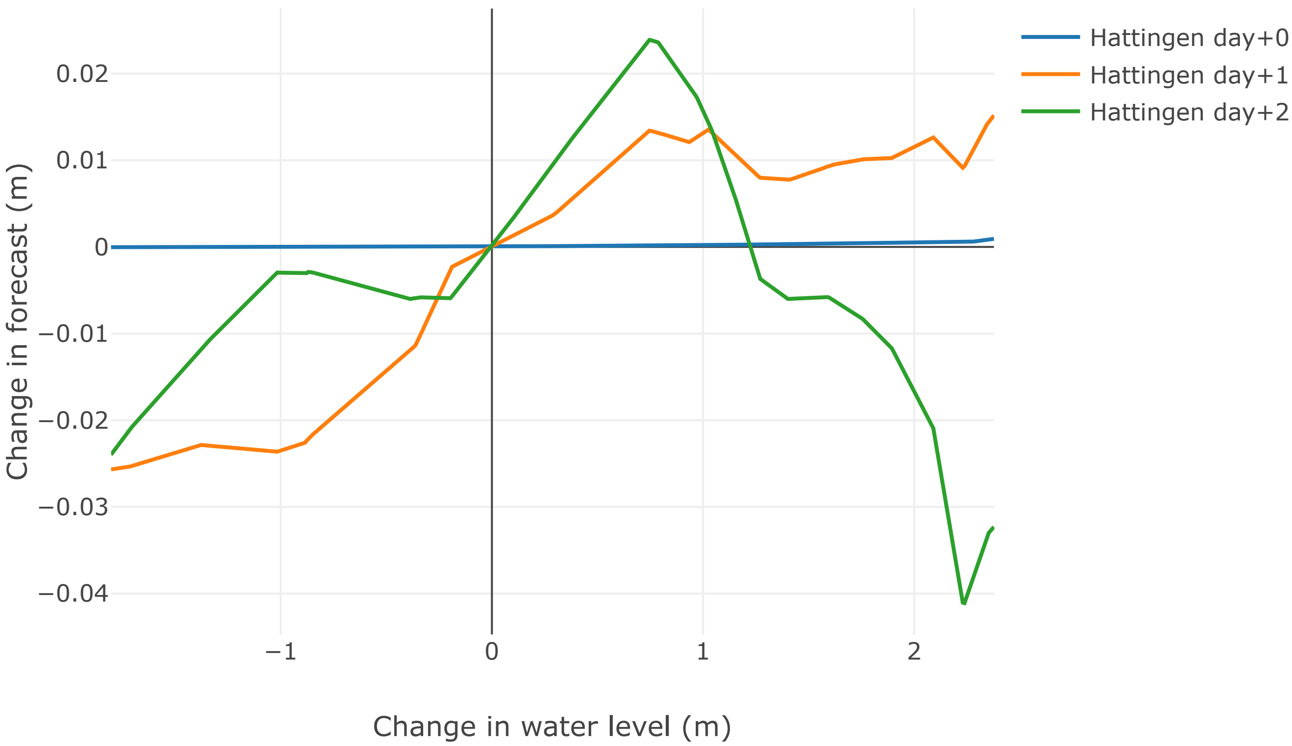

Figure 53: Sensitivity analysis for Hattingen with low water levels and no precipitation

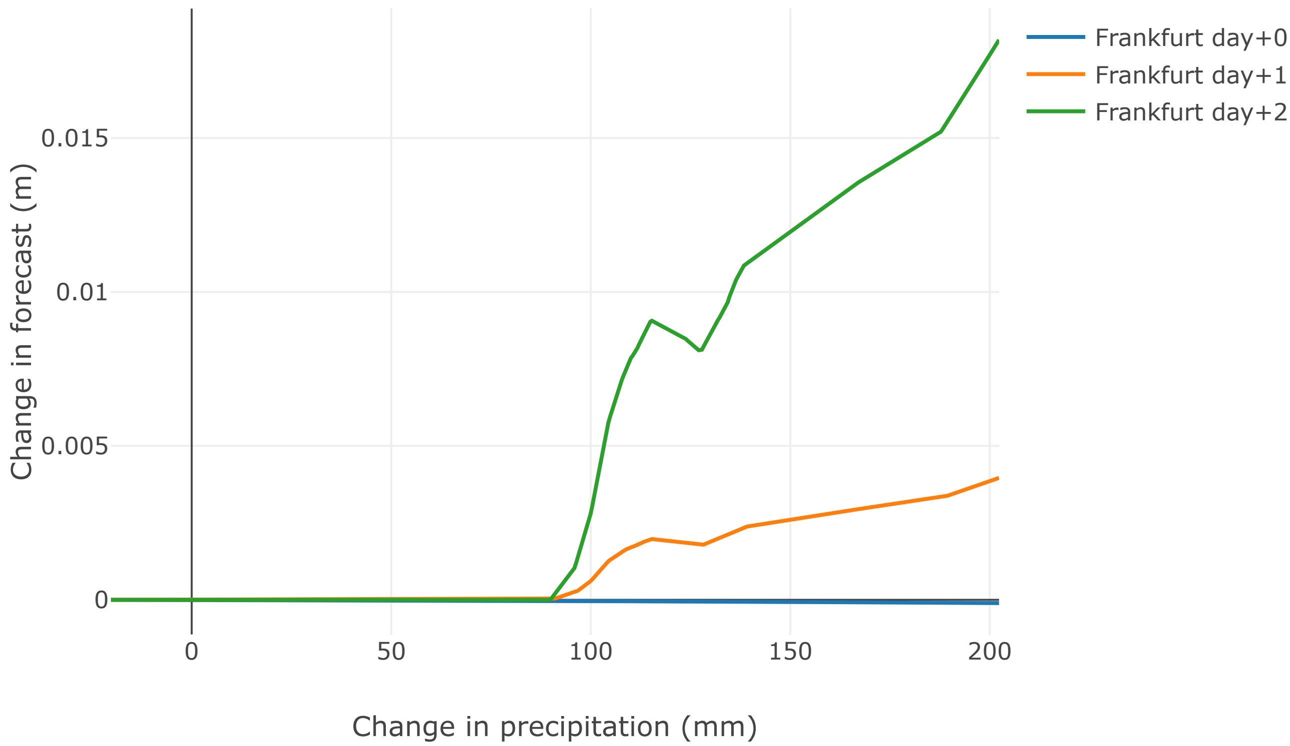

Figure 54: Sensitivity analysis for Frankfurt with low water levels and no precipitation

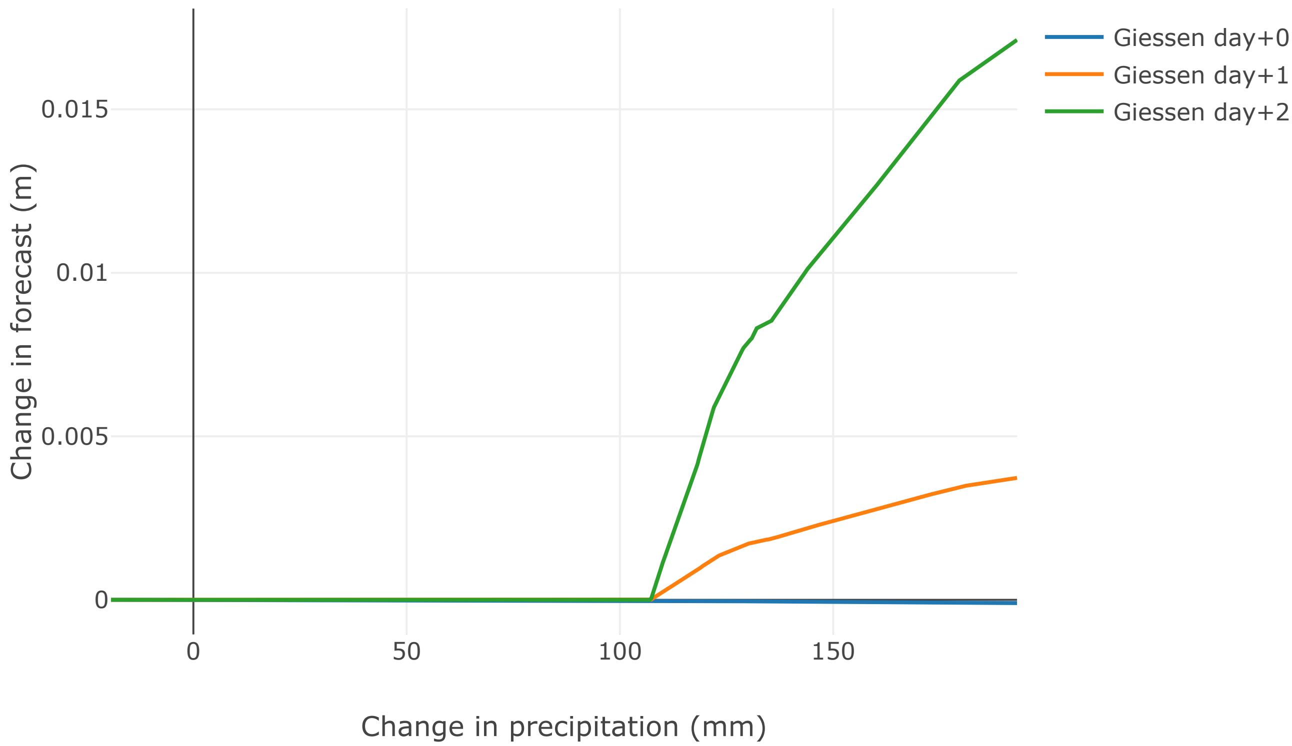

Figure 55: Sensitivity analysis for Giessen with low water levels and no precipitation

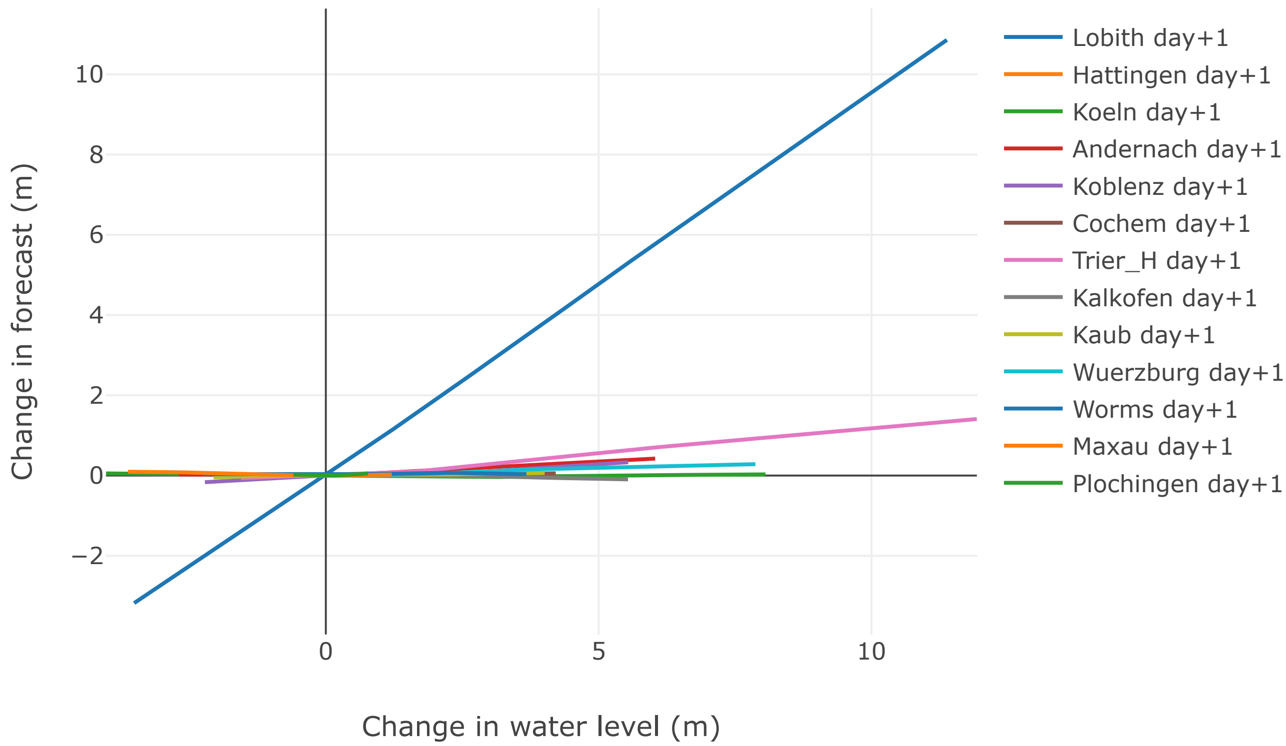

Figure 56: Sensitivity analysis for Water levels (day+1) with low water levels and no precipitation

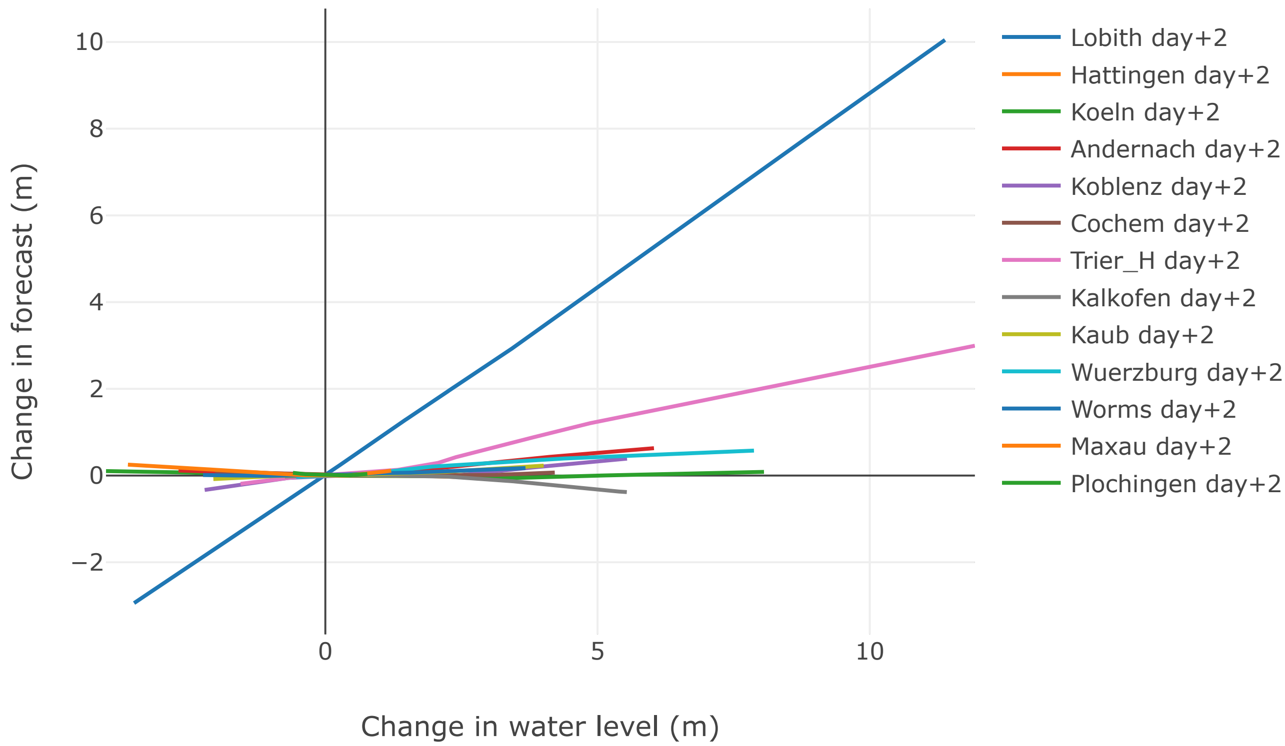

Figure 57: Sensitivity analysis for Water levels (day+2) with low water levels and no precipitation

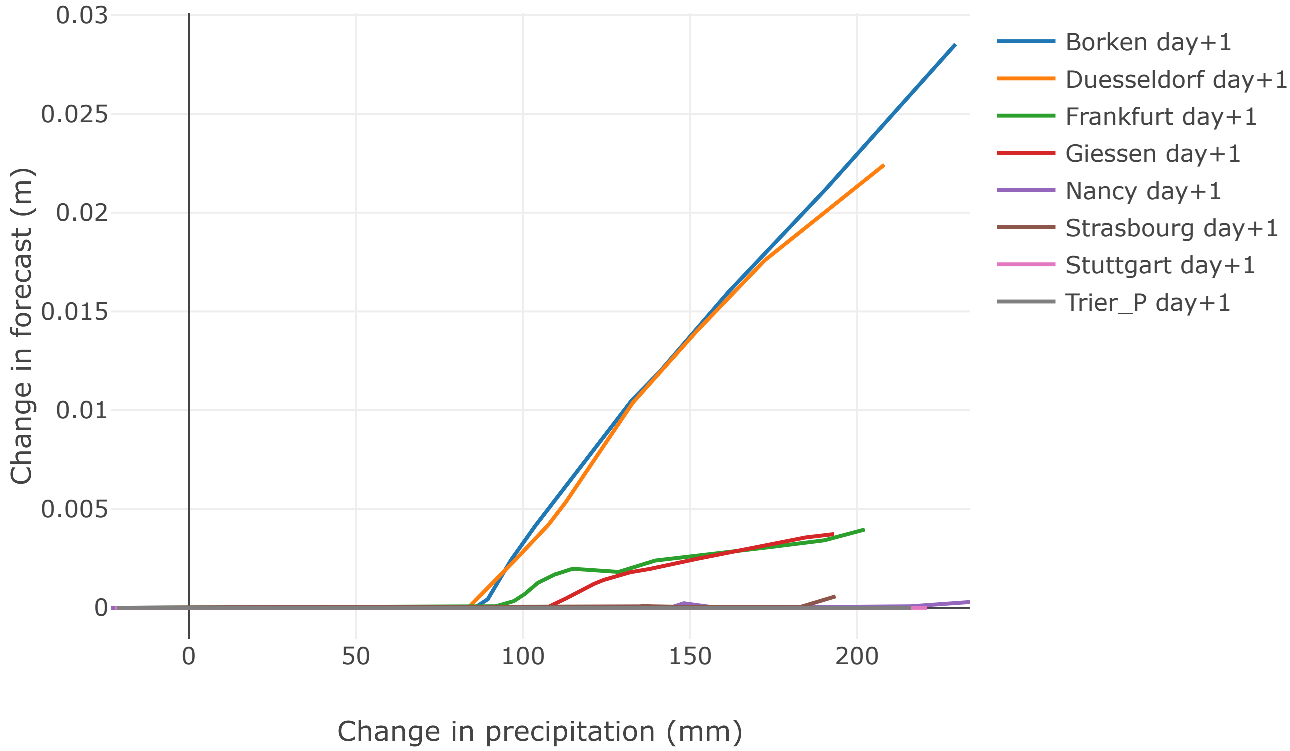

Figure 58: Sensitivity analysis for Precipitation (day+1) with low water levels and no precipitation

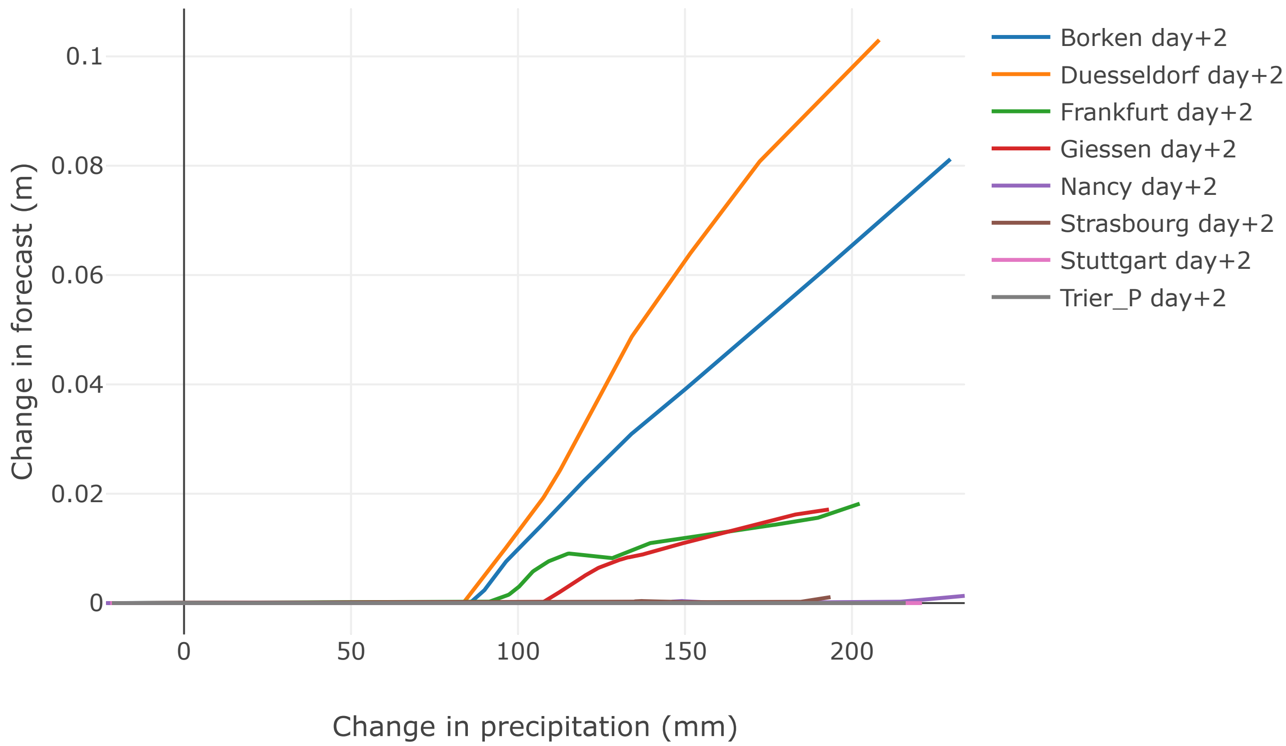

Figure 59: Sensitivity analysis for Precipitation (day+2) with low water levels and no precipitation

A.5 Average water levels and average precipitation for a larger domain

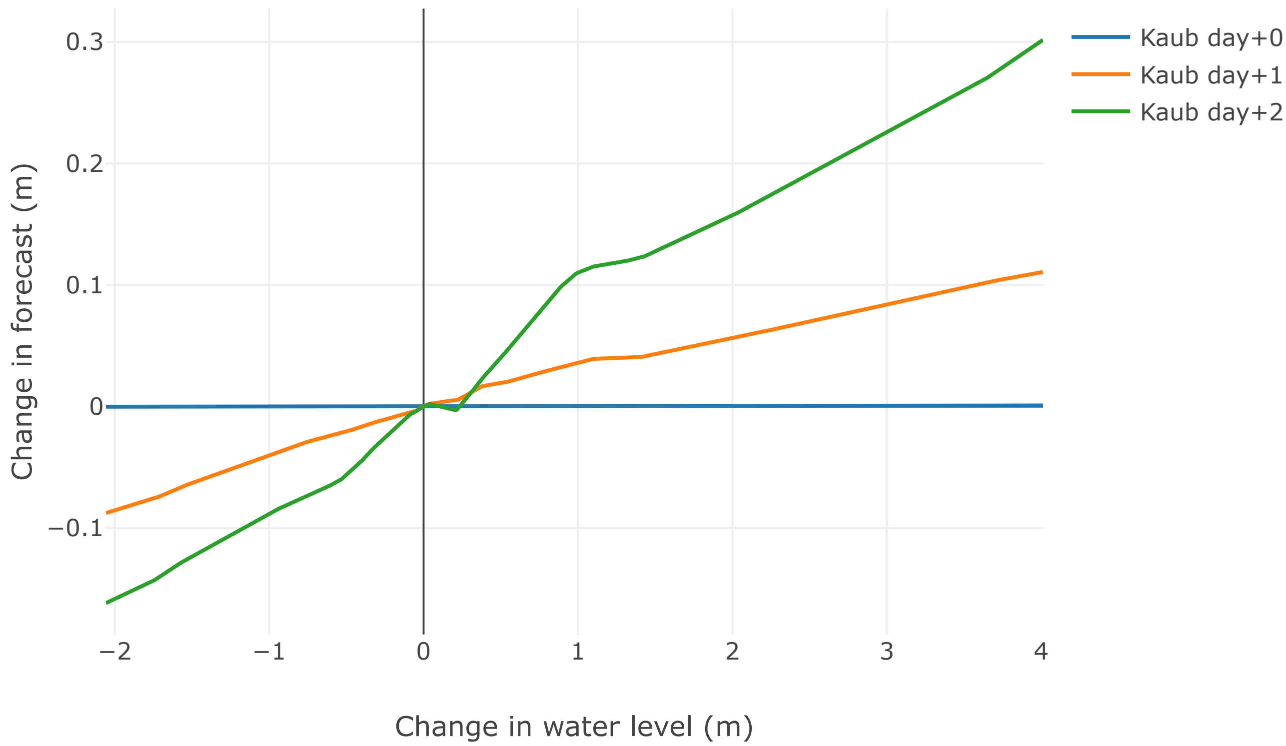

Figure 60: Sensitivity analysis for Kaub with average water levels and average precipitation for a larger domain

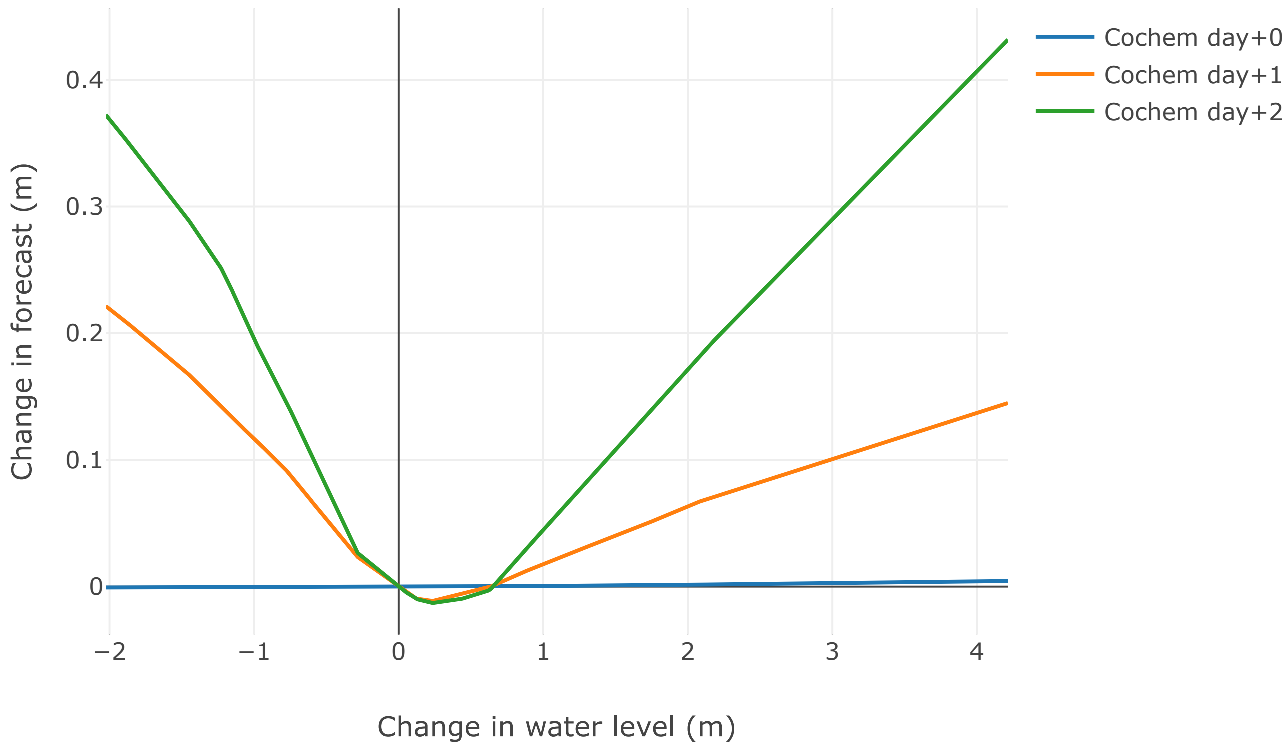

Figure 61: Sensitivity analysis for Cochem with average water levels and average precipitation for a larger domain

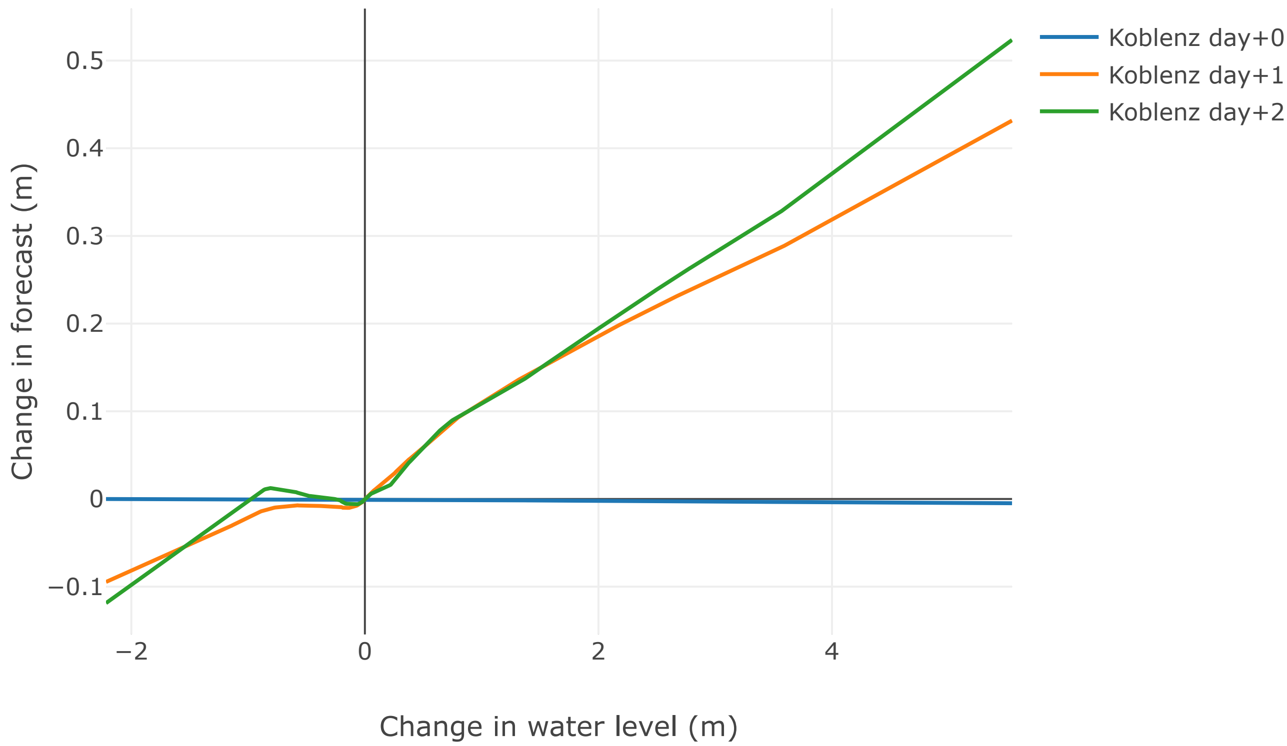

Figure 62: Sensitivity analysis for Koblenz with average water levels and average precipitation for a larger domain

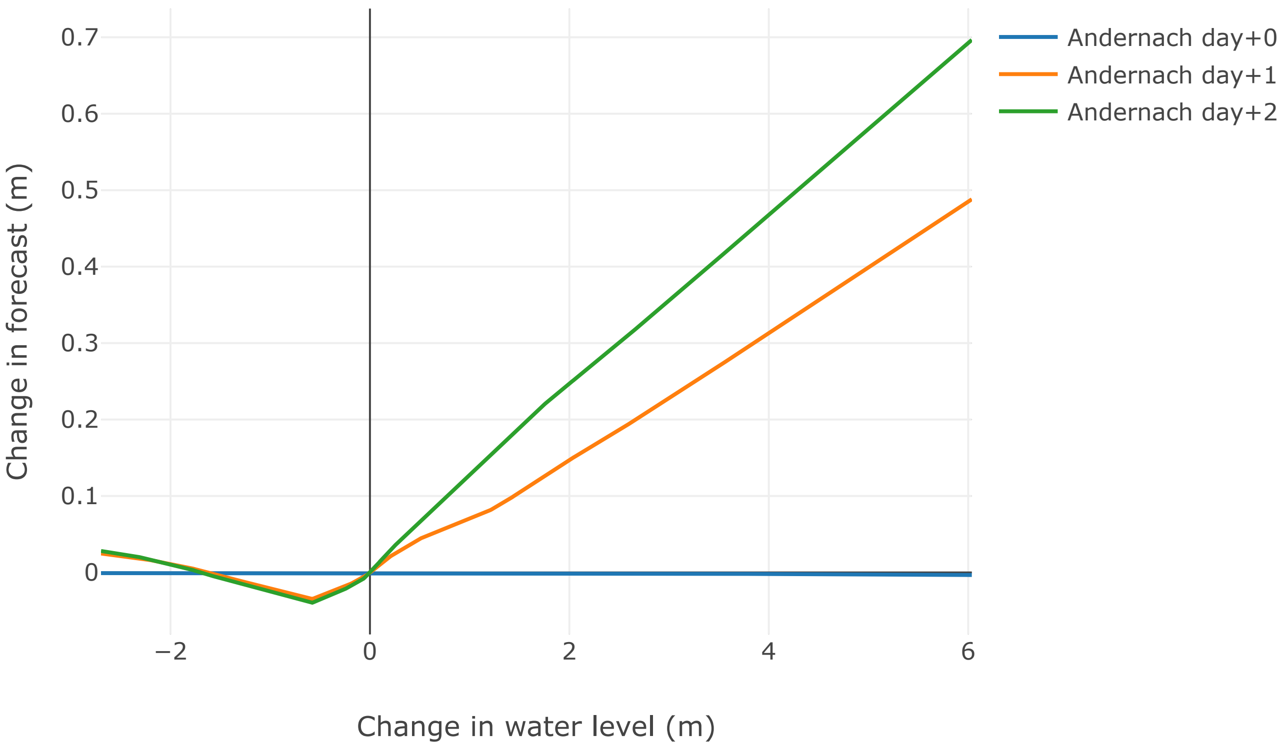

Figure 63: Sensitivity analysis for Andernach with average water levels and average precipitation for a larger domain

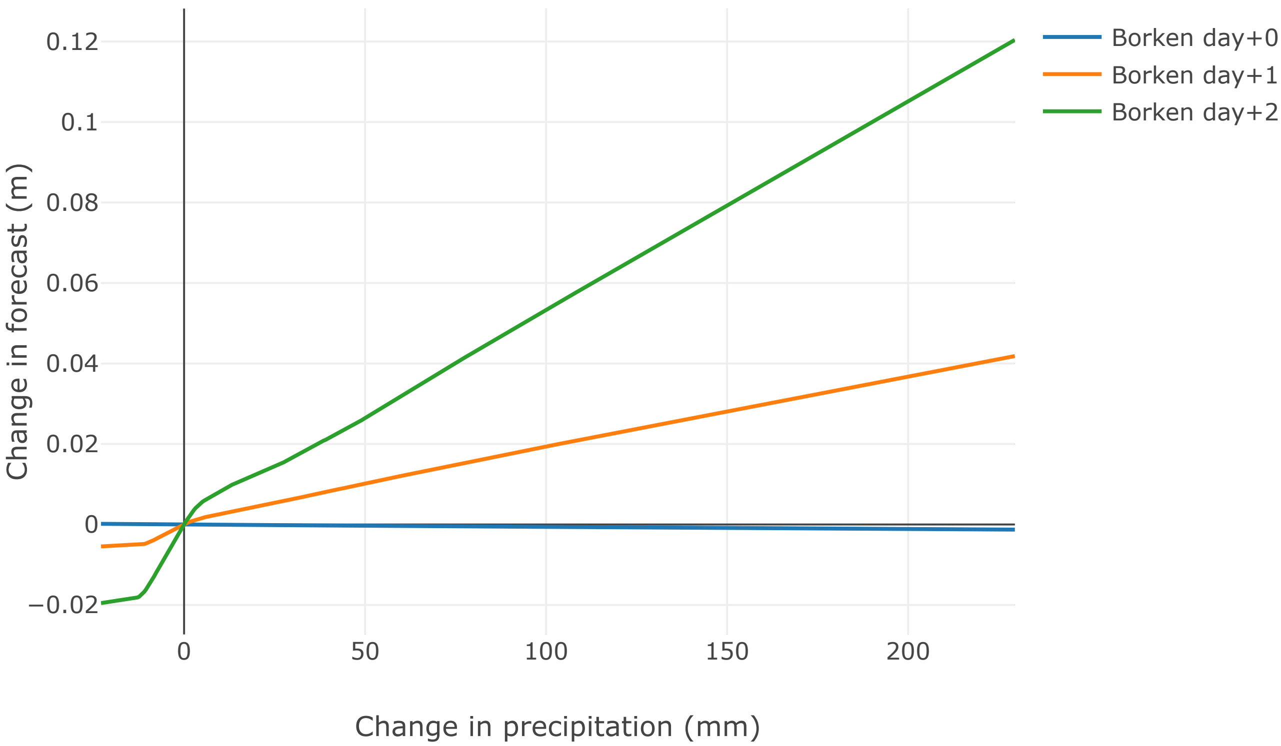

Figure 64: Sensitivity analysis for Borken with average water levels and average precipitation for a larger domain

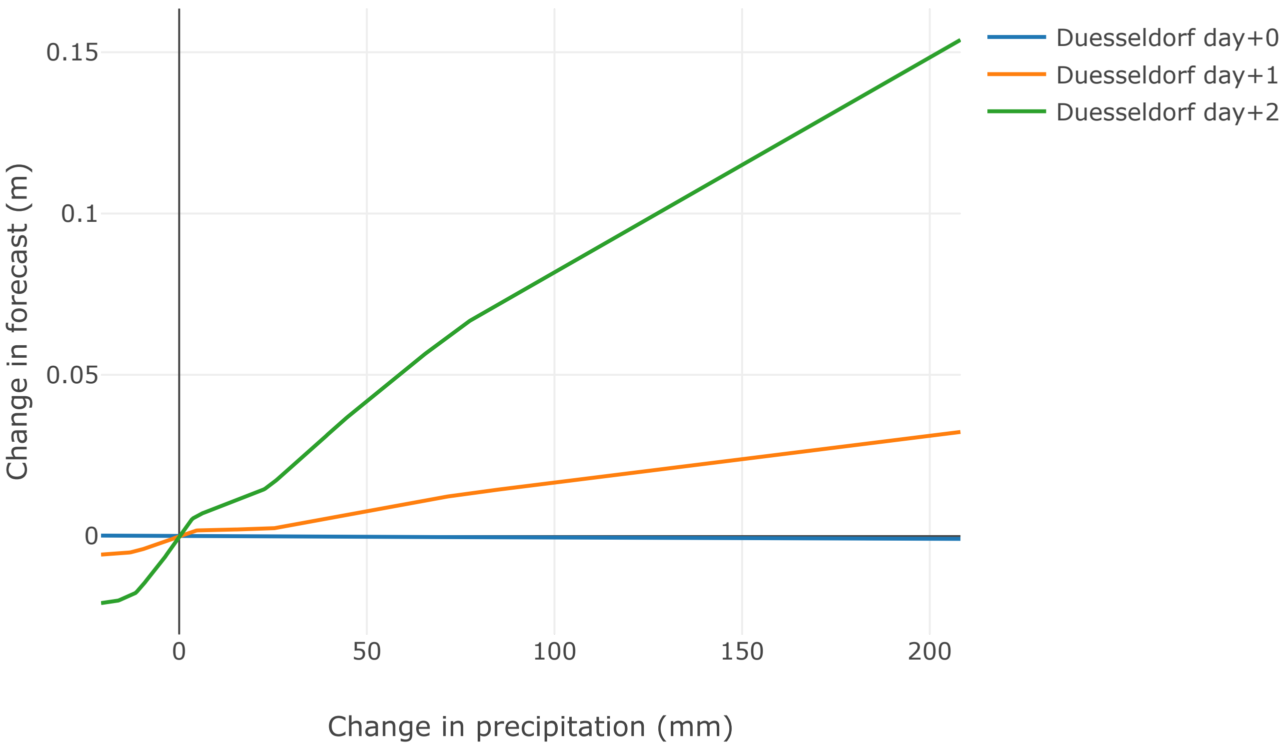

Figure 65: Sensitivity analysis for Düsseldorf with average water levels and average precipitation for a larger domain

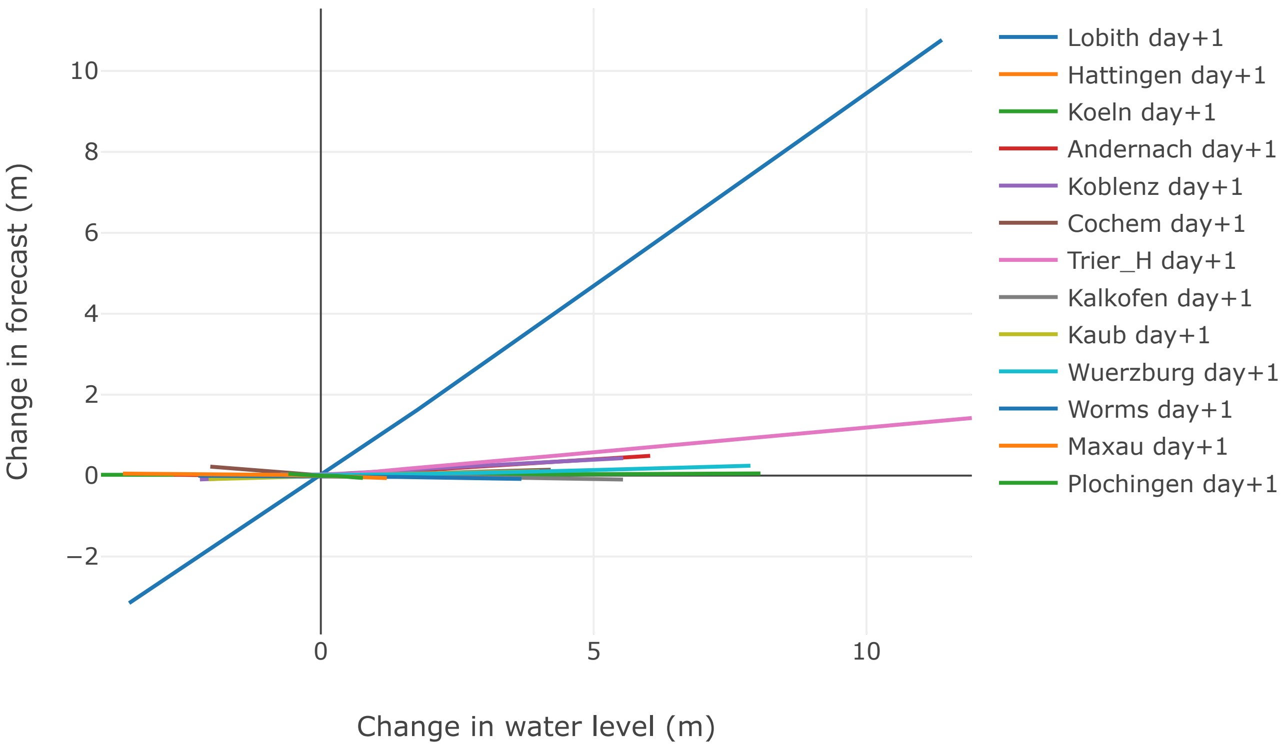

Figure 66: Sensitivity analysis for Water levels (day+1) with average water levels and average precipitation for a larger domain

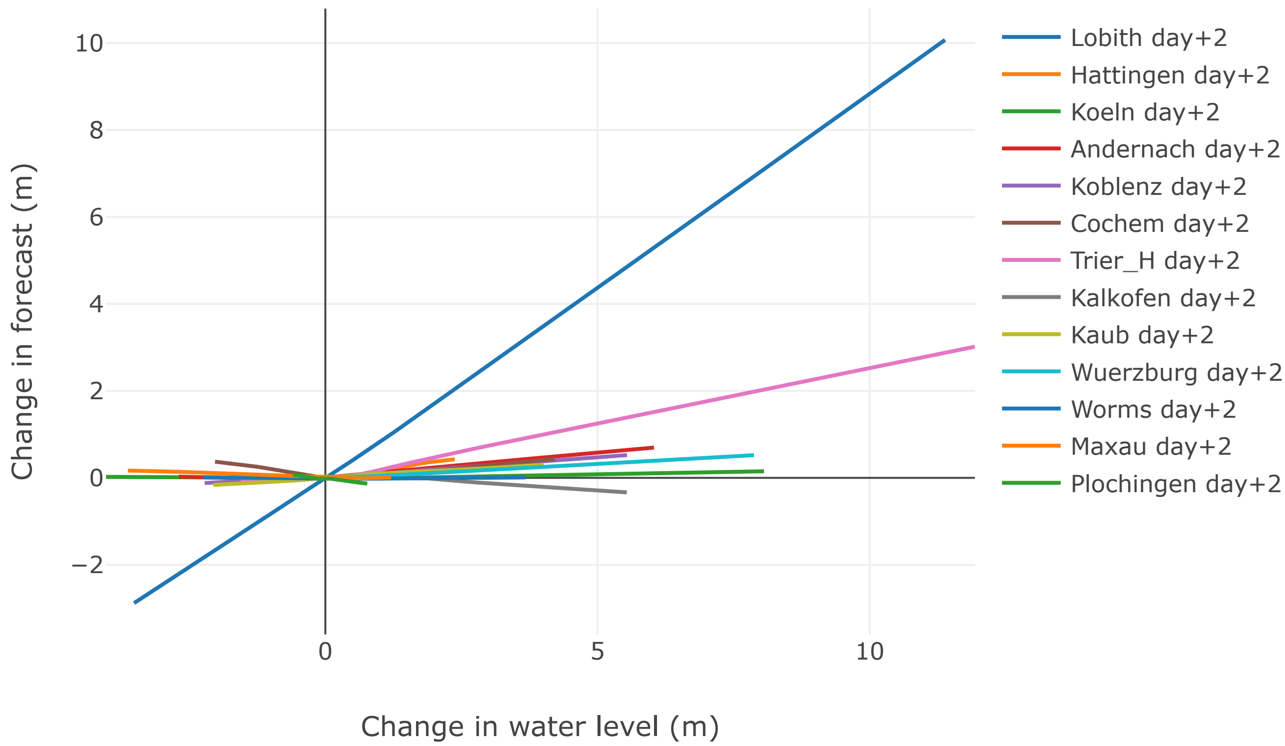

Figure 67: Sensitivity analysis for Water levels (day+2) with average water levels and average precipitation for a larger domain

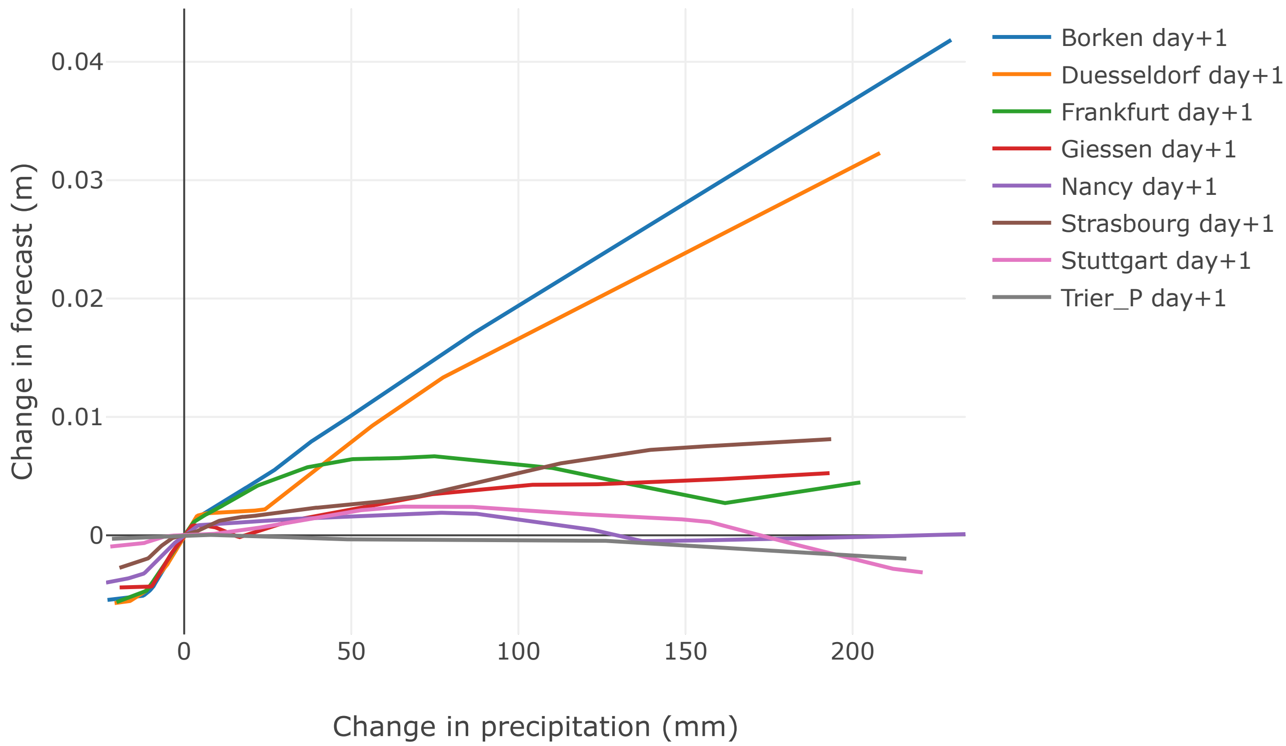

Figure 68: Sensitivity analysis for Precipitation (day+1) with average water levels and average precipitation for a larger domain

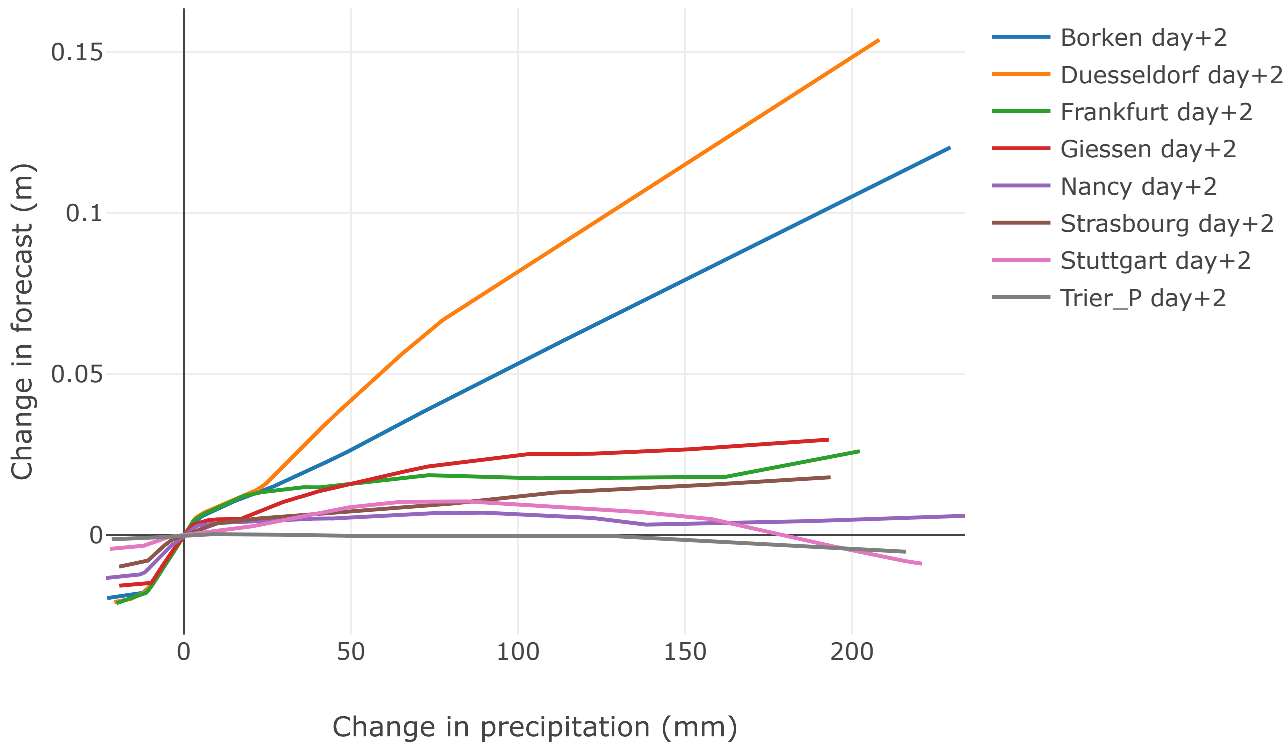

Figure 69: Sensitivity analysis for Precipitation (day+2) with average water levels and average precipitation for a larger domain

A.6 Increased water levels and increased precipitation

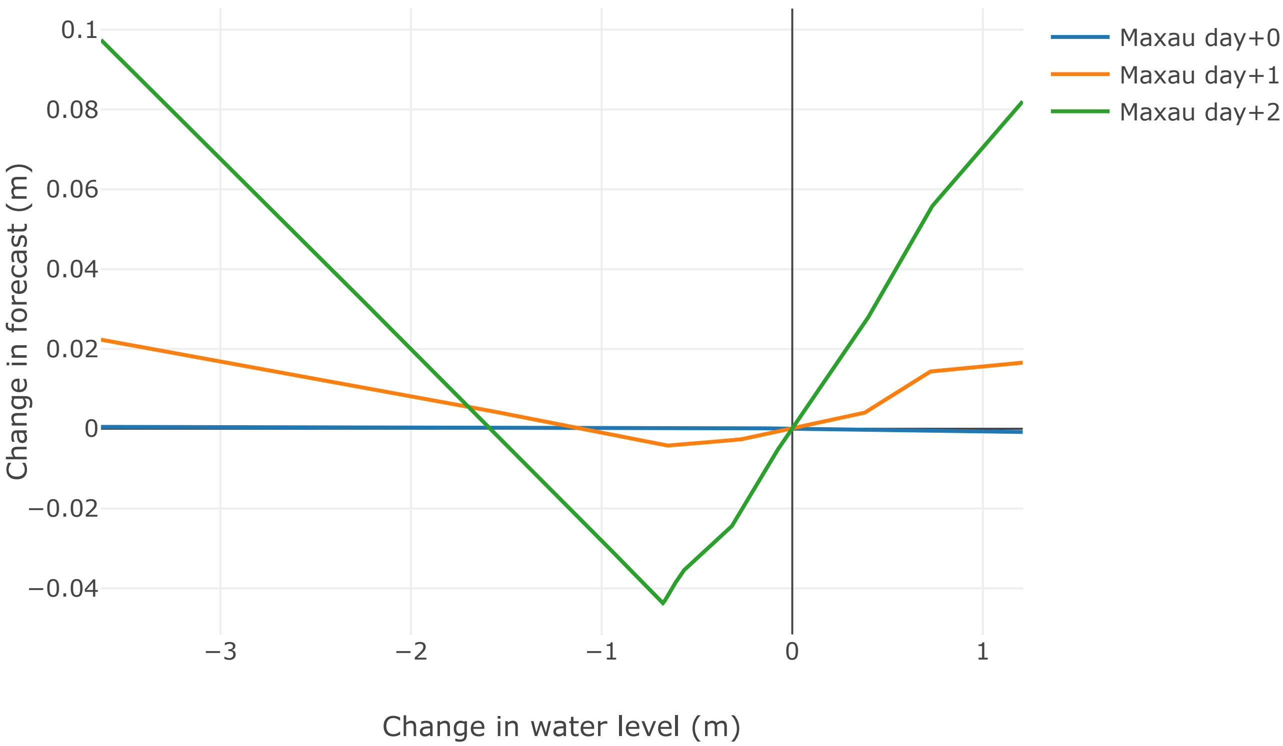

Figure 70: Sensitivity analysis for Maxau with increased water levels and increased precipitation

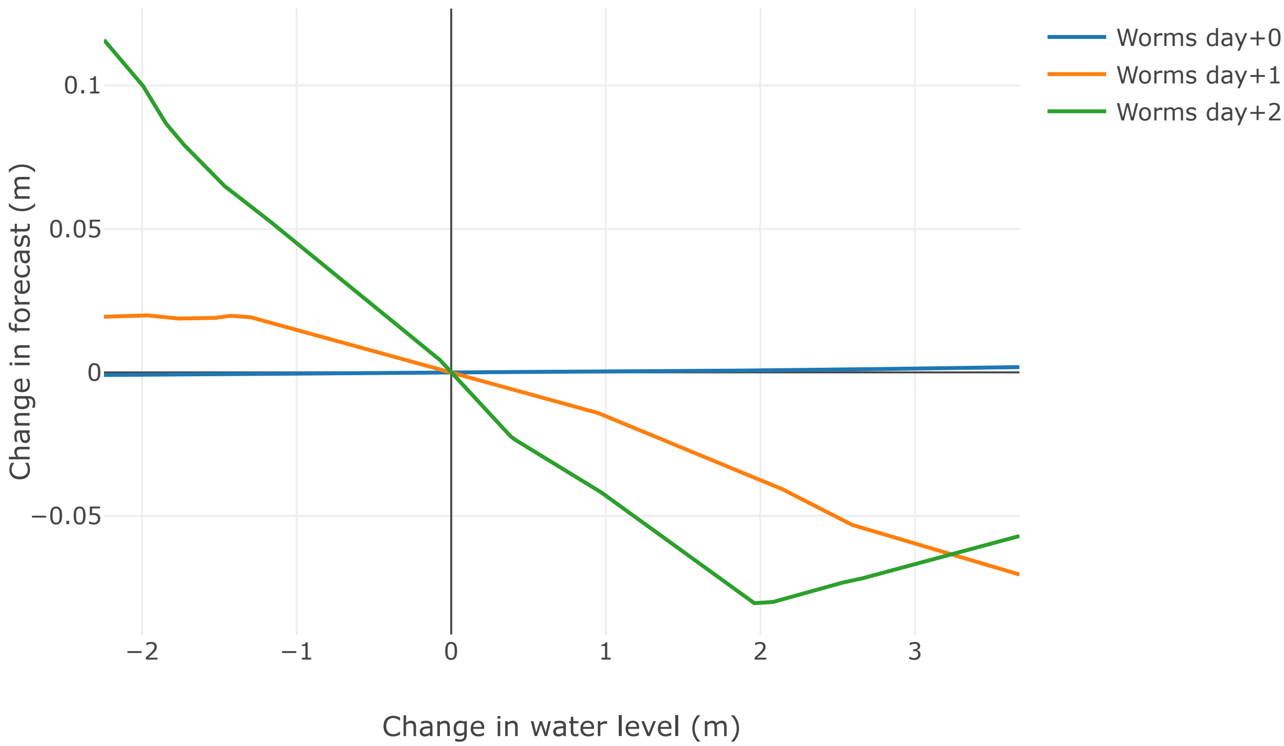

Figure 71: Sensitivity analysis for Worms with increased water levels and increased precipitation

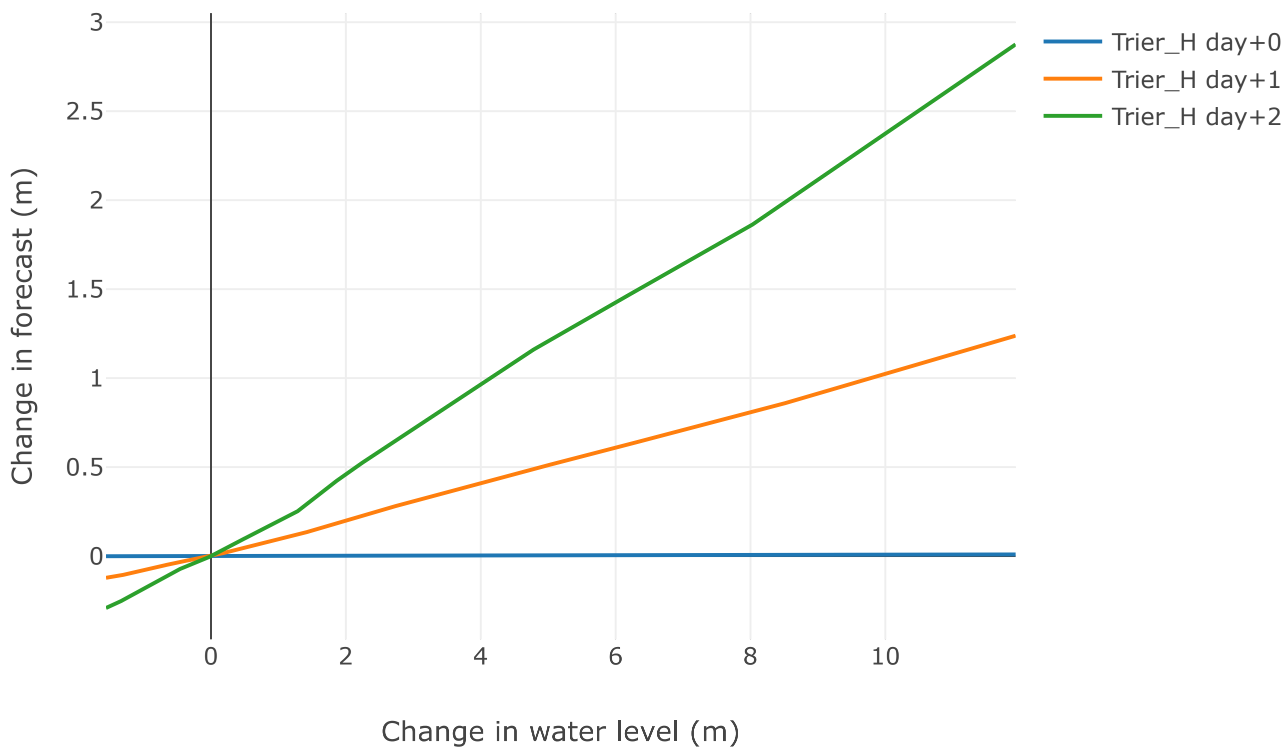

Figure 72: Sensitivity analysis for Trier (Water levels) with increased water levels and increased precipitation

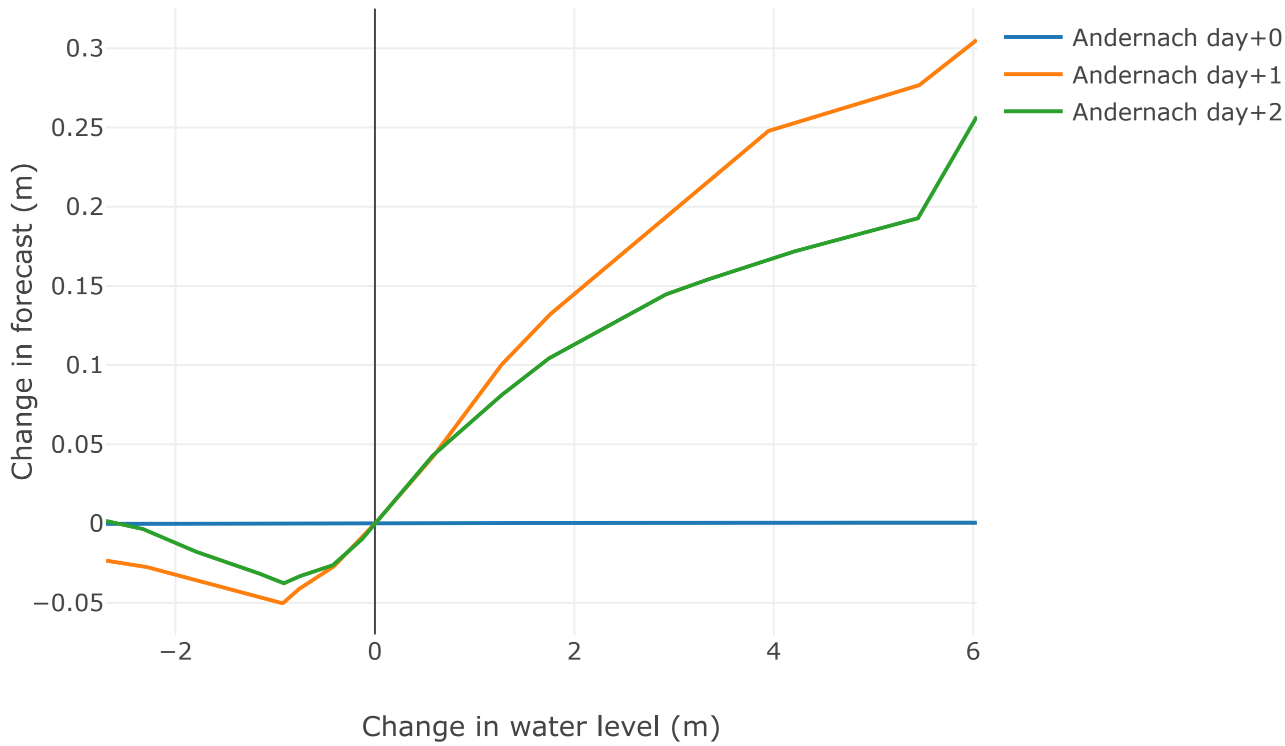

Figure 73: Sensitivity analysis for Andernach with increased water levels and increased precipitation

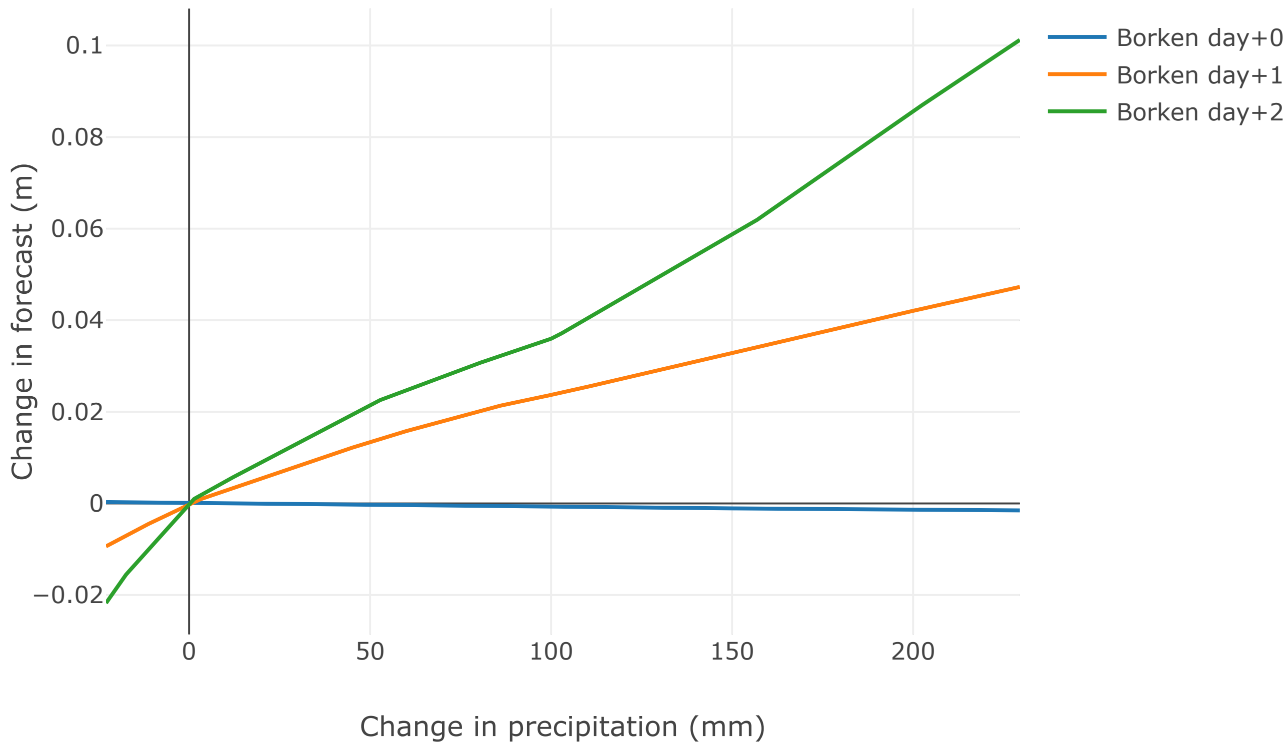

Figure 74: Sensitivity analysis for Borken with increased water levels and increased precipitation

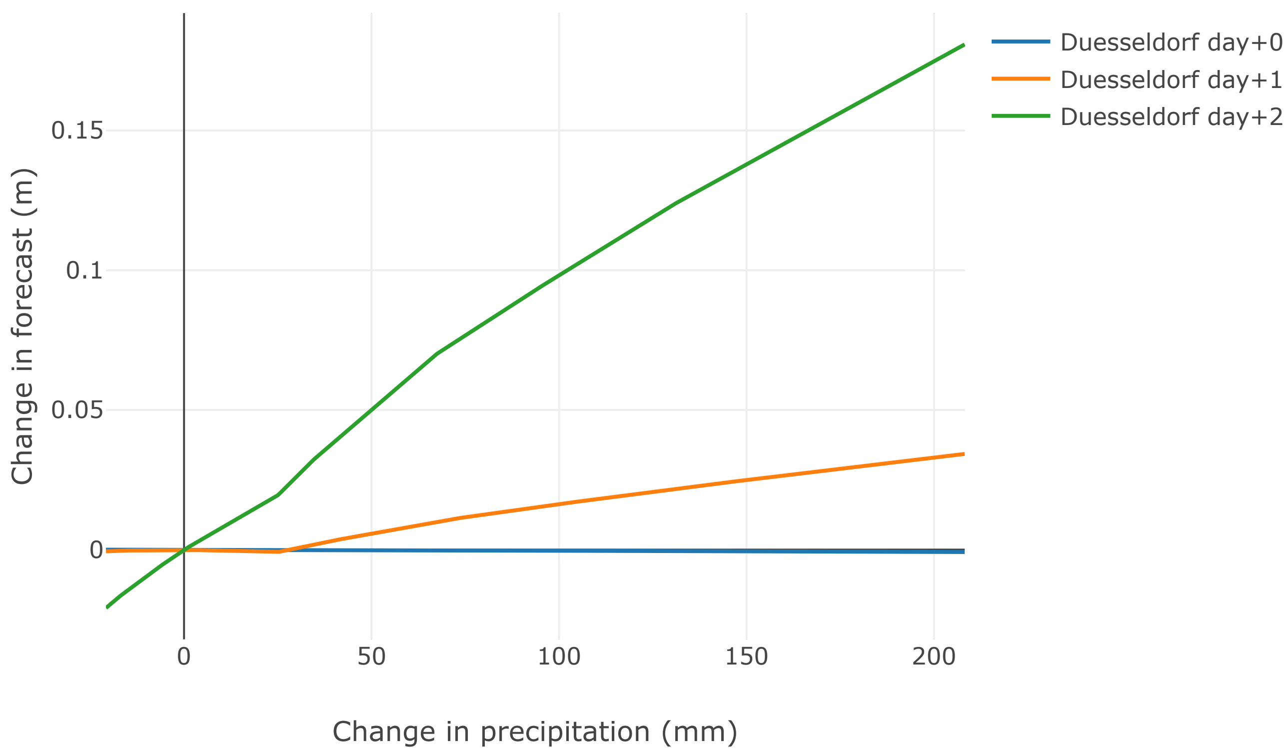

Figure 75: Sensitivity analysis for Düsseldorf with increased water levels and increased precipitation

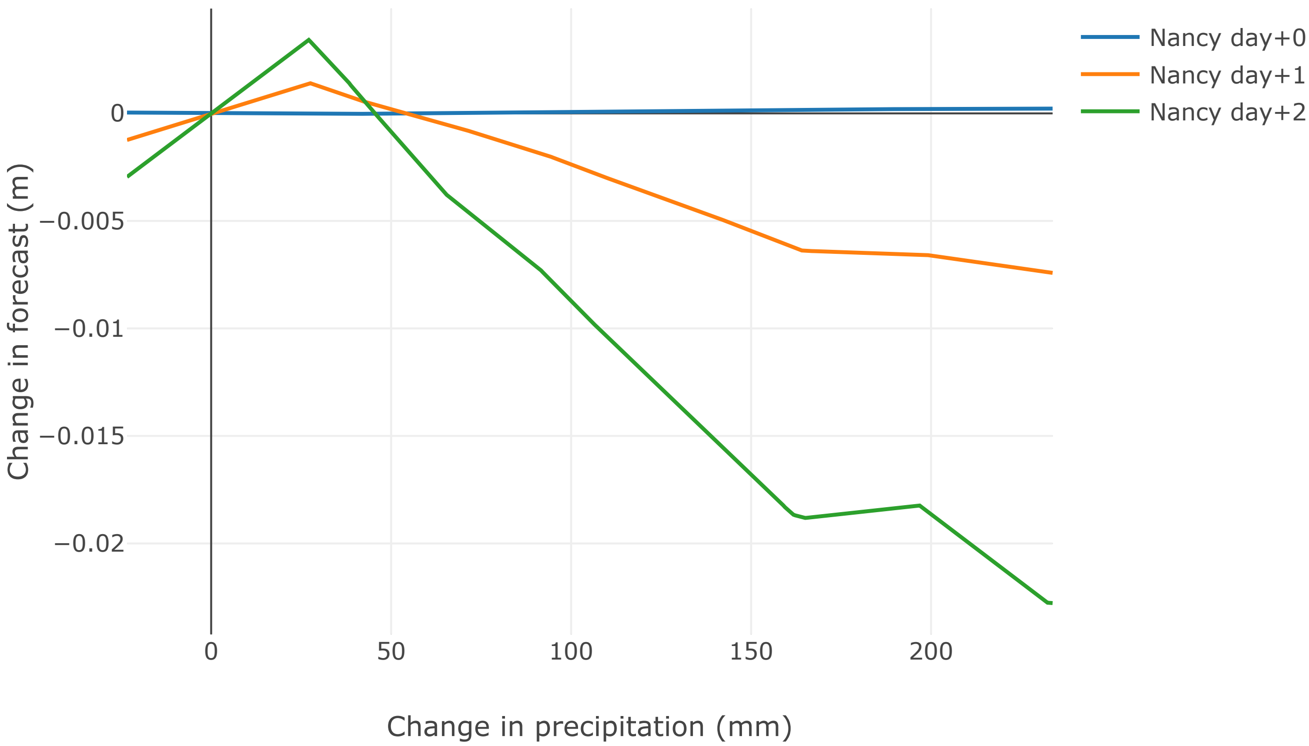

Figure 76: Sensitivity analysis for Nancy with increased water levels and increased precipitation

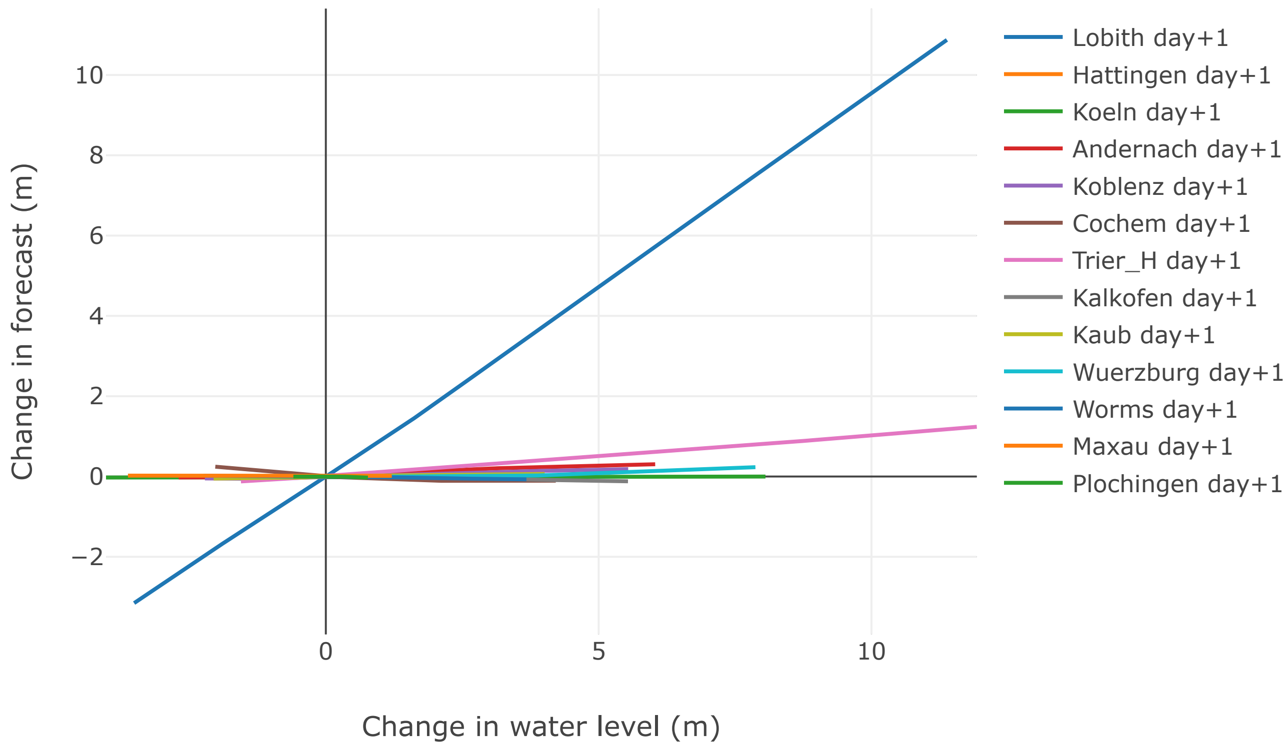

Figure 77: Sensitivity analysis for Water levels (day+1) with increased water levels and increased precipitation

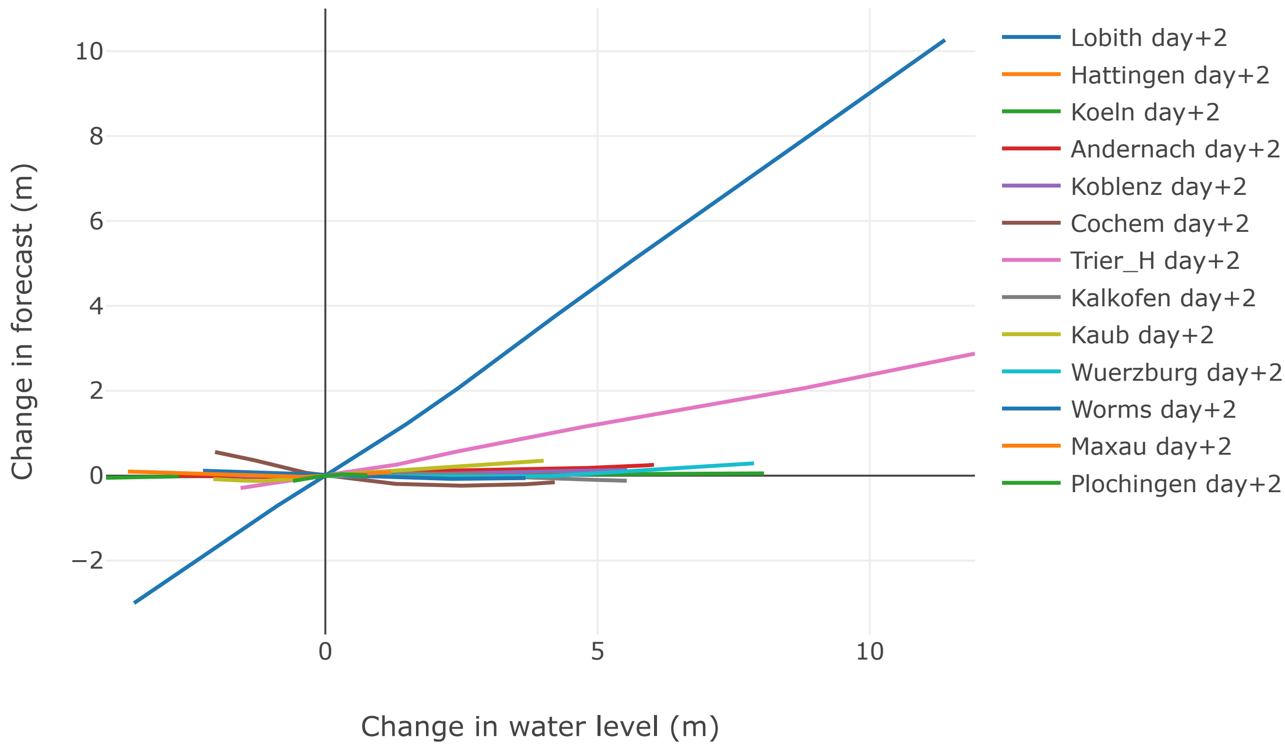

Figure 78: Sensitivity analysis for Water levels (day+2) with increased water levels and increased precipitation

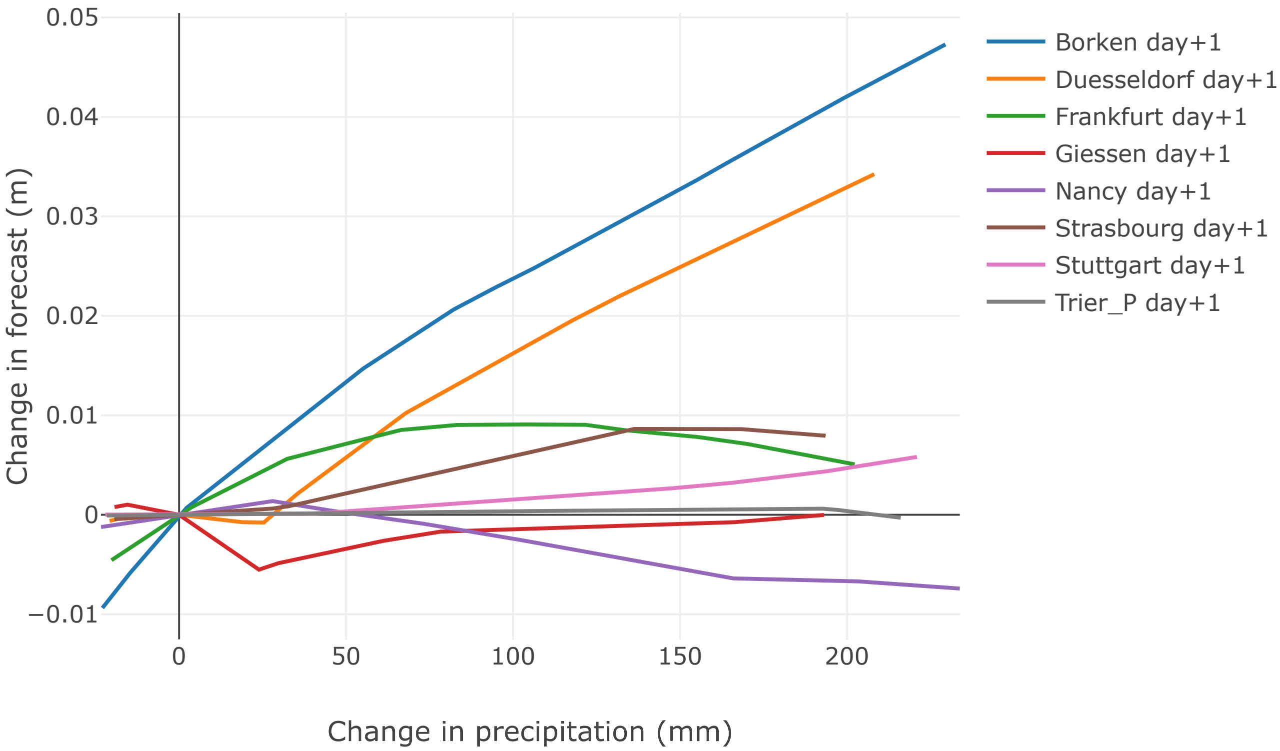

Figure 79: Sensitivity analysis for Precipitation (day+1) with increased water levels and increased precipitation

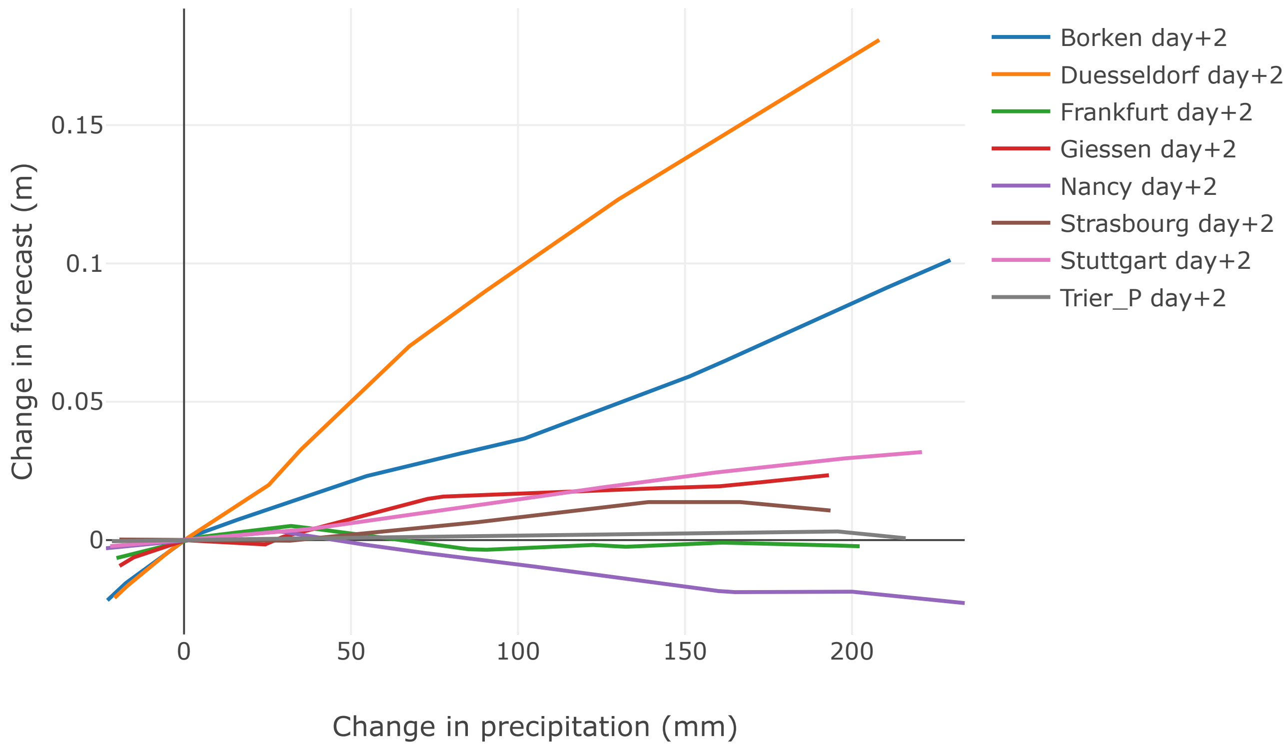

Figure 80: Sensitivity analysis for Precipitation (day+2) with increased water levels and increased precipitation

A.7 High water levels and high precipitation

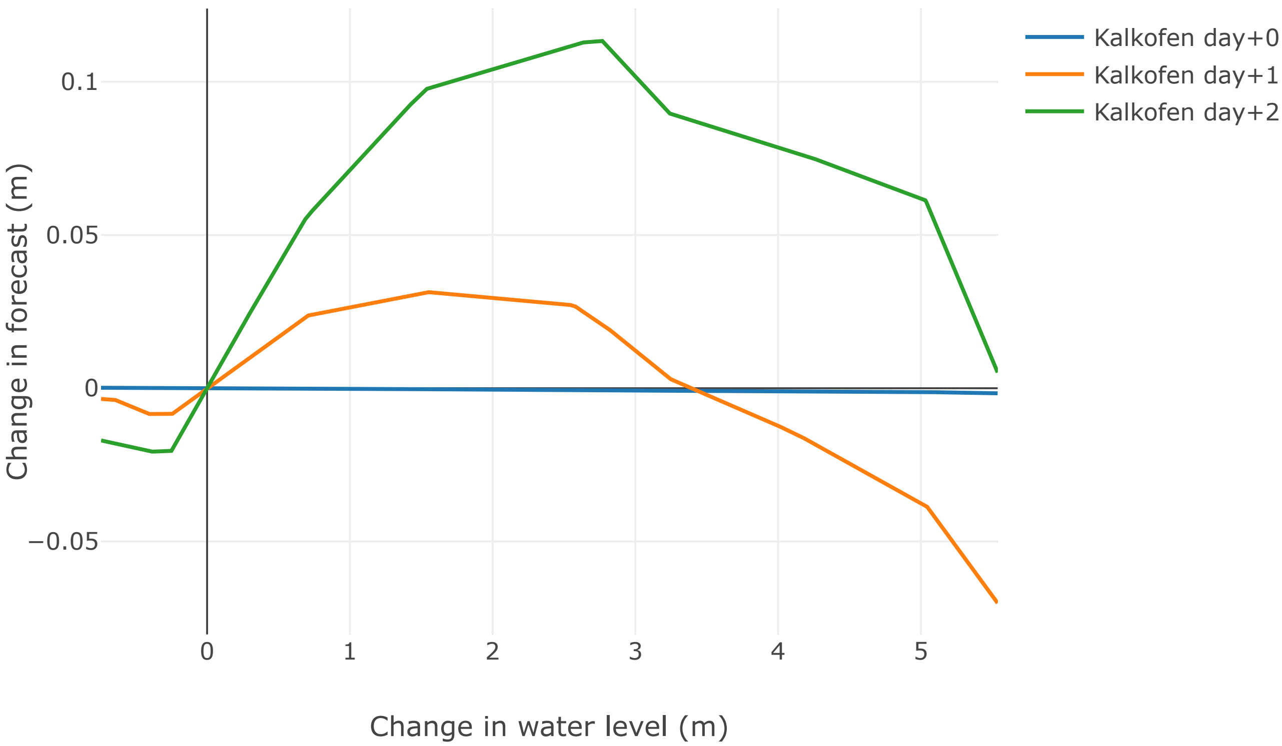

Figure 81: Sensitivity analysis for Kalkofen with high water levels and high precipitation

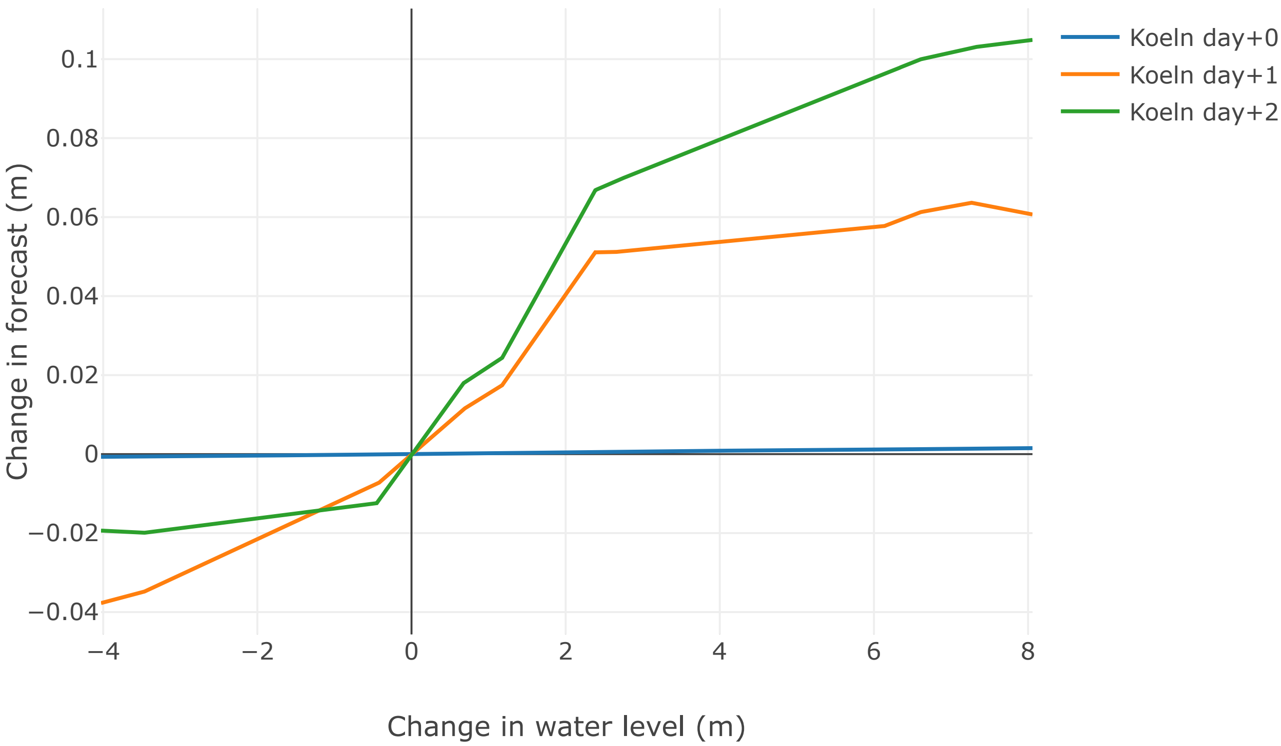

Figure 82: Sensitivity analysis for Köln with high water levels and high precipitation

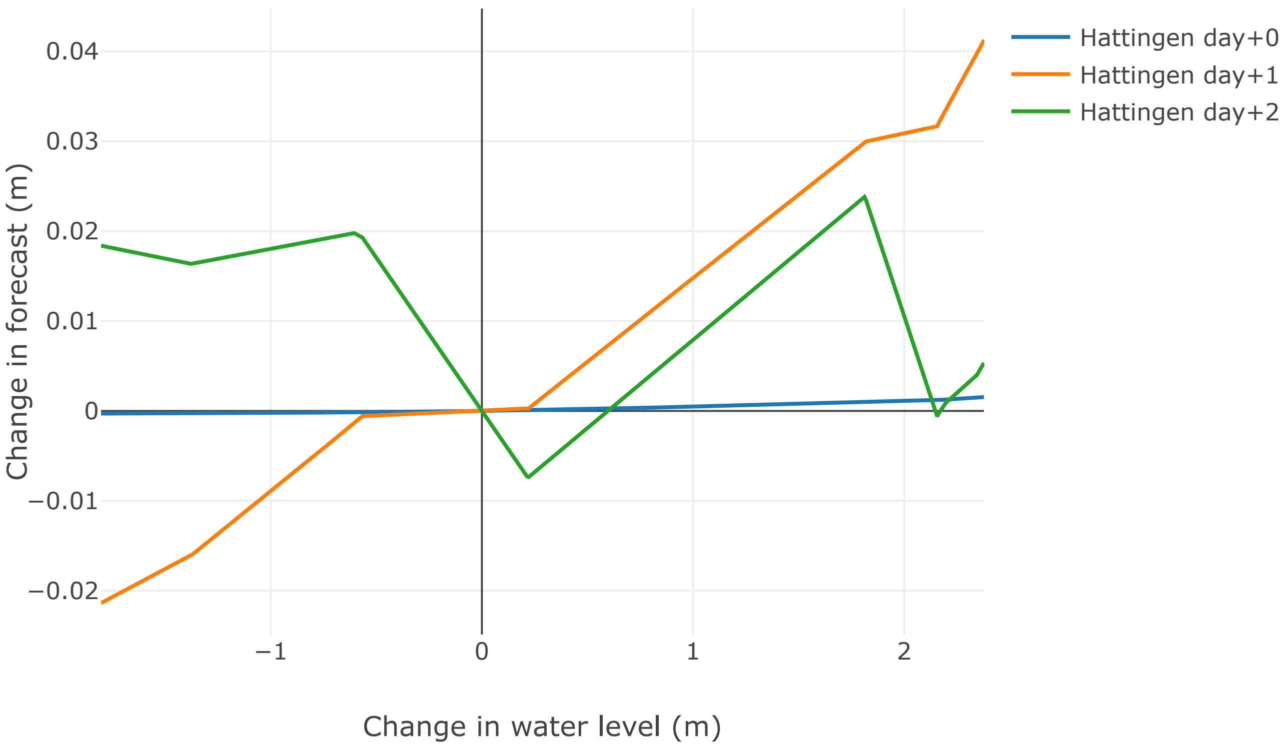

Figure 83: Sensitivity analysis for Hattingen with high water levels and high precipitation

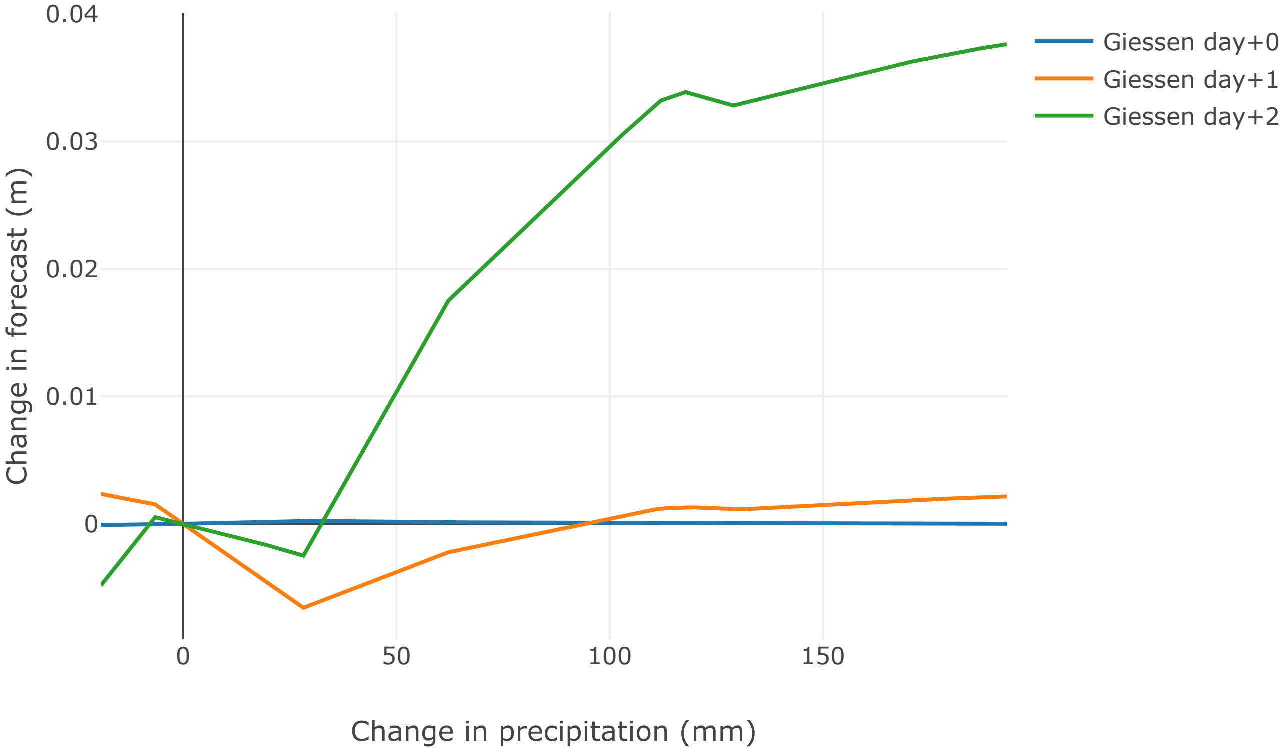

Figure 84: Sensitivity analysis for Giessen with high water levels and high precipitation

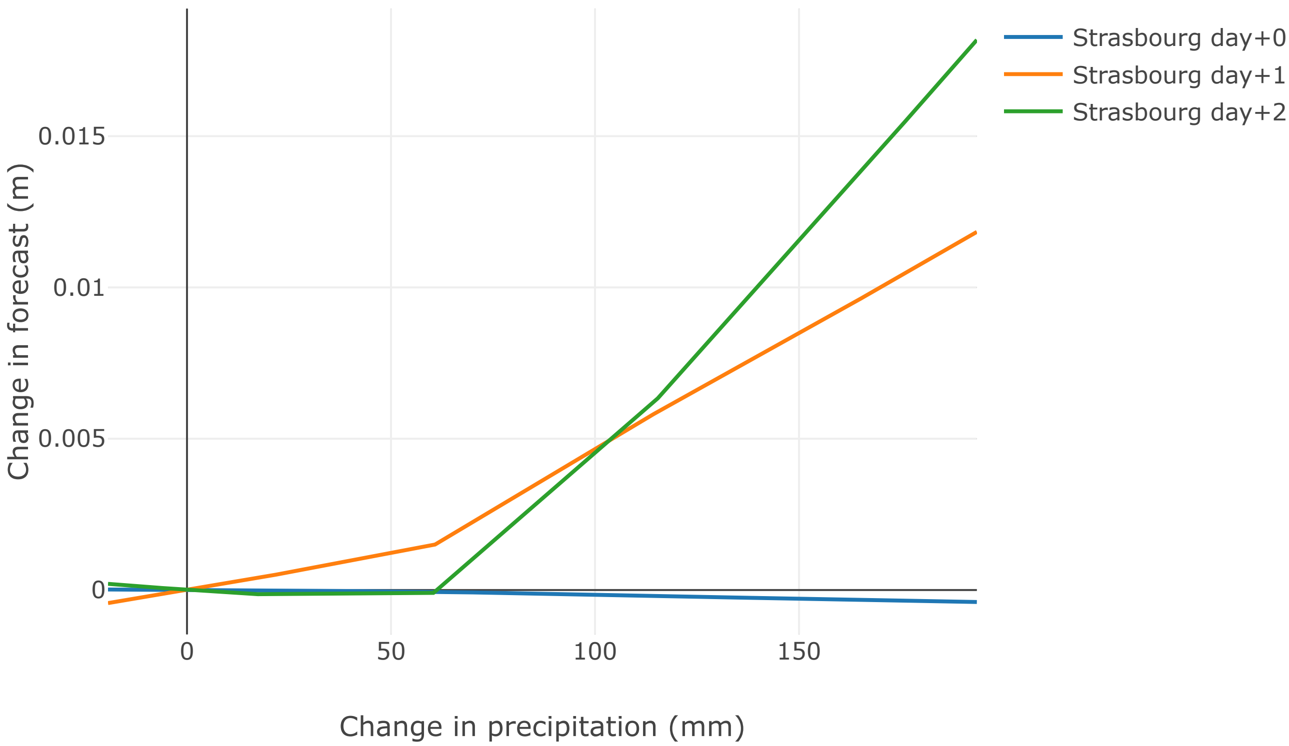

Figure 85: Sensitivity analysis for Strasbourg with high water levels and high precipitation

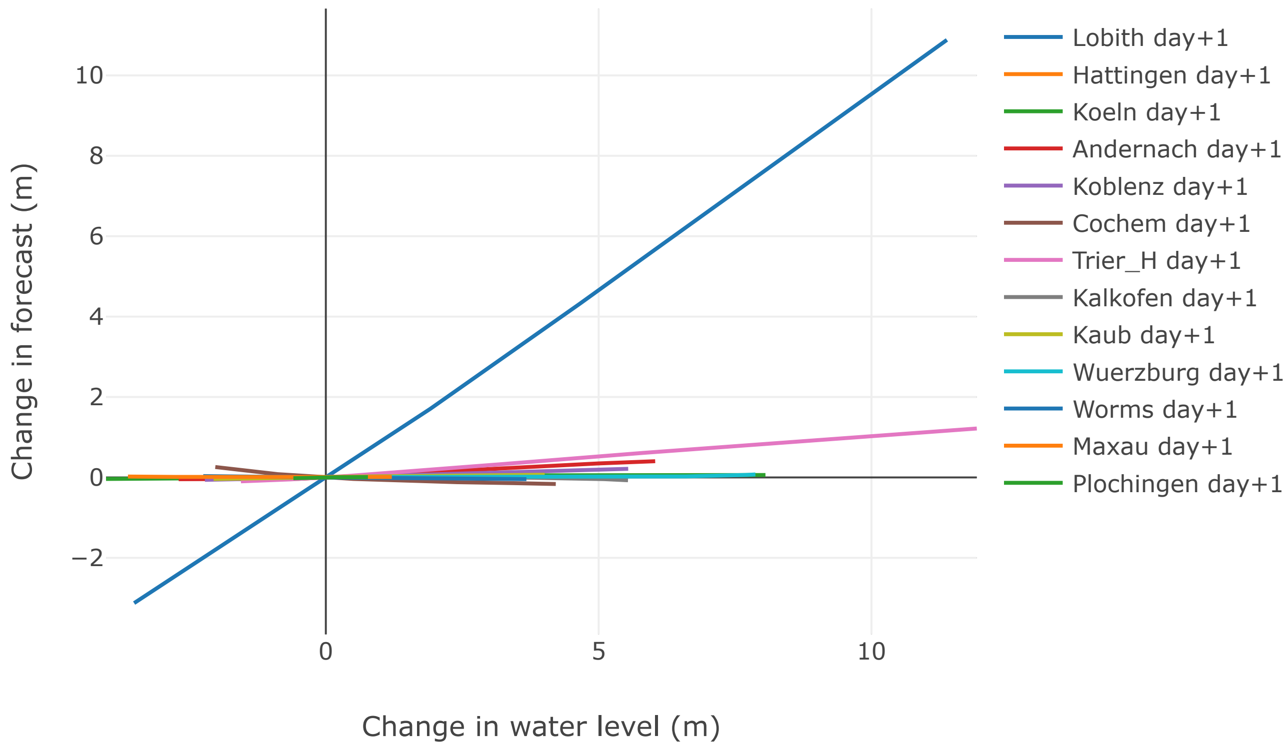

Figure 86: Sensitivity analysis for Water levels (day+1) with high water levels and high precipitation

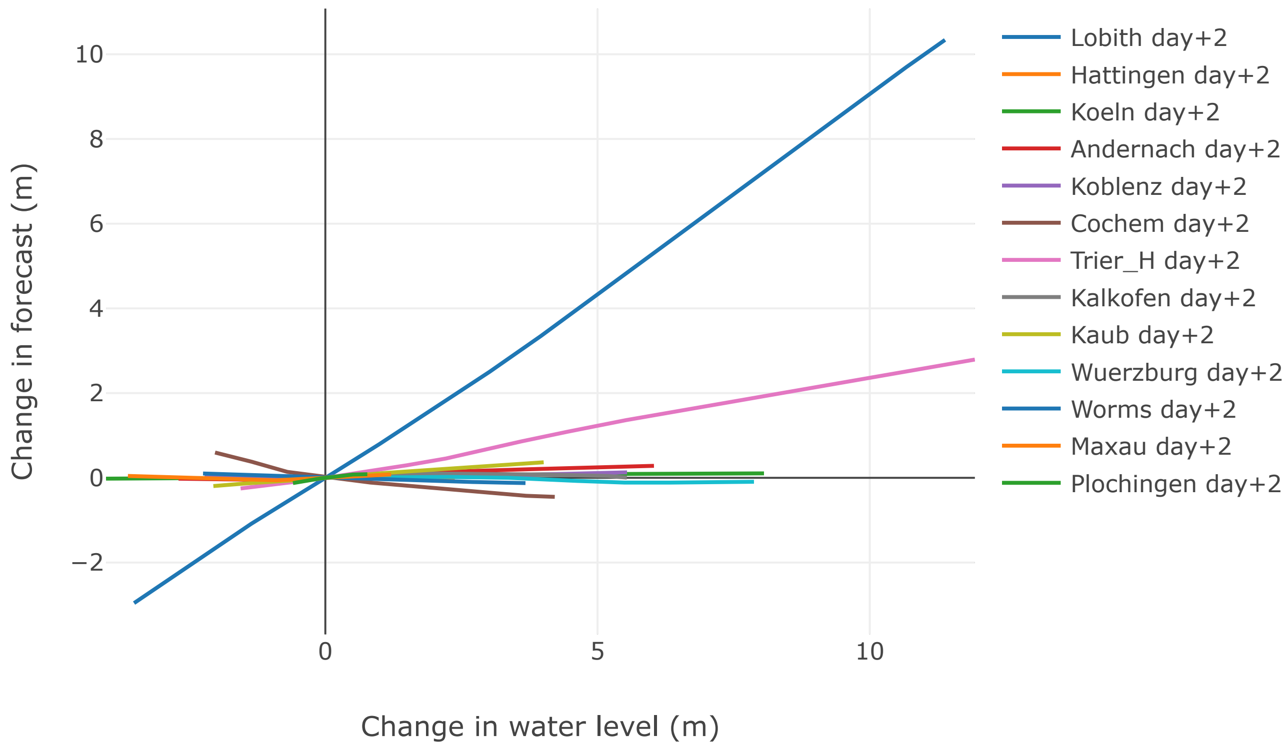

Figure 87: Sensitivity analysis for Water levels (day+2) with high water levels and high precipitation

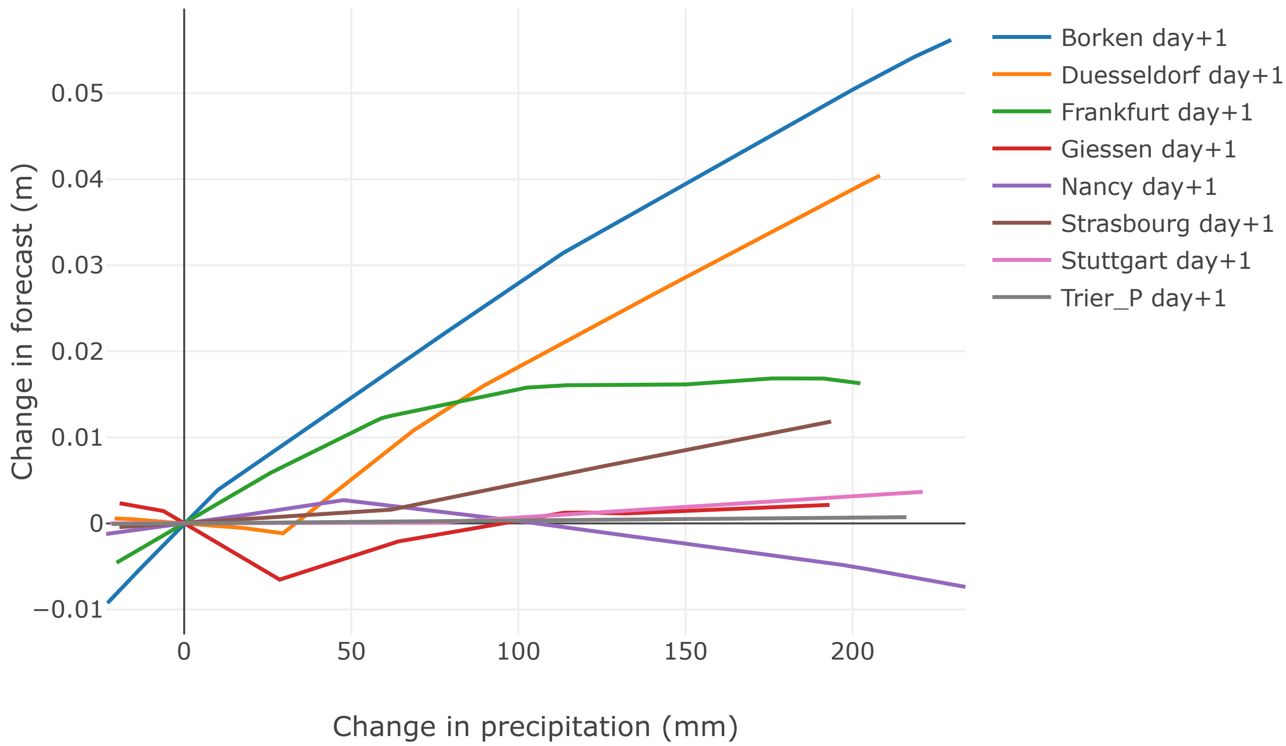

Figure 88: Sensitivity analysis for Precipitation (day+1) with high water levels and high precipitation

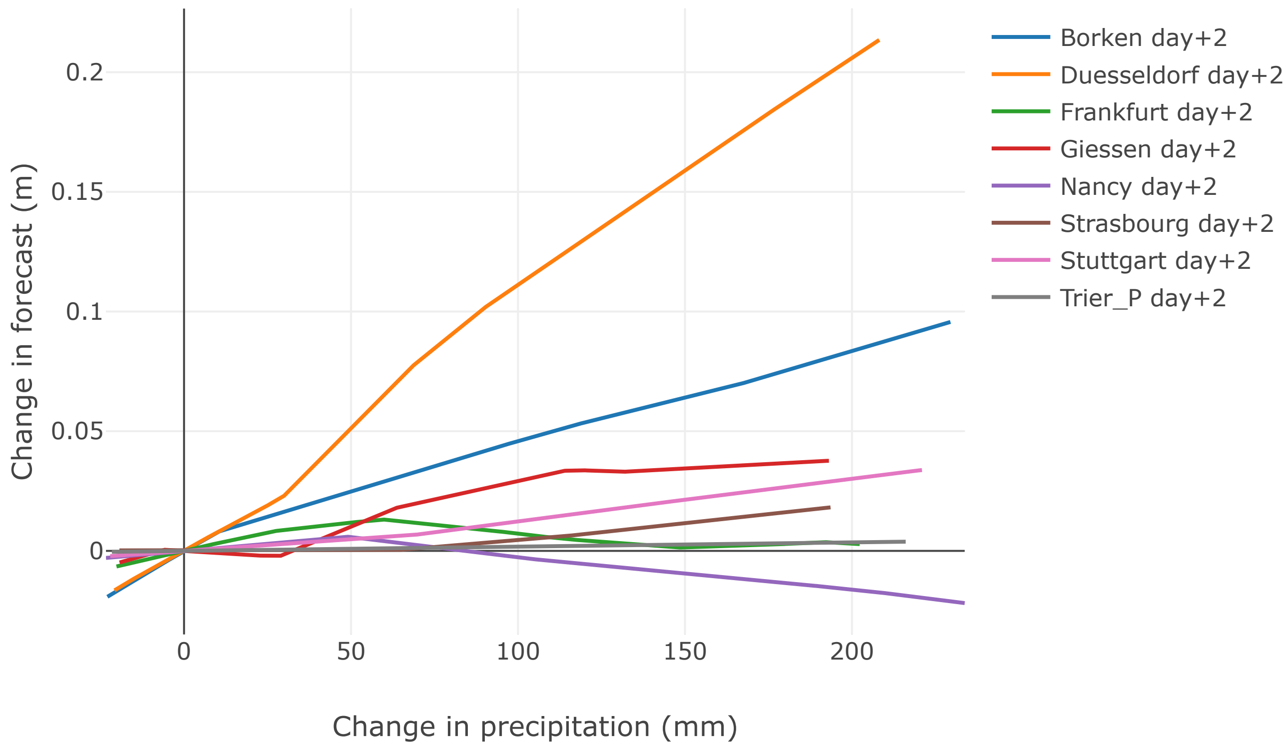

Figure 89: Sensitivity analysis for Precipitation (day+2) with high water levels and high precipitation

A.8 Very high water levels and very high precipitation

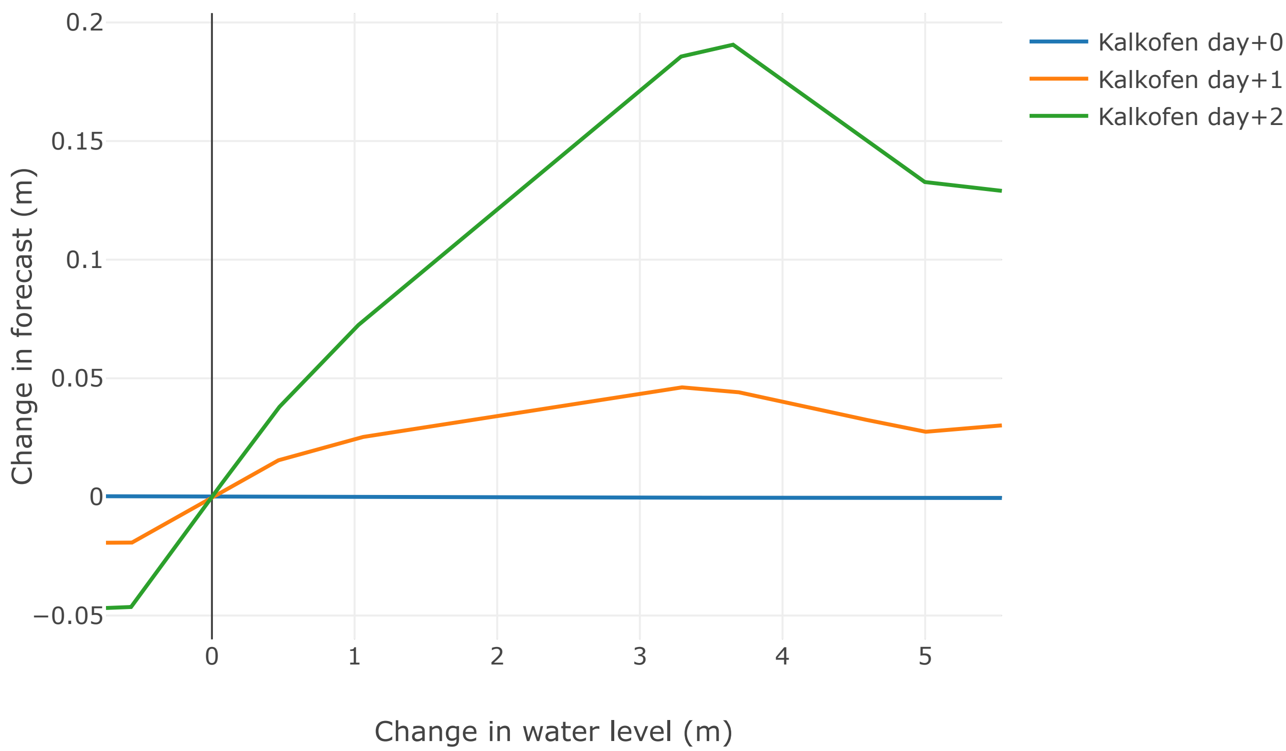

Figure 90: Sensitivity analysis for Kalkofen with very high water levels and very high precipitation

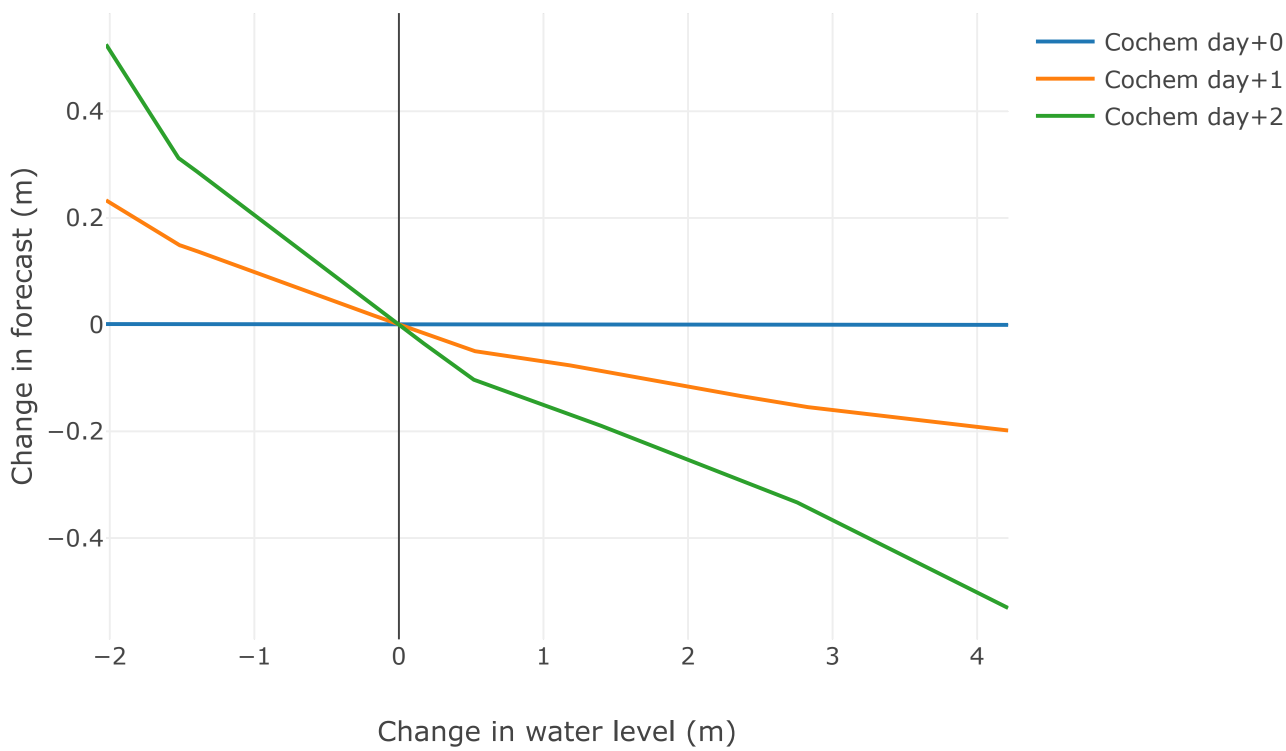

Figure 91: Sensitivity analysis for Cochem with very high water levels and very high precipitation

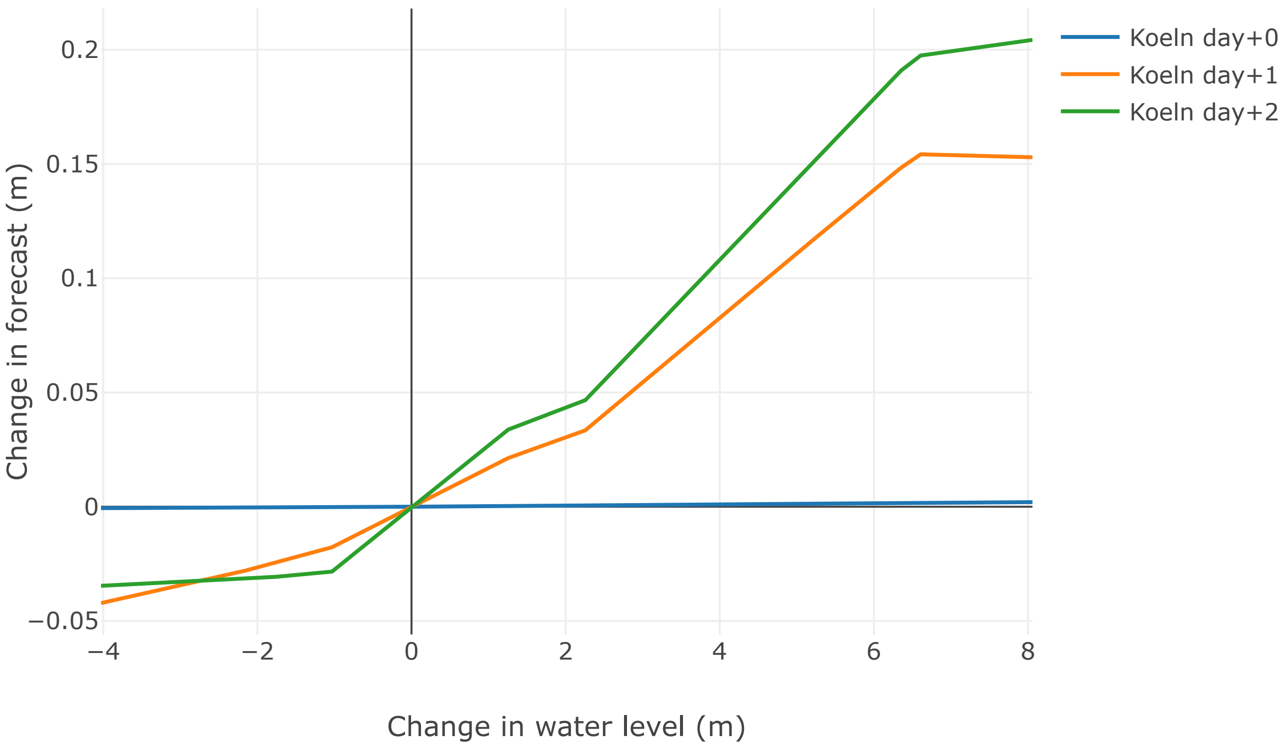

Figure 92: Sensitivity analysis for Köln with very high water levels and very high precipitation

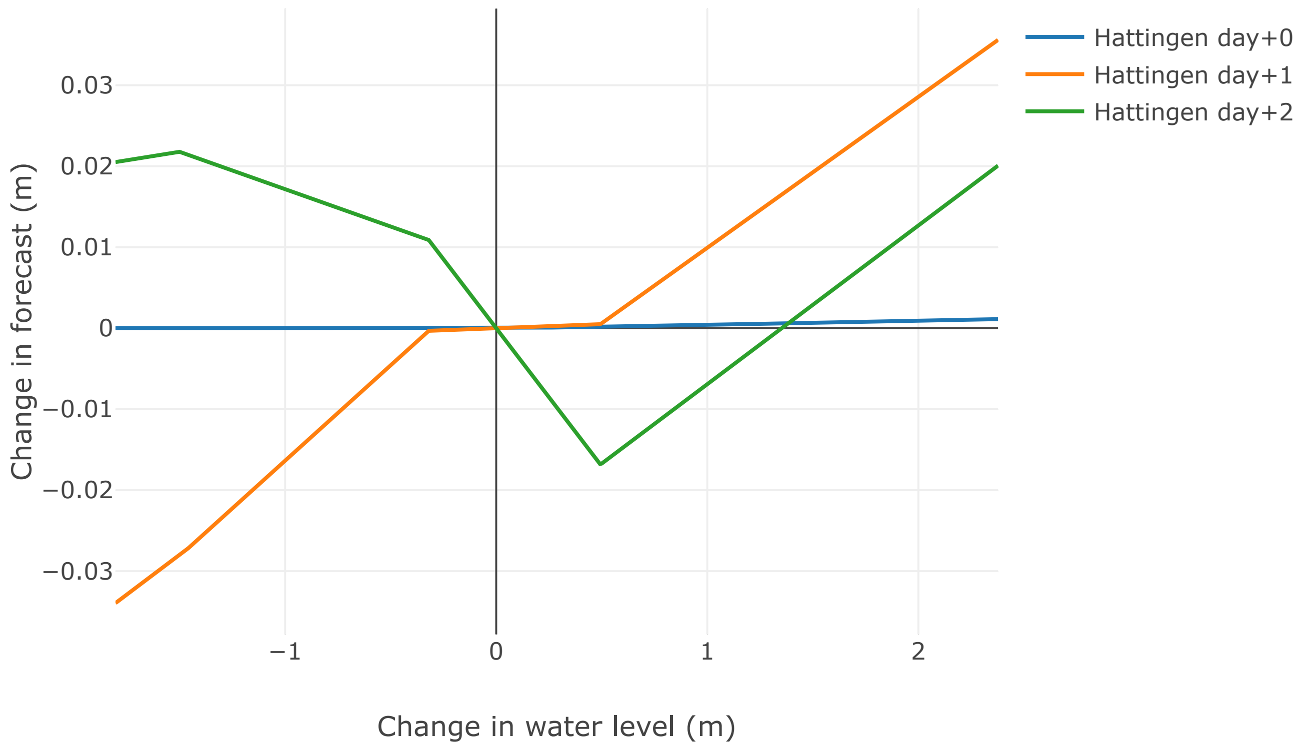

Figure 93: Sensitivity analysis for Hattingen with very high water levels and very high precipitation

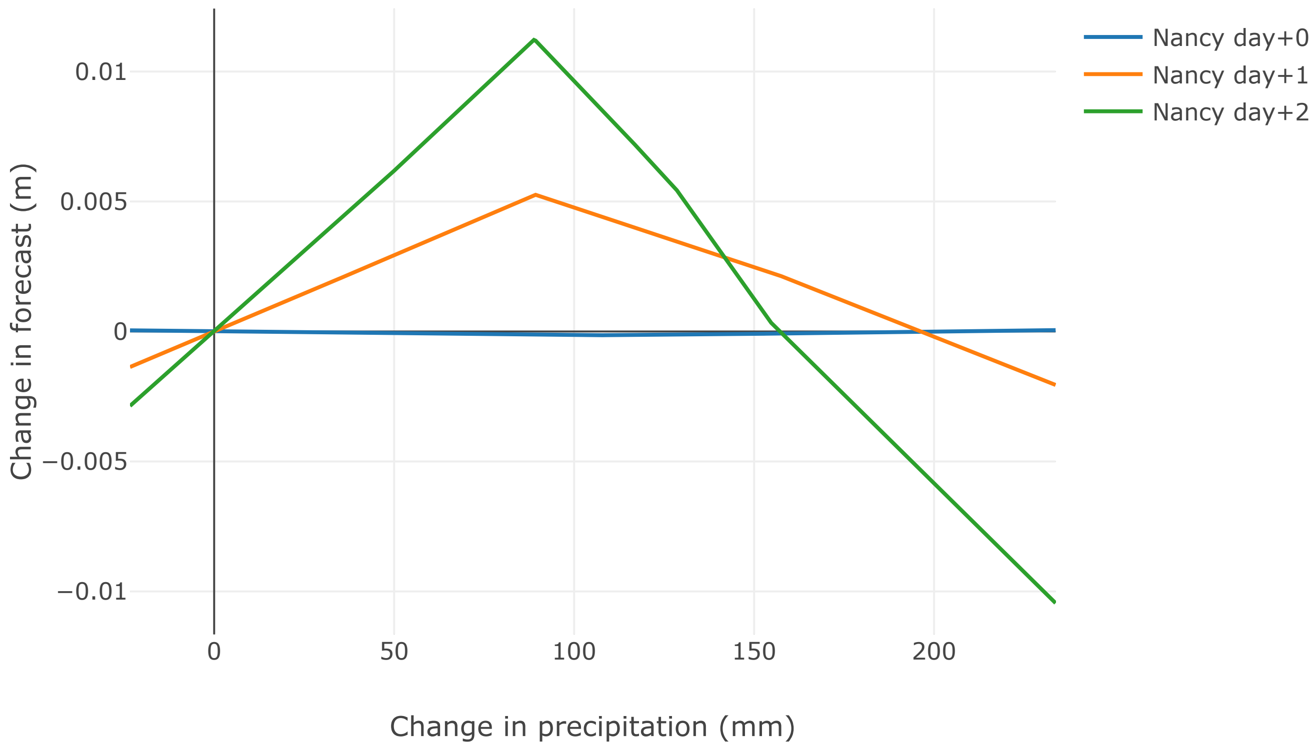

Figure 94: Sensitivity analysis for Nancy with very high water levels and very high precipitation

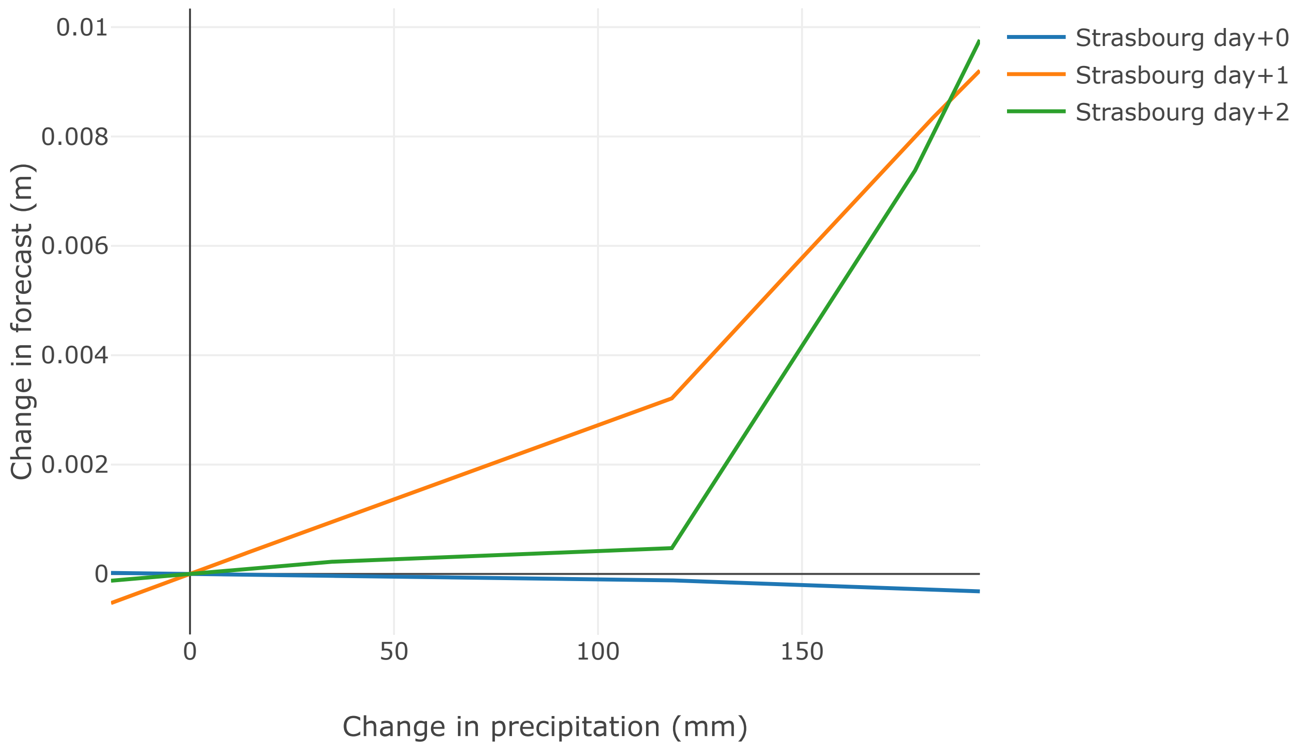

Figure 95: Sensitivity analysis for Strasbourg with very high water levels and very high precipitation

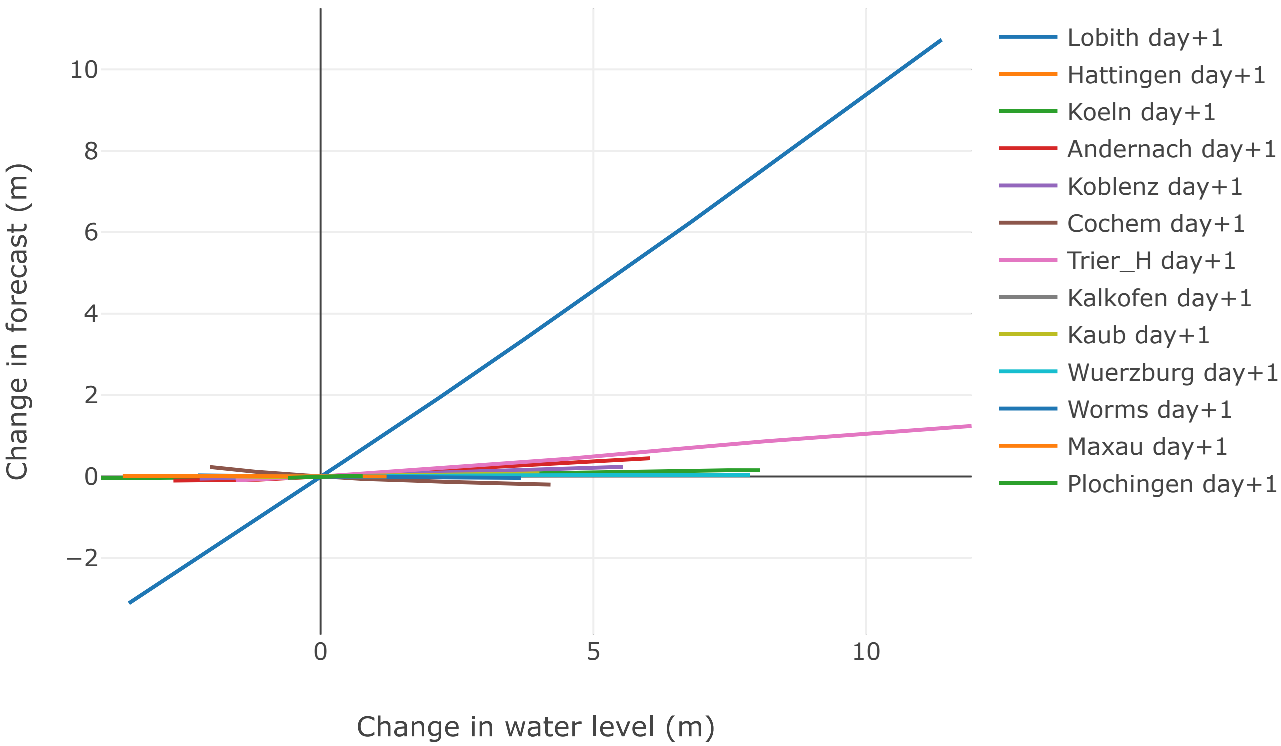

Figure 96: Sensitivity analysis for Water levels (day+1) with very high water levels and very high precipitation

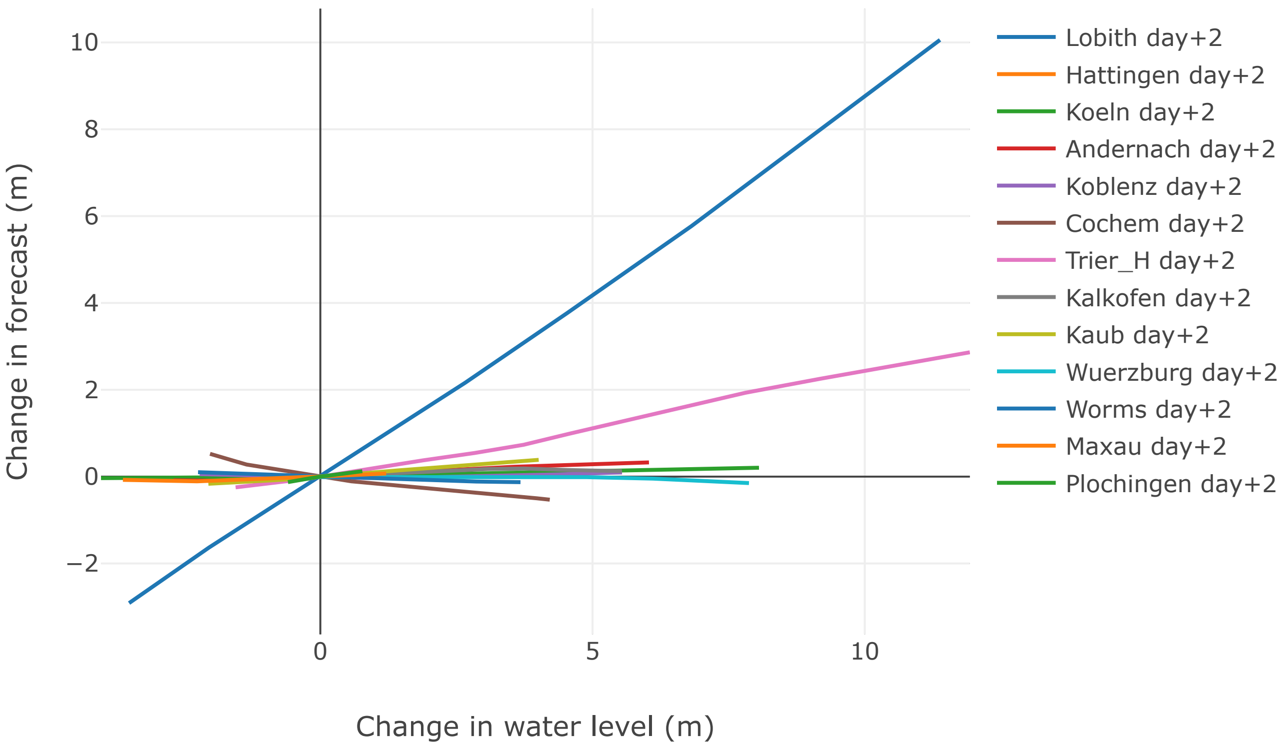

Figure 97: Sensitivity analysis for Water levels (day+2) with very high water levels and very high precipitation

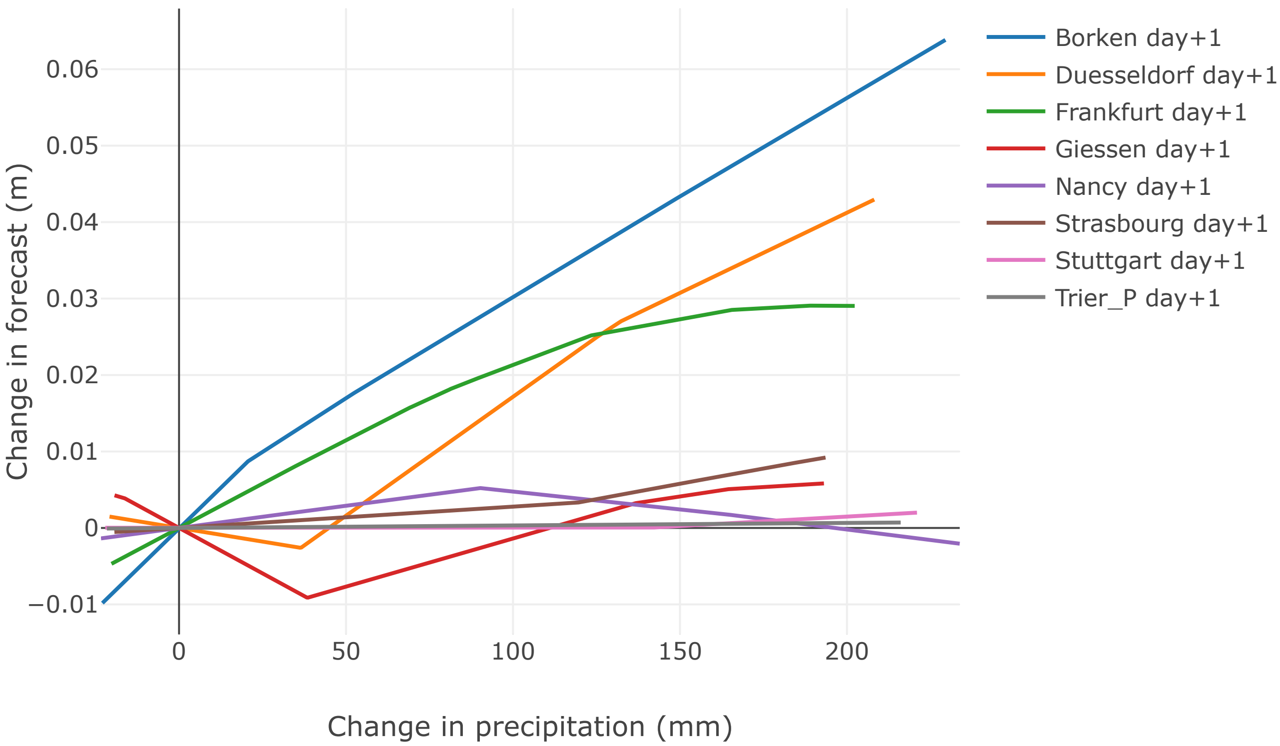

Figure 98: Sensitivity analysis for Precipitation (day+1) with very high water levels and very high precipitation

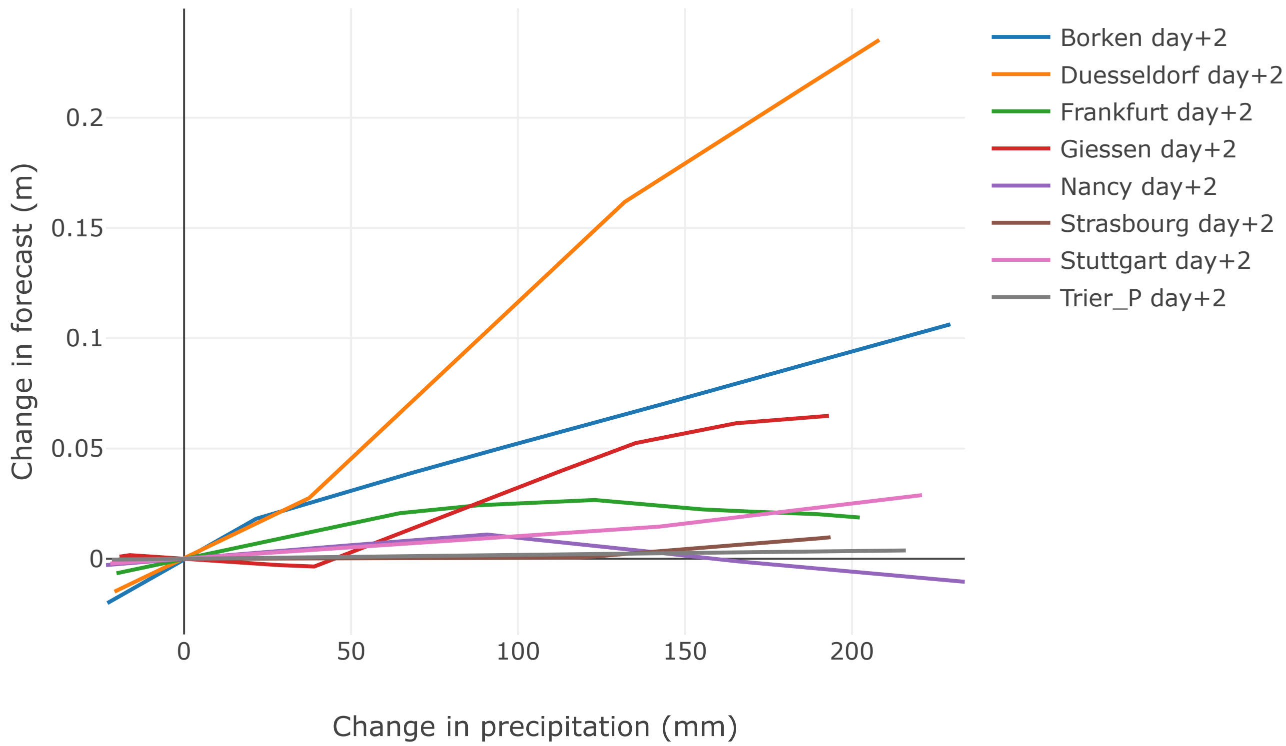

Figure 99: Sensitivity analysis for Precipitation (day+2) with very high water levels and very high precipitation

A.9 Extremely high water levels and extremely high precipitation

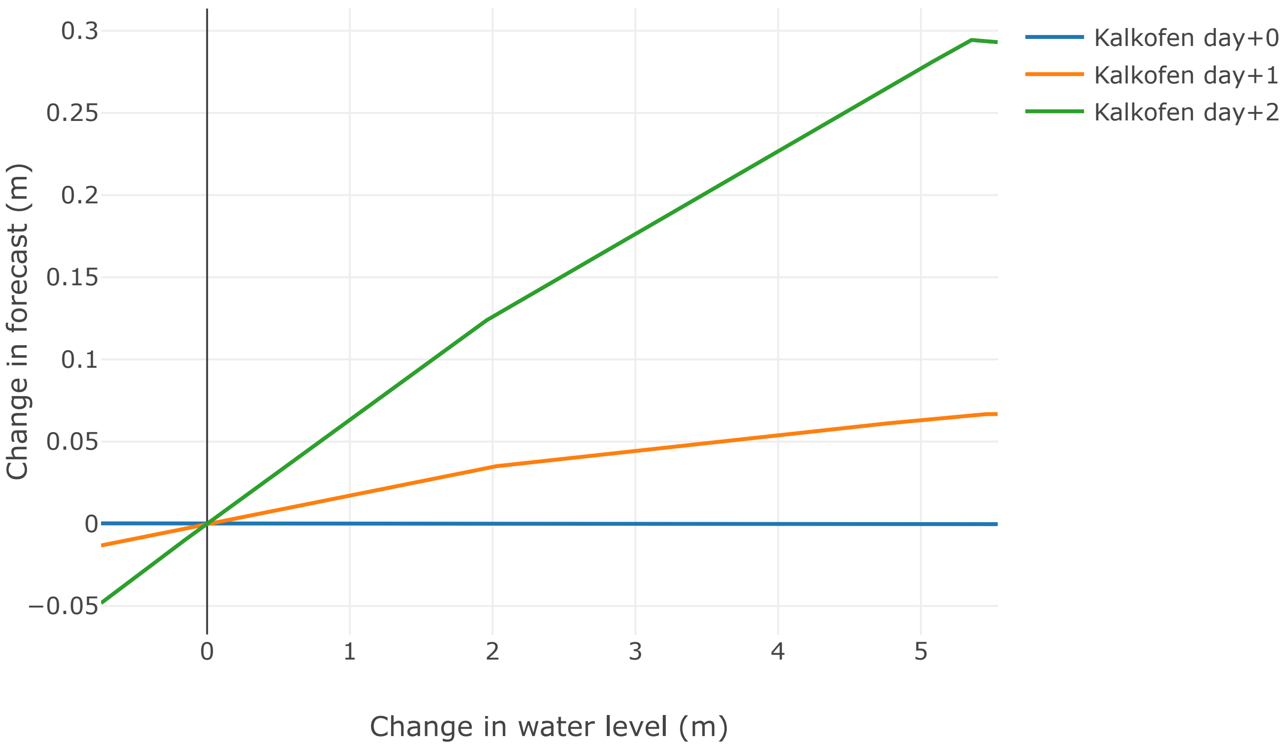

Figure 100: Sensitivity analysis for Kalkofen with extremely high water levels and extremely high precipitation

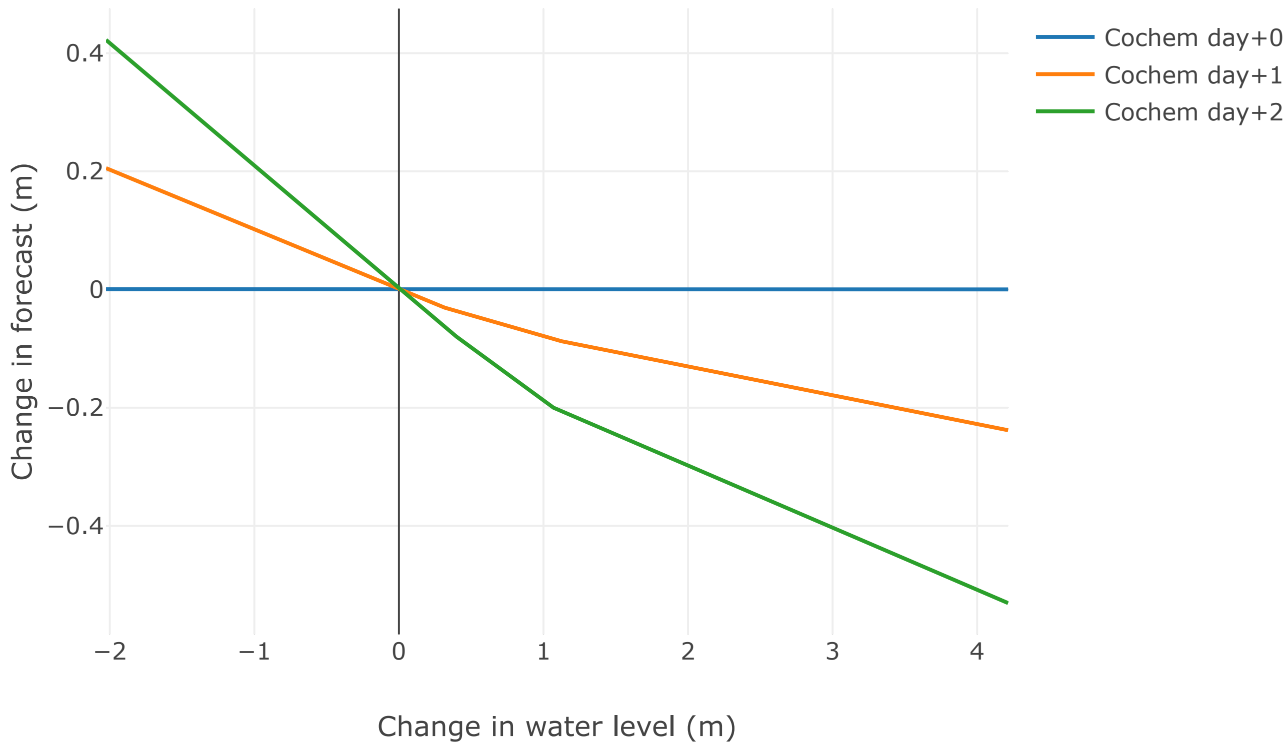

Figure 101: Sensitivity analysis for Cochem with extremely high water levels and extremely high precipitation

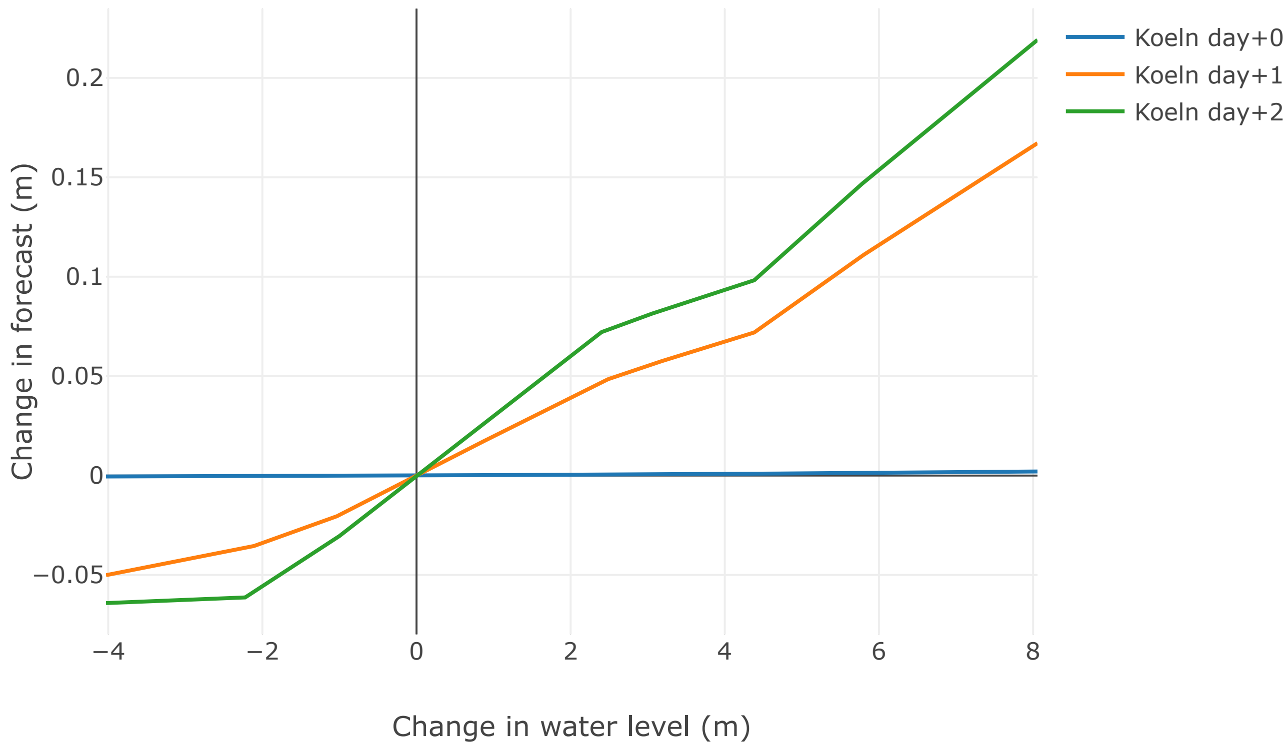

Figure 102: Sensitivity analysis for Köln with extremely high water levels and extremely high precipitation

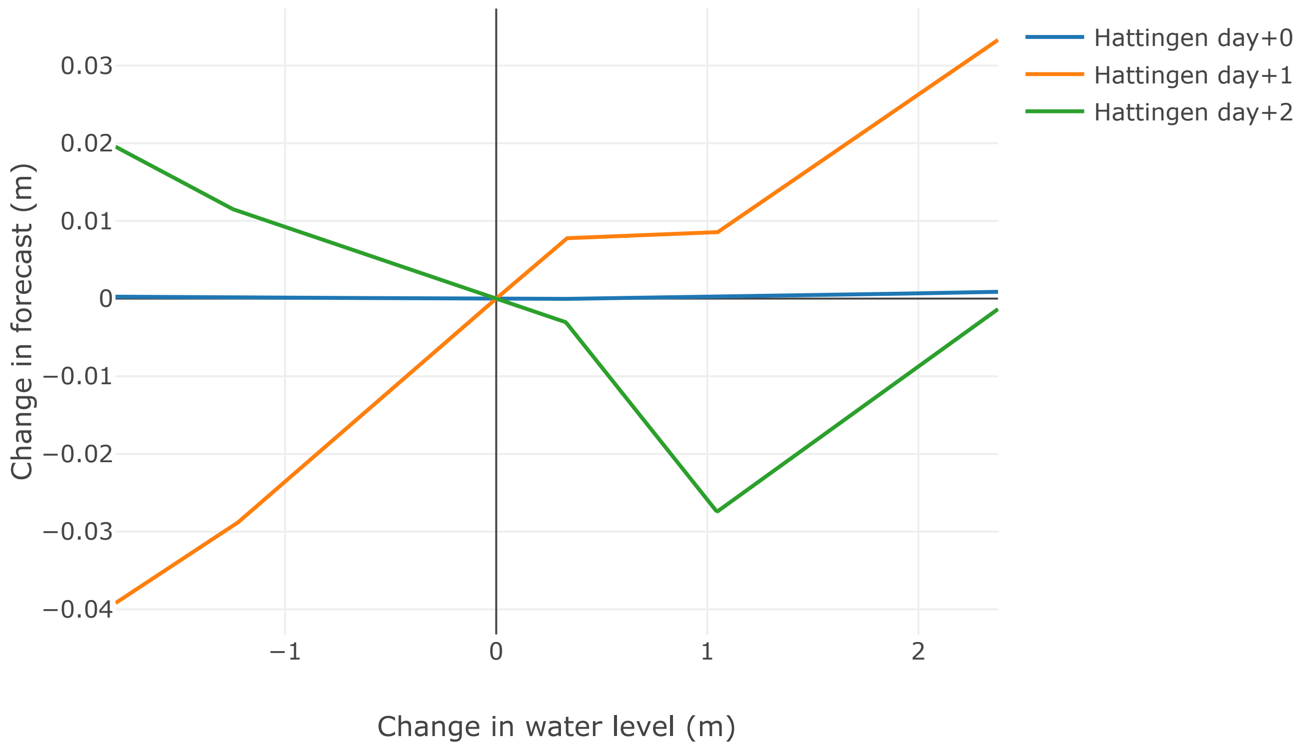

Figure 103: Sensitivity analysis for Hattingen with extremely high water levels and extremely high precipitation

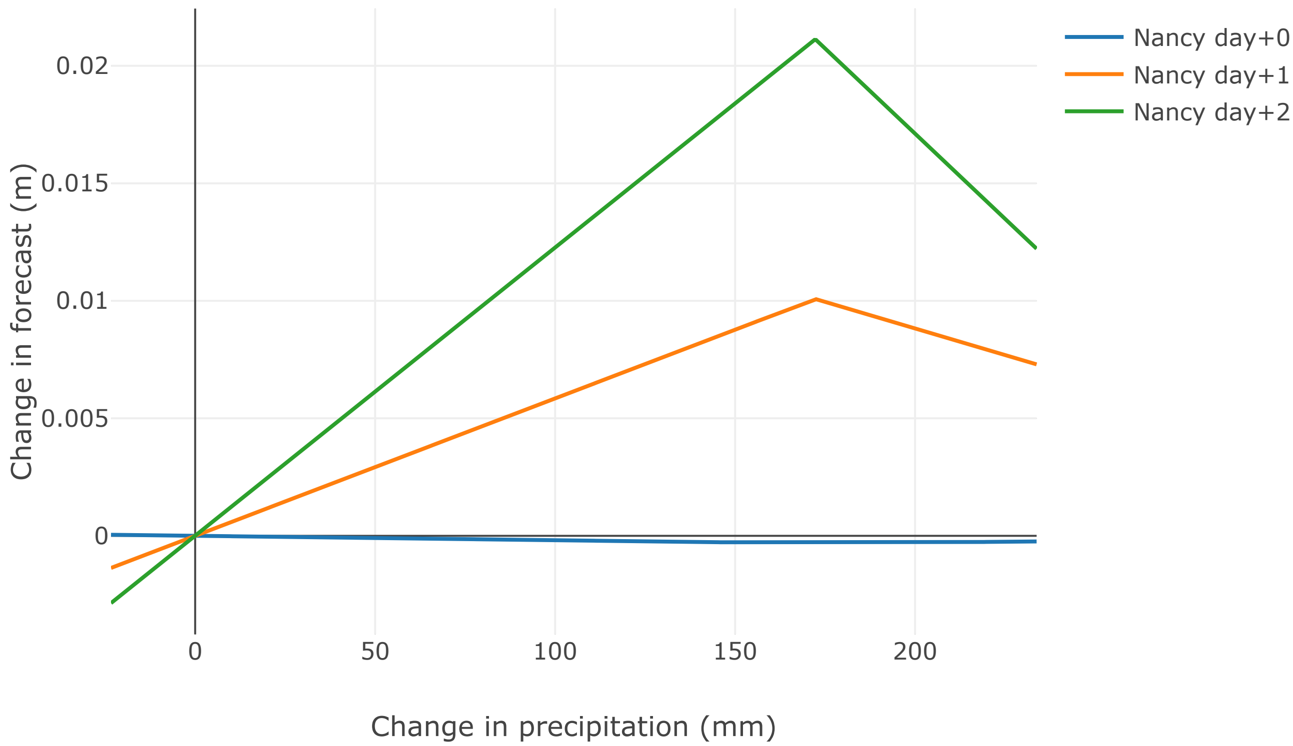

Figure 104: Sensitivity analysis for Nancy with extremely high water levels and extremely high precipitation

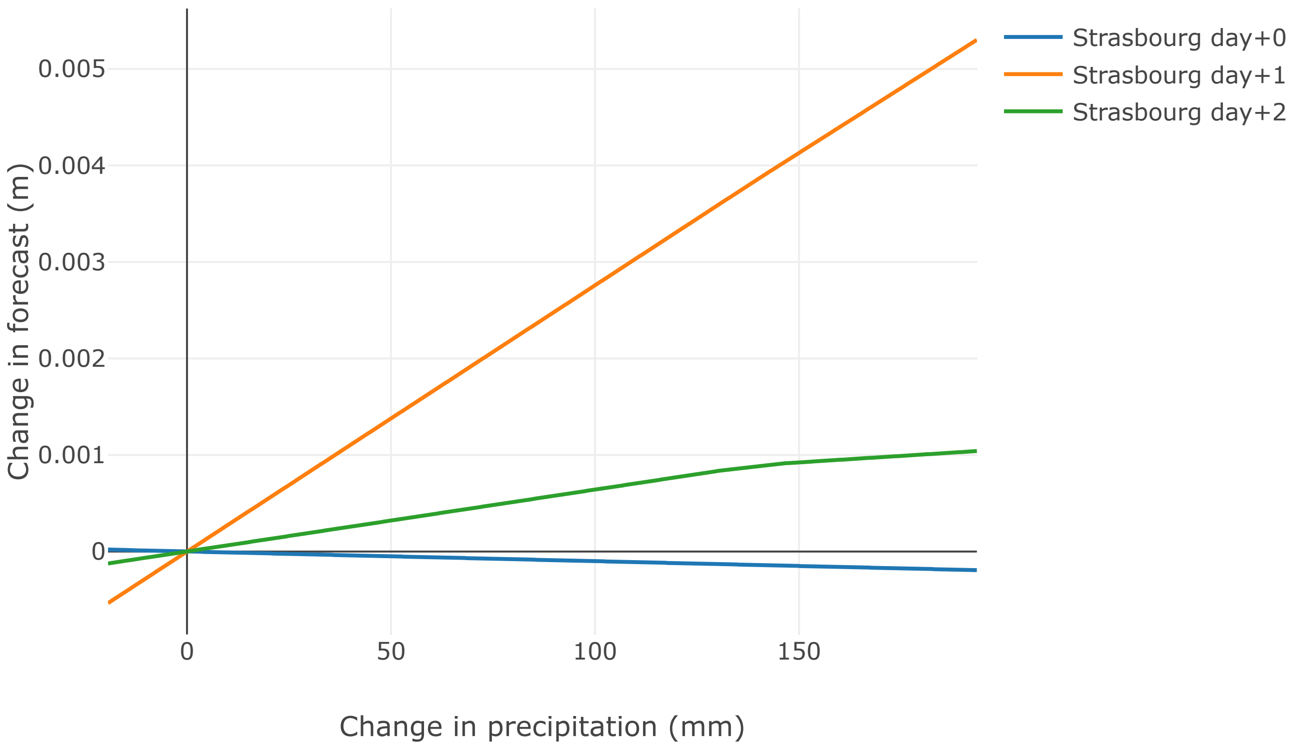

Figure 105: Sensitivity analysis for Strasbourg with extremely high water levels and extremely high precipitation

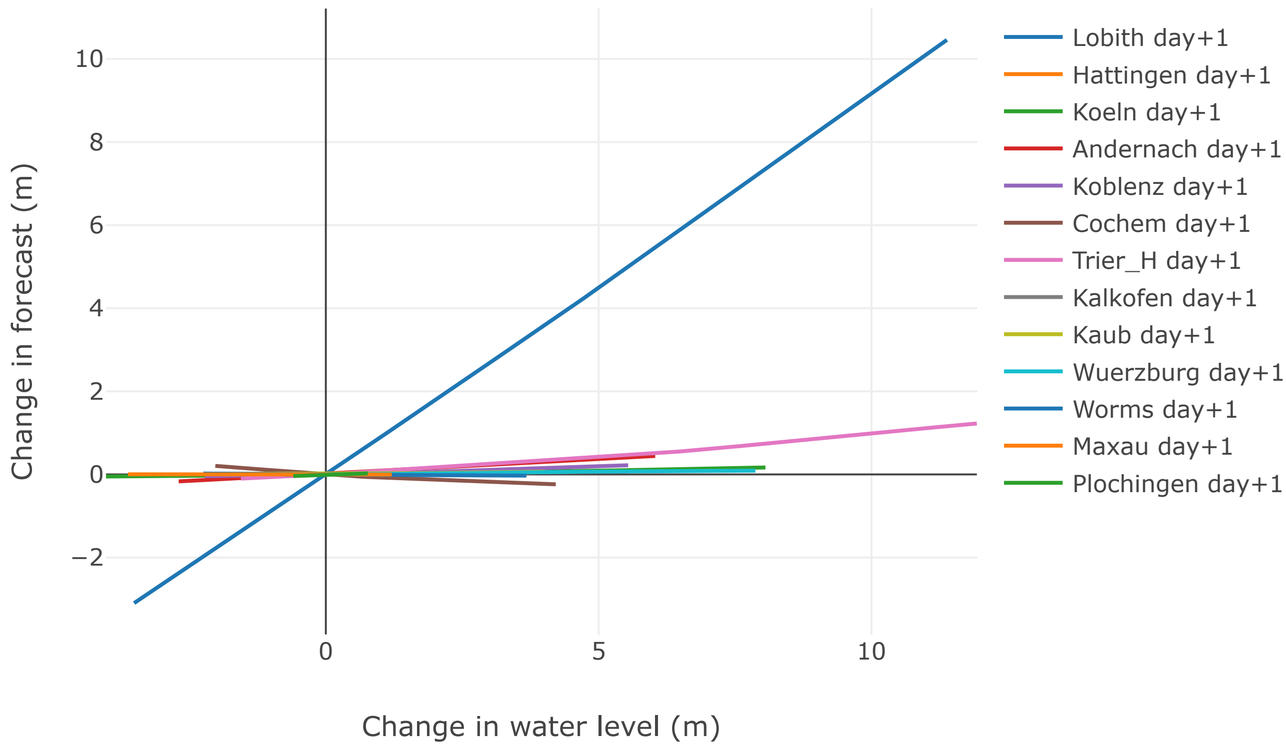

Figure 106: Sensitivity analysis for Water levels (day+1) with extremely high water levels and extremely high precipitation

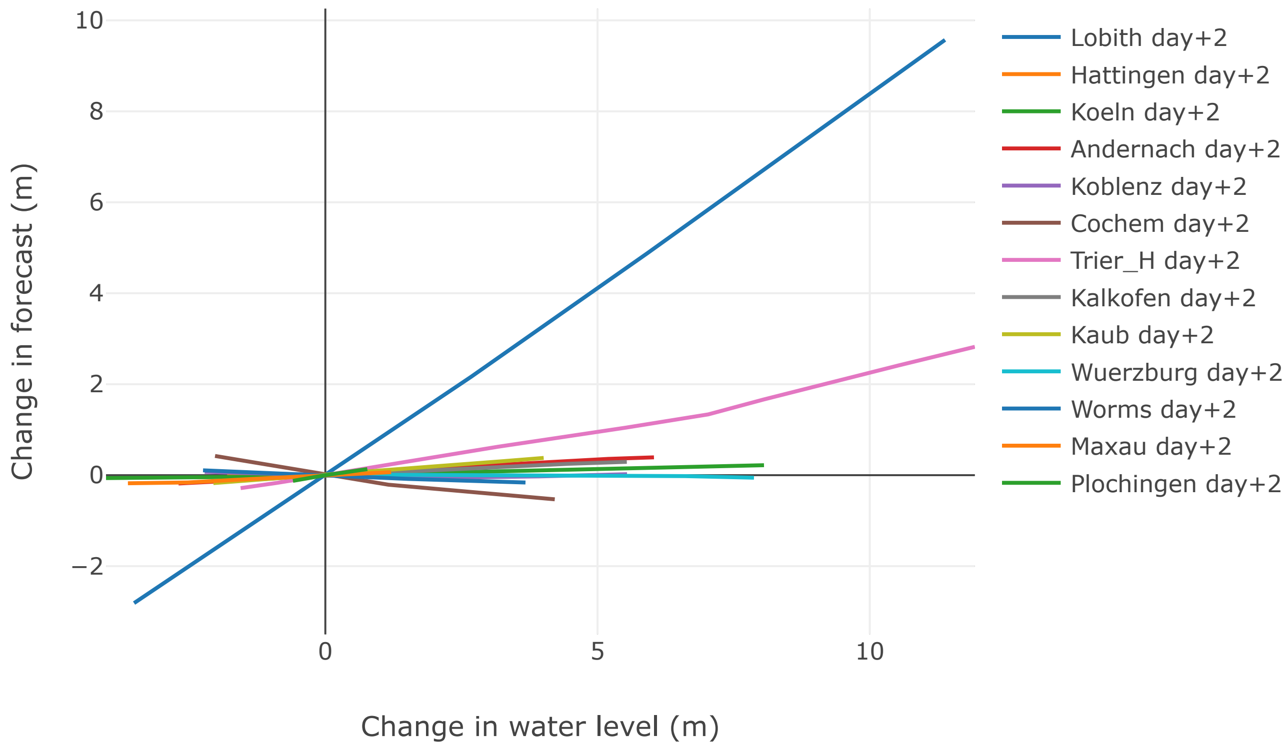

Figure 107: Sensitivity analysis for Water levels (day+2) with extremely high water levels and extremely high precipitation

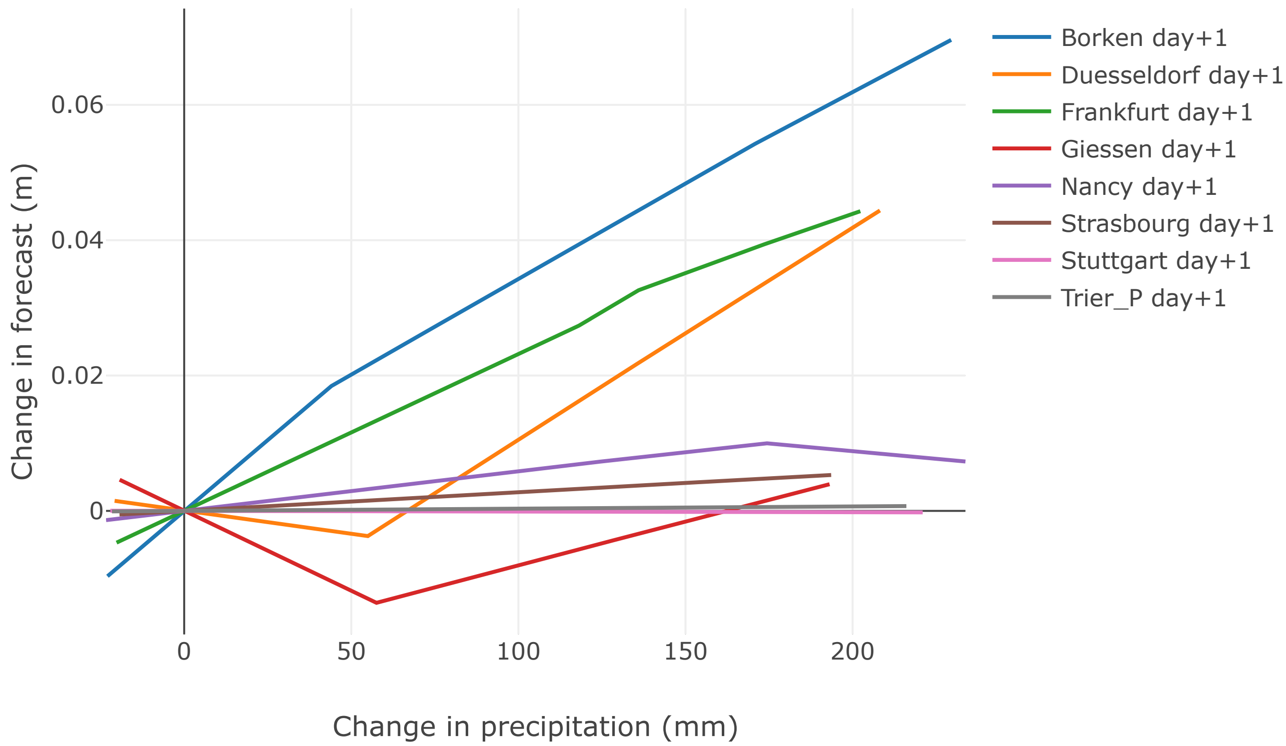

Figure 108: Sensitivity analysis for Precipitation (day+1) with extremely high water levels and extremely high precipitation

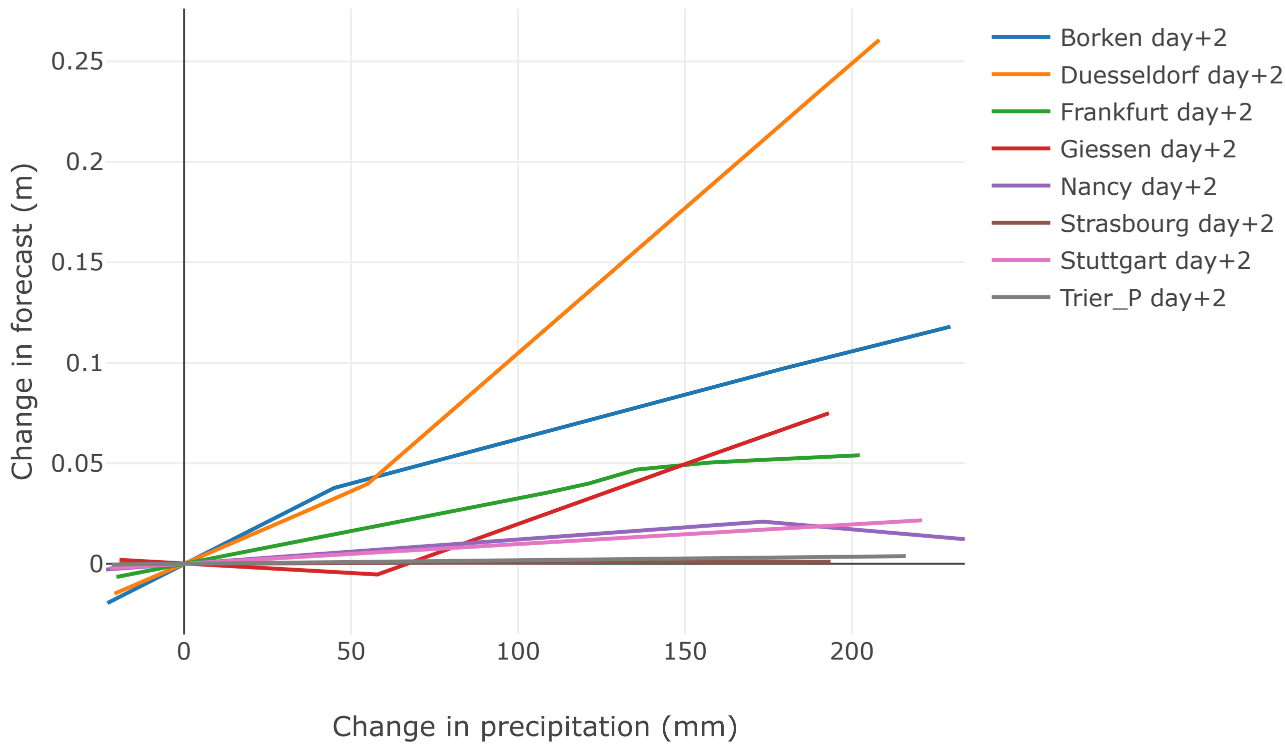

Figure 109: Sensitivity analysis for Precipitation (day+2) with extremely high water levels and extremely high precipitation

A.10 Extremely low water levels and high precipitation

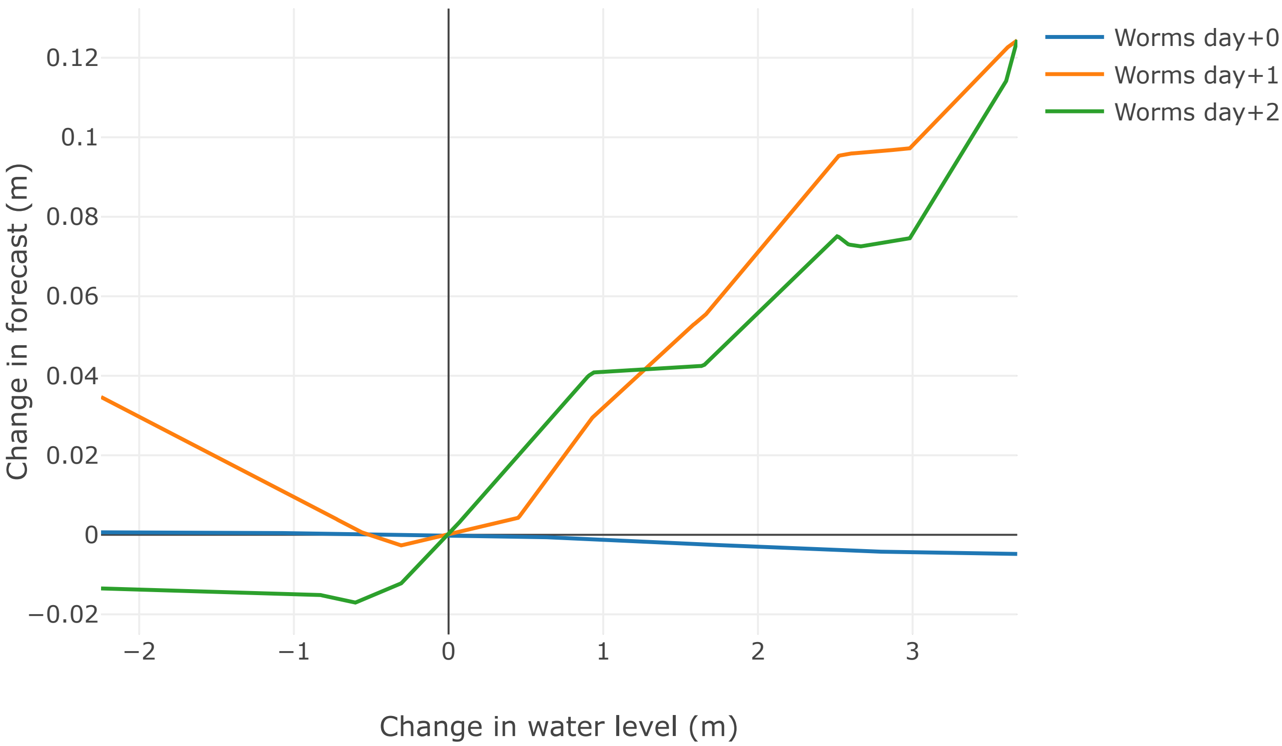

Figure 110: Sensitivity analysis for Worms with extremely low water levels and high precipitation

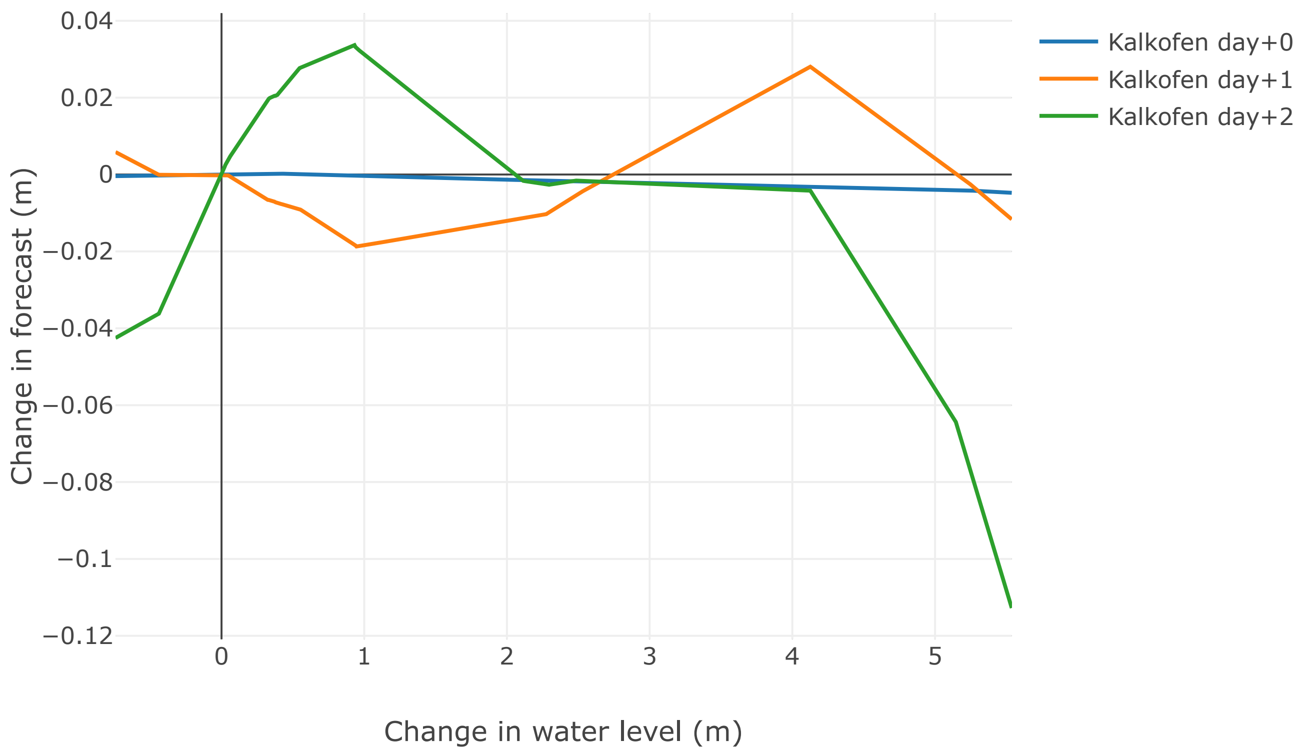

Figure 111: Sensitivity analysis for Kalkofen with extremely low water levels and high precipitation

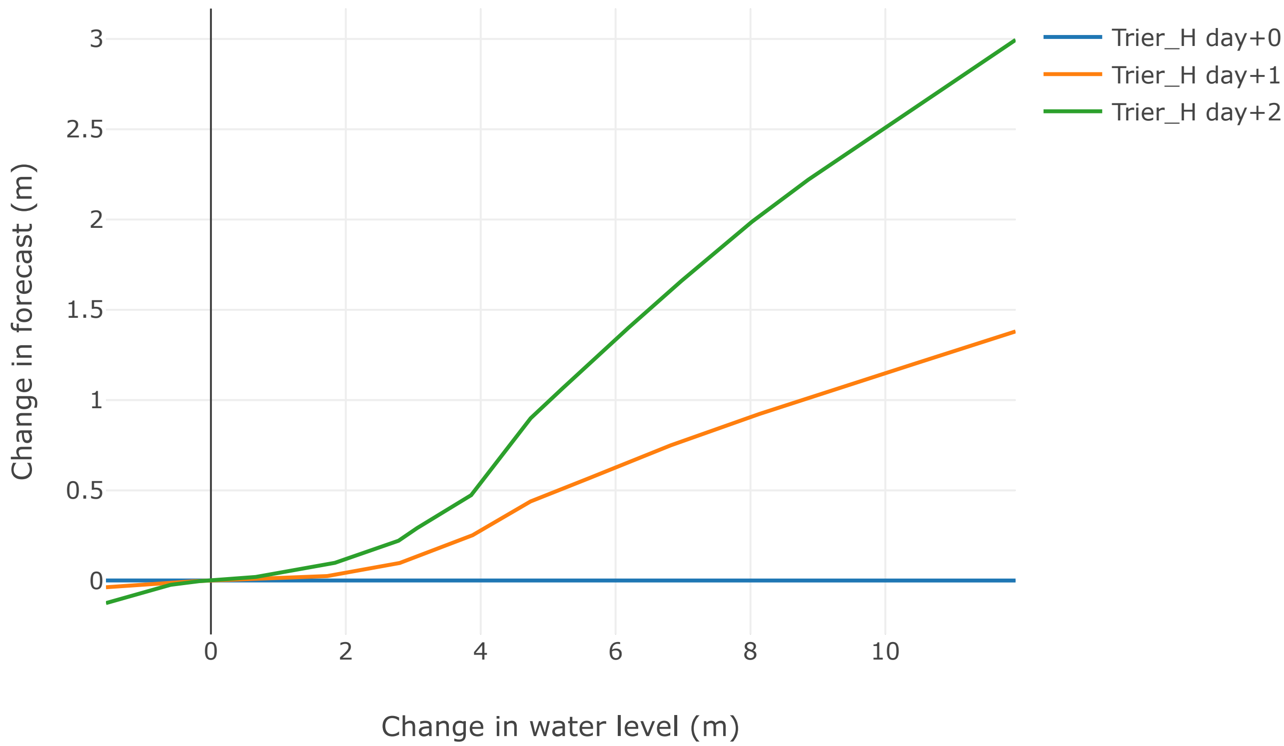

Figure 112: Sensitivity analysis for Trier (Water levels) with extremely low water levels and high precipitation

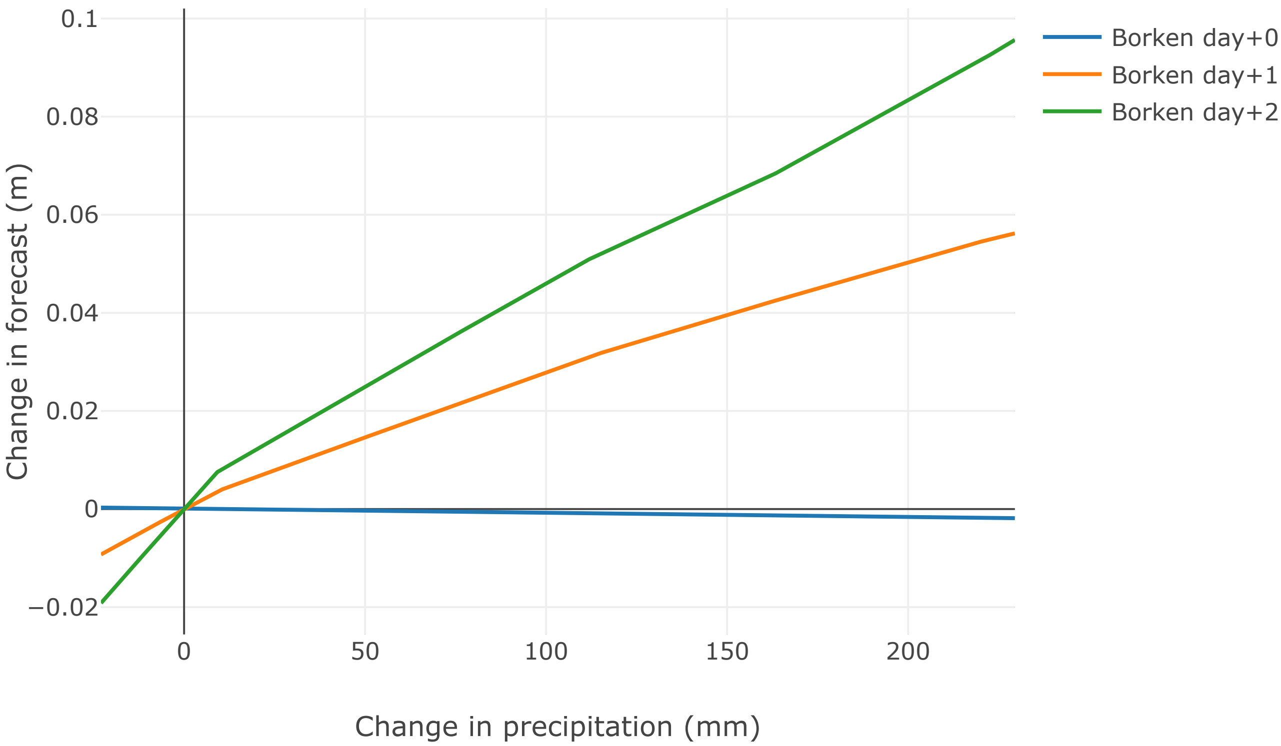

Figure 113: Sensitivity analysis for Borken with extremely low water levels and high precipitation

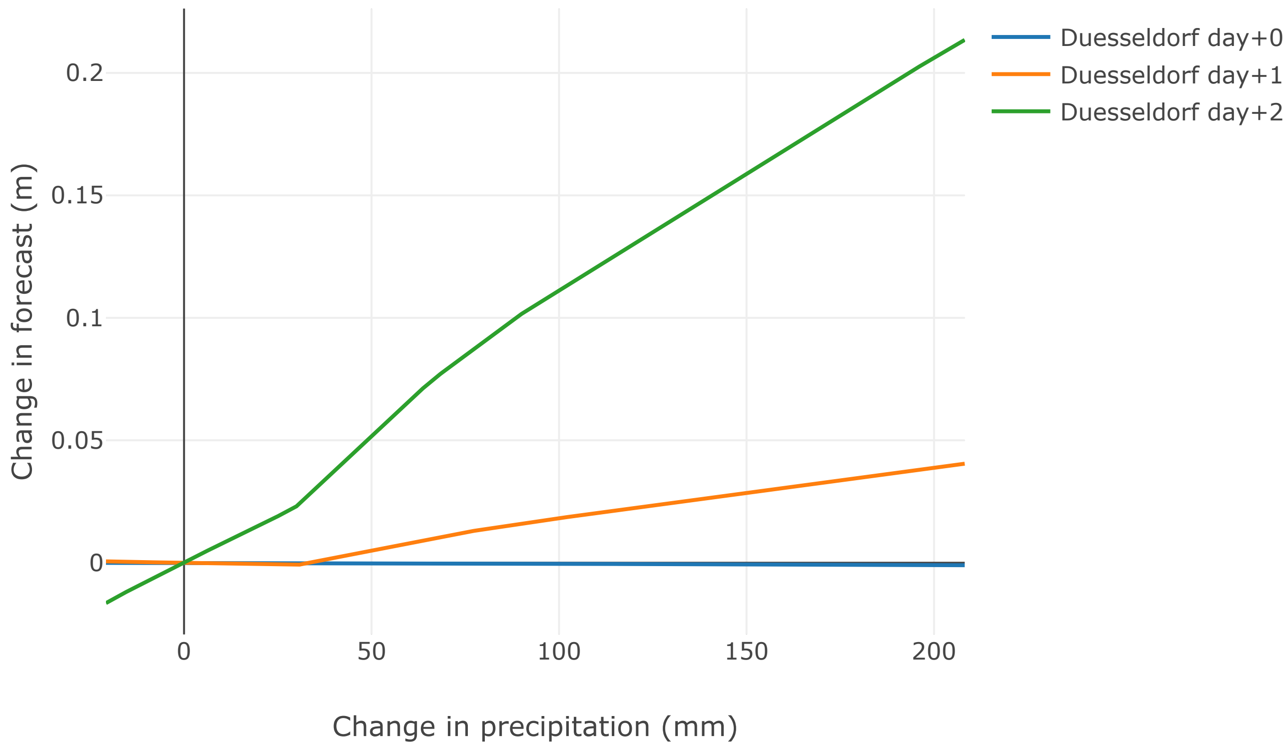

Figure 114: Sensitivity analysis for Düsseldorf with extremely low water levels and high precipitation

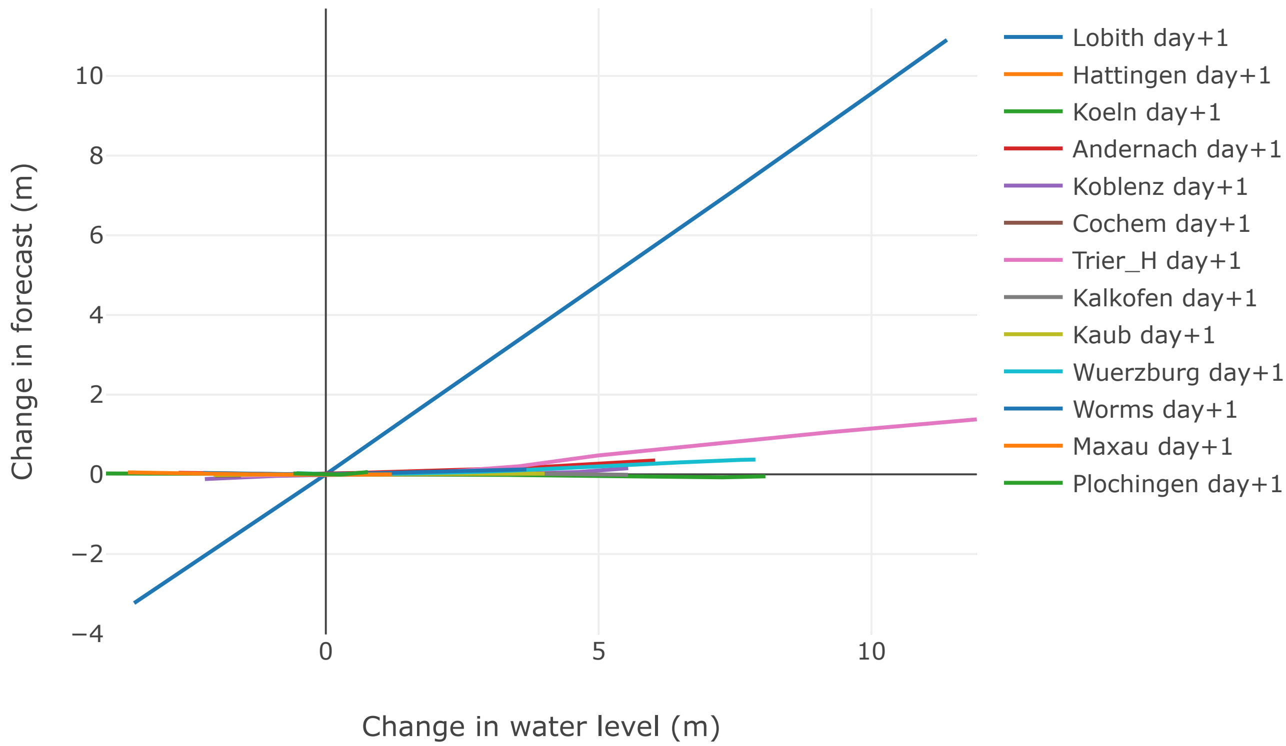

Figure 115: Sensitivity analysis for Water levels (day+1) with extremely low water levels and high precipitation

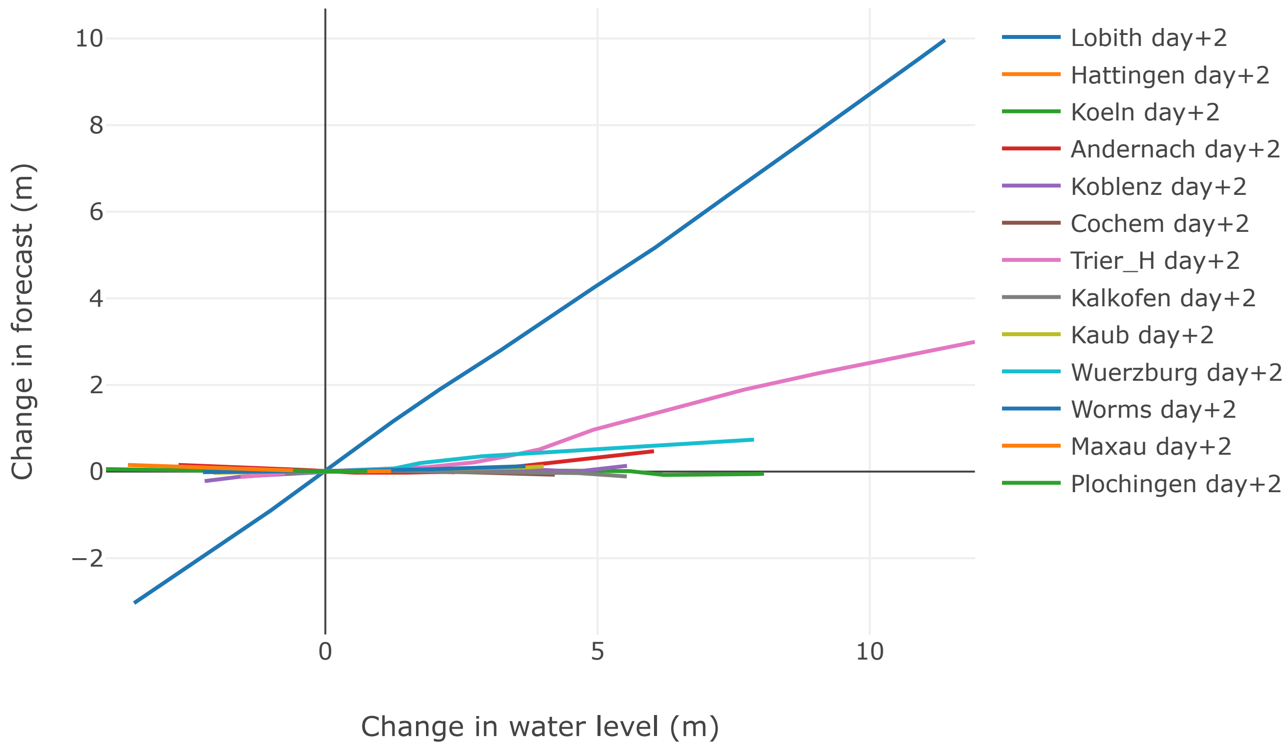

Figure 116: Sensitivity analysis for Water levels (day+2) with extremely low water levels and high precipitation

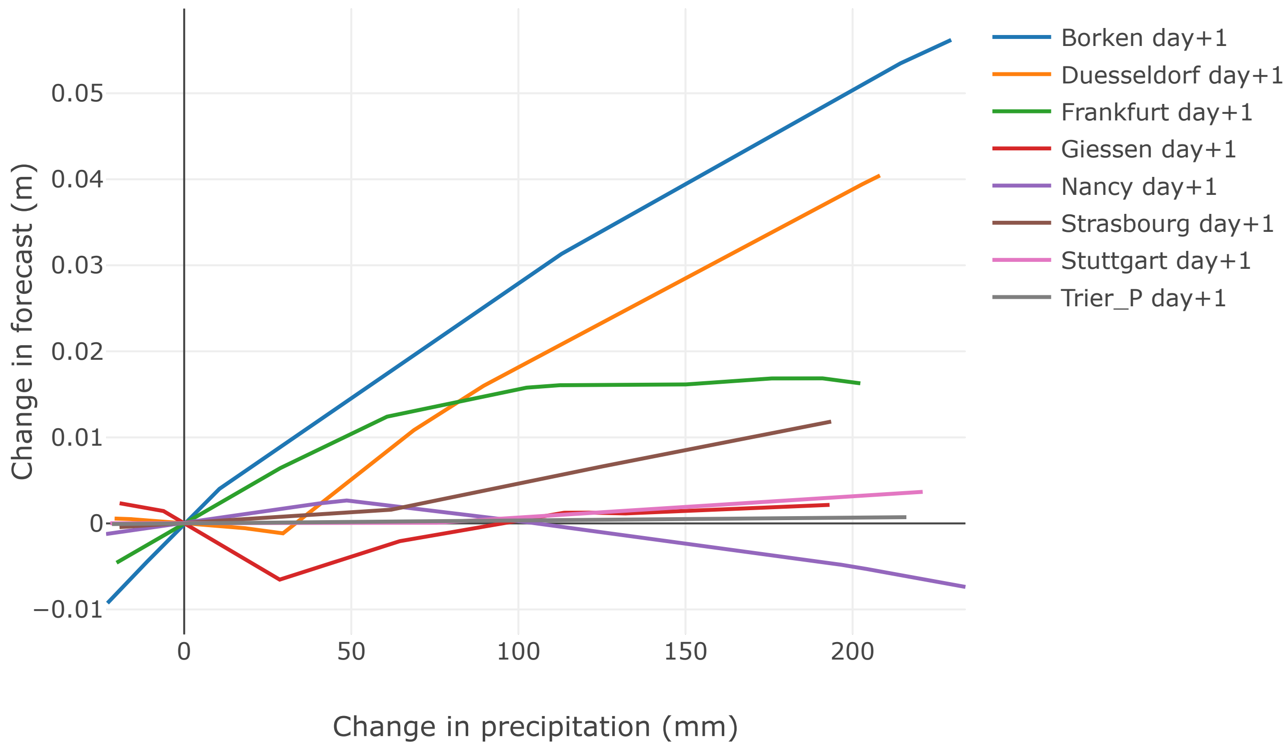

Figure 117: Sensitivity analysis for Precipitation (day+1) with extremely low water levels and high precipitation

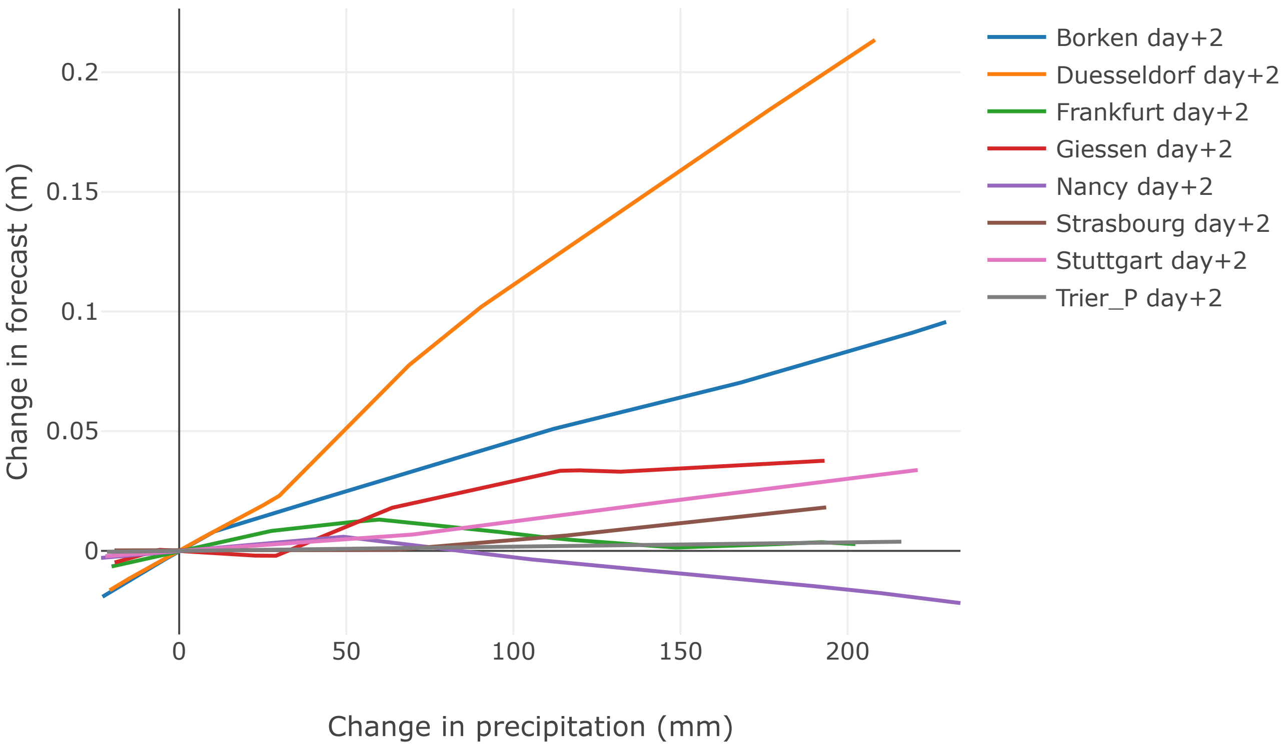

Figure 118: Sensitivity analysis for Precipitation (day+2) with extremely low water levels and high precipitation