TUSSENRAPPORT

March 7, 2025

1 Introduction

Last September, the Wien River, normally a small trickle, swelled into a raging torrent, having a serious impact on public transport. Damage to the public transport was kept to a minimum thanks to the flood alarm plan, but still almost one-million-liter water had to be pumped out of the subway lines (Krone.At, 2024b). The Wien River is one of the largest rivers of Vienna and has a catchment area of 230 km2. Along a reach of over 8 km, the subway line U4 follows the river in an open section on the right bank. Flooding on the Wien River is critical because of the large area of impervious surfaces in the catchment area. Wien River floodings are typically flash floodings. The threat regarding flooding in Vienna is caused by large channel slopes and flow velocities, rapid increase of discharge and the absence of natural retention areas. Furthermore, the low hills and mountains in the area intensify storm events compared to plain areas through intensified convective air movement (Compton et al., 2009, pp. 13–14). Dore (2005) states in his article about climate change and changes in global precipitation patterns that due to climate change, precipitation is expected to increase in the Northern Hemisphere. The wet areas will get wetter, and the rainfall will get more intense. Changes in precipitation due to climate change may affect the water level and discharge of the Wien River, posing potential risks to the operation and safety of the adjacent U4 subway line.

Flood risk management is critical for urban resilience, especially in places where natural waters are closely linked to infrastructure. Compton et al. (2009) highlight in their study on uncertainty and disaster risk management how an approach based on catastrophe modeling can provide a useful framework for comparing different mitigation strategies as well as integrate the risk perspectives of different technical disciplines. For their study they use hydraulic models to obtain probability of failure for different storm return periods and states of the flood control reservoirs. This report will focus on flood risk as well but shifts the focus towards how the discharge and water levels in the Wien River will change due to climate change, influencing the flood risk for the U4 subway line. Hydrological models with different climate change scenarios will be implemented to simulate the future discharge scenarios of the Wien River. The report will focus solely on changes in flood frequency due to climate change and excludes the current flood protection infrastructures and adaption measures these might require. This research will contribute to Vienna's flood risk management and is relevant for the transportation authorities, policymakers and urban developers in Vienna who are seeking to make the city future-proof for increasing threats due to climate change.

In this report the following research question will be answered: "What is the impact of climate change on the hydrology of the Wien River and what are the implications for flooding of the adjacent U4 subway line?" This is done using the following sub-questions: - What is the current maximum discharge (m3/s) in the Wien above which the U4 subway line will flood? - How often does the discharge currently exceed the maximum? - How often will the discharge exceed this maximum in the future under different climate change scenarios?

The research question will be answered using the sub-questions. To determine the maximum discharge threshold for flooding of the U4, literature study needs to be done. Historical events, flood risk maps, research papers and monitoring stations need to be analyzed. The current frequency at which the discharge exceeds this maximum can be determined using eWaterCycle. Past streamflow can be simulated with a hydrological model. The simulated discharge data then can be compared to the flood threshold determined before. The model should be calibrated using real-world data. The frequency of flooding of the U4 with current discharge data can be conducted with return period calculations. The future discharge can be simulated with the use of future climate projections. Climate models provided by CMIP6 will be used. Different IPCC scenarios give different projected climate variables which can be used in hydrological models using eWaterCycle to simulate future discharge. These modeled future discharge scenarios should be compared to the flood threshold to estimate the future frequency of exceedance for different climate change scenarios.

The eWaterCycle platform provides the hydrological community with models, all written in different programming languages, that can all be accessed in a similar manner, through the Jupyter notebook environment in eWaterCycle.

In Chapter 1 the current maximum discharge (m3/s) is determined above which the U4 subway line will flood. Chapter 2 determines how often the discharge currently exceeds this maximum using the observation data from eWaterCycle. In Chapter 3 the hydrological model is calibrated. In Chapter 4 different climate change scenarios are projected in hydrological models to simulate future discharge. These future discharge scenarios are compared to the flood threshold to estimate the future flooding frequency of the U4 subway line. In Chapter 5 the conclusion and discussion can be found.

2 Chapter 1: Current maximum discharge before flooding of the U4

The Wien River finds its origin in the Wienerwald, west of Vienna, and enters the city after approximately 20 km. The river discharges into the Donaukanal. The historical hydrology of the Wien River cannot be reconstructed with certainty. However, before the construction of intercepting sewers along the river in the 1830s and its regulation and channelization at the end of the 19th century, the estimated mean annual discharge was approximately 2 m^3/s (Pollack et al., 2016).
Since the flood retention basins that were made in the early 1800's, the 10-year return flood was estimated at 140 m3/s, and the 100-year return flood at 200 m3/s. Due to the high potential losses in the city of Vienna, the Wien River is designed to withstand a 1000-year discharge return period (Faber & Nachtnebel, 2002).
Compton et al. (2009, p. 54) state: "A failure that results in the release of water to the U4 occurs when the discharge into the Wien River exceeds the given threshold, resulting either in overtopping of the floodwall or collapse of the floodwall due to either foundation scouring or hydrostatic pressure." While failure due to overtopping is a function of the flow rate in the channel, uncertainties in the water flow rate at are expected to be minimal since the Wien River is a channelized river with well characterized geometry. More uncertainty is expected in the erosive failure and wall collapse which are a function of the shear at the channel bed and the shear strength of the invert.
According to the report, the failure leading to overflowing of the U4 is expected to occur at a

discharge of 530 m3/s. Given the uncertainties in the floodwall's resistance parameters, this critical discharge is modeled as a normal distribution with mean value of 530 m3/s and a standard deviation of 10 m3/s. This means that at a discharge of around 510 m3/s failure could occur with a probability of 5 percent, and at a discharge of around 550 m3/s with a probability of 95 percent. (Compton et al., 2009)

The study of Faber (2006) also analyzed flood risk in an Austrian context, and specifically for the Wien River. He estimated peak flow frequencies using the rainfall-runoff model IHW for the rural catchment and ITWH for the urban areas, and he used Monte Carlo simulations to account for uncertainties. A total of 7000 simulations were performed within the critical range of 400 to 600 m3/s where failures were most likely to occur. Figure 1 shows that the flood walls can handle discharges up to 500 m3/s, while overtopping of the floodwall is almost certain at a discharge of 560 m3/s. The mean value of the discharge capacity before overtopping amounts to 534 m3/s, with a standard deviation of 14 m3/s. The mean value of discharge for structural floodwall failure is 541 m3/s with a standard deviation of 16 m3/s (Faber, 2006).
Faber also analyzed the probabilities of the different failure events, overtopping and structural damage of the flood wall, individually and in combination. The probability of structural flood wall failure without overtopping was not observed in any simulation. The overall system reliability is above 99 percent, which indicates that failure of the flood wall is extremely rare with the used past peak flows. He further analyzed the return periods of the failure events. The installation of the controlled retention basins in 1998 increased the return period of failure from approximately 550 years to 1100 years. This return period exceeds the 1000-year discharge return period the Wien River is designed for (Faber & Nachtnebel, 2002). This deviation is due to limitations of the return period-based design, which does not fully account for uncertainties in flood frequency and magnitude.

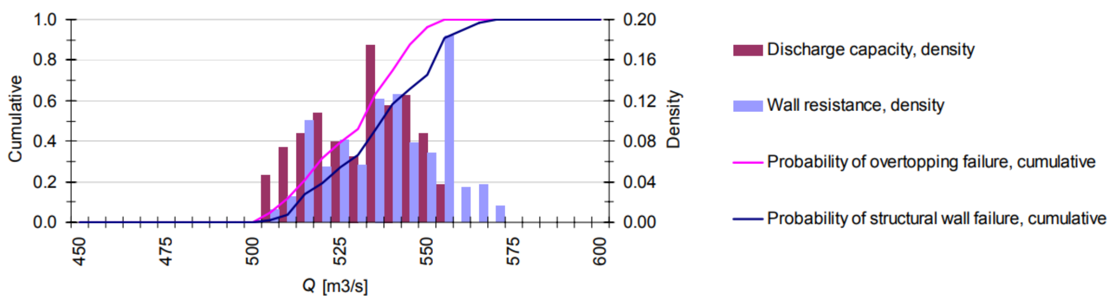


Figure 1: "Distribution of the resistance of the hydraulic system in terms of the bankfull discharge and the flow related to structural floodwall failure"(Faber, 2006)

It can be concluded that the critical event for flooding of the U4 subway line is overtopping rather than structure failure of the flood wall. According to Faber (2006), the mean failure discharge at which overtopping happens is 534 m3/s, with a 5 percent probability at 511 m3/s, and a 95% probability at 557 m3/s. These values align with the threshold values determined by Compton et al. (2009), who estimated a mean failure discharge of 530 m3/s, with 5 and 95 percent probabilities of failure at discharges of approximately 510 and 550 m3/s. The threshold values are normally distributed, so looking at 1 critical threshold value would be a simplification. The probability of exceeding a threshold is heavily dependent on where that threshold is situated in the normal distribution. For this reason the return periods of all discharges in the normal distribution are calculated. This will give an indication of the return period of a certain discharge, and the probability that this specific discharge will lead to flooding of the U4 subway line.

3 Chapter 2: Current frequency of threshold exceedance

In this chapter the current frequency of exceeding the threshold determined in chapter 1 wil be analysed. This is done by looking at the available observation data of the catchment area of the Wien River. This observation data is available through eWaterCycle. As determined in chapter 1, the Wien River is designed for a 1000-year discharge return period. The observation data is unlikely to cover a period of 1000 years, so we will need to extrapolate it to estimate the discharge corresponding to a 1000-year return period and determine the return period of the previously established threshold.

3.1 General

First of all, some general python and eWaterCycle libraries need to be imported.

eWaterCycle provides access to the Caravan dataset. This dataset contains data on rainfall, potential evaporation and discharge for all the catchments in the different Camel datasets. The Caravan dataset contains a Camel dataset of the catchment of the Wien River. This catchment area is loaded below:

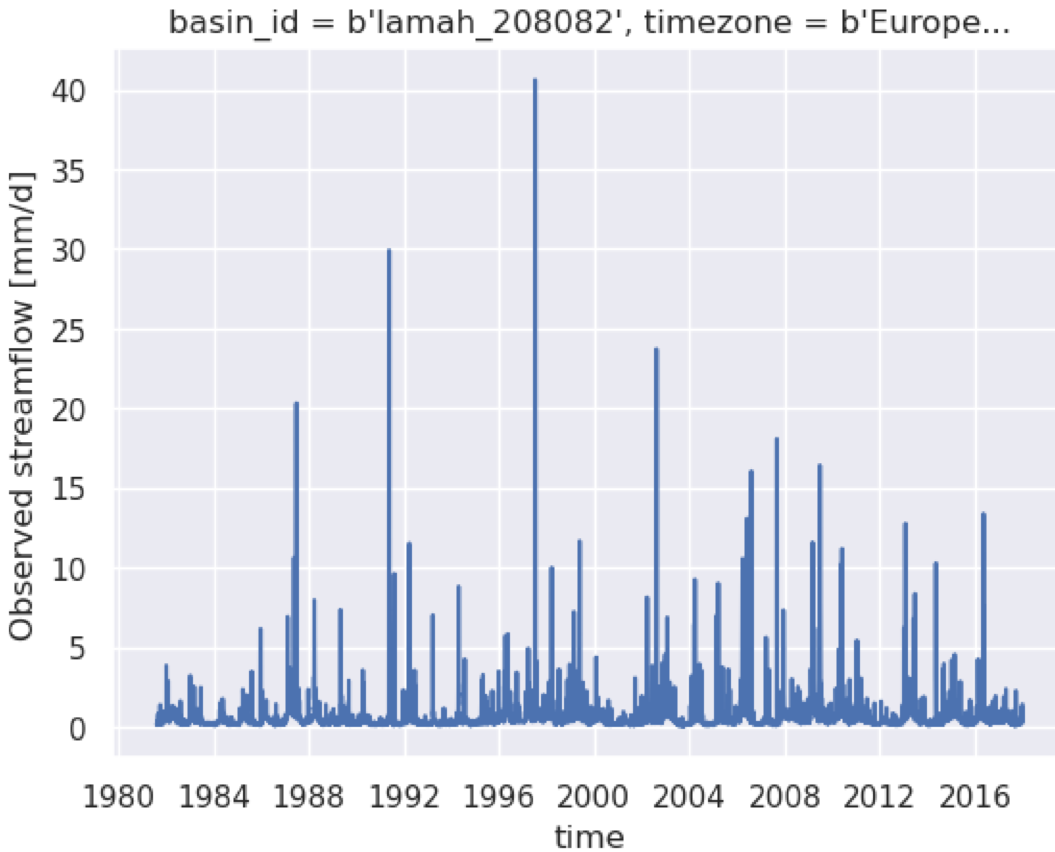
The start and end date of the experiment need to be specified. The start and end date of the available observation data are determined further below, and are hardcoded in the following cell:

The forcing data can be generated or previously generated data can be loaded:

```
CaravanForcing(
    start_time='1981-08-01T00:00:00Z',
    end_time='2030-12-31T00:00:00Z',
    directory=PosixPath('/home/thirza/forcing/lamah_208082/caravan'),
    shape=PosixPath('/home/thirza/forcing/lamah_208082/caravan/lamah_208082.
↪shp'),
    filenames={
        'tasmax': 'lamah_208082_1981-08-01_2030-12-31_tasmax.nc',
        'tas': 'lamah_208082_1981-08-01_2030-12-31_tas.nc',
        'tasmin': 'lamah_208082_1981-08-01_2030-12-31_tasmin.nc',
        'Q': 'lamah_208082_1981-08-01_2030-12-31_Q.nc',
        'pr': 'lamah_208082_1981-08-01_2030-12-31_pr.nc',
        'evspsblpot': 'lamah_208082_1981-08-01_2030-12-31_evspsblpot.nc'
    }
)
```

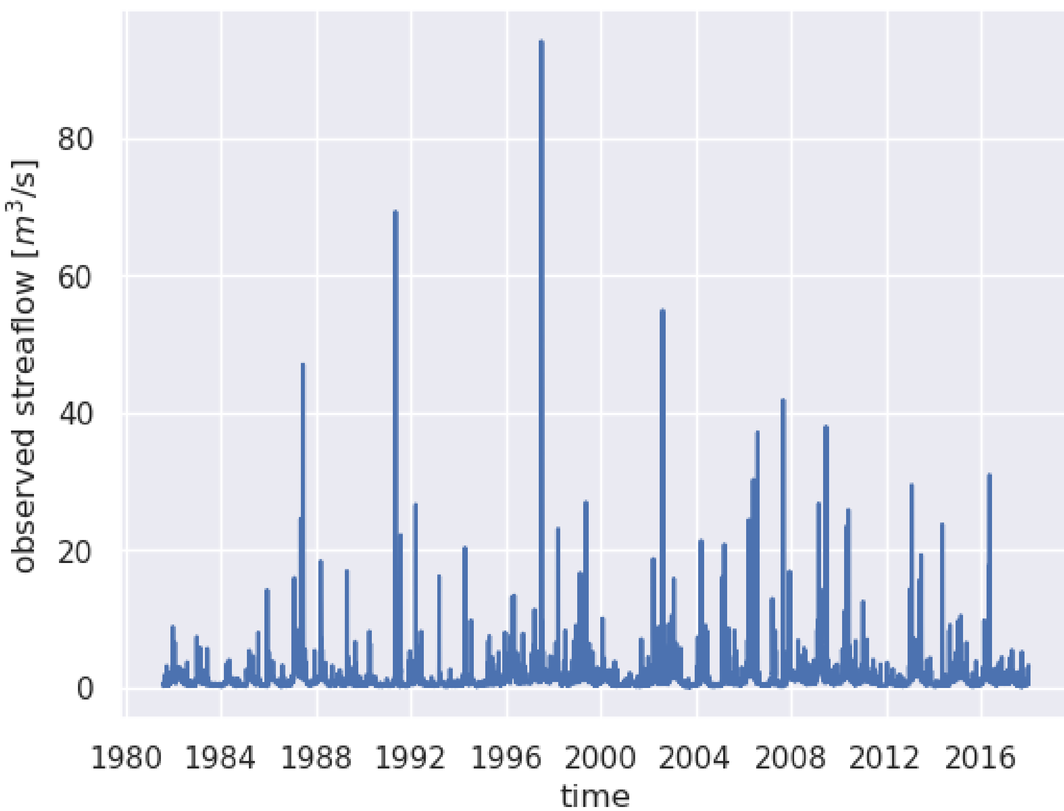
Above, it can be seen that the forcing data contains precipitation, potential evaporation, discharge and the near-surface temperatures (tas). For determining the threshold exceedance frequency, only the discharge data are used. The discharge data is loaded from the forcing below. The data contains the maximum discharge values per day.

```
['1981-08-01T00:00:00.000000000' '1981-08-02T00:00:00.000000000'
 '1981-08-03T00:00:00.000000000' … '2020-12-29T00:00:00.000000000'
 '2020-12-30T00:00:00.000000000' '2020-12-31T00:00:00.000000000']
```



Since the threshold values determined in chapter 2 are in m3/s, the observed discharge data, now in mm/d, is converted to m3/s as well.

```
Text(0, 0.5, 'observed streaflow [$m^3$/s]')
```

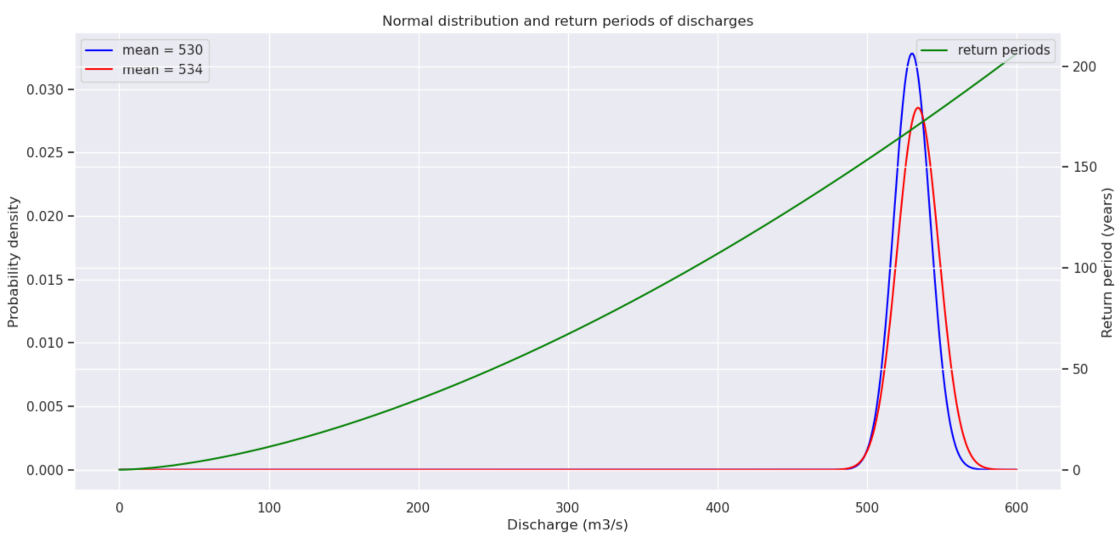


The maximum discharge of the observed data can be extracted.

```
The maximum observed discharge in the observed data is 94.052 m3/s.
```

The observed discharge data can be used to calculate the returnperiods of the normally distributed threshold values. This is done using the Generalized Extreme Value distribution. The return period of the mean threshold value of 530 m3/s is calculated below:

Below both the normal distribution of the exceedance threshold values and the return periods of discharges are plotted below. This graph shows the return period and the probability density are related to the discharge. A discharge value more to the right of the normal distribution, has a higher return period, but also has a longer probability of actually causing flooding of the U4 subway line.



4 Chapter 3: Calibration of the HBV model

In this chapter the HBV model is calibrated using the observation data. A set of parameters is used by the HBV model to predict the discharge. These parameters are optimized using calibration. The model requires forcings, rainfall and potential evaporation, as inputs. With the calibrated parameters, it can calculate modelled discharge at the outlet of the catchment.

The HBV model is available through eWaterCycle. The developer of the model, Sten Bergström (1992), says the HBV model can best be classified as a semi-distributed conceptual model. The model consists of three main components: - subroutines for snow accumulation and melt - subroutines for soil moisture accounting - response and river routing subroutines

Precipitation and air temperature are the model inputs, and data on potential evapotranspiration is needed for the accounting of soil moisture. (Bergström, 1992)

A visual representation of the HBV model can be seen below:

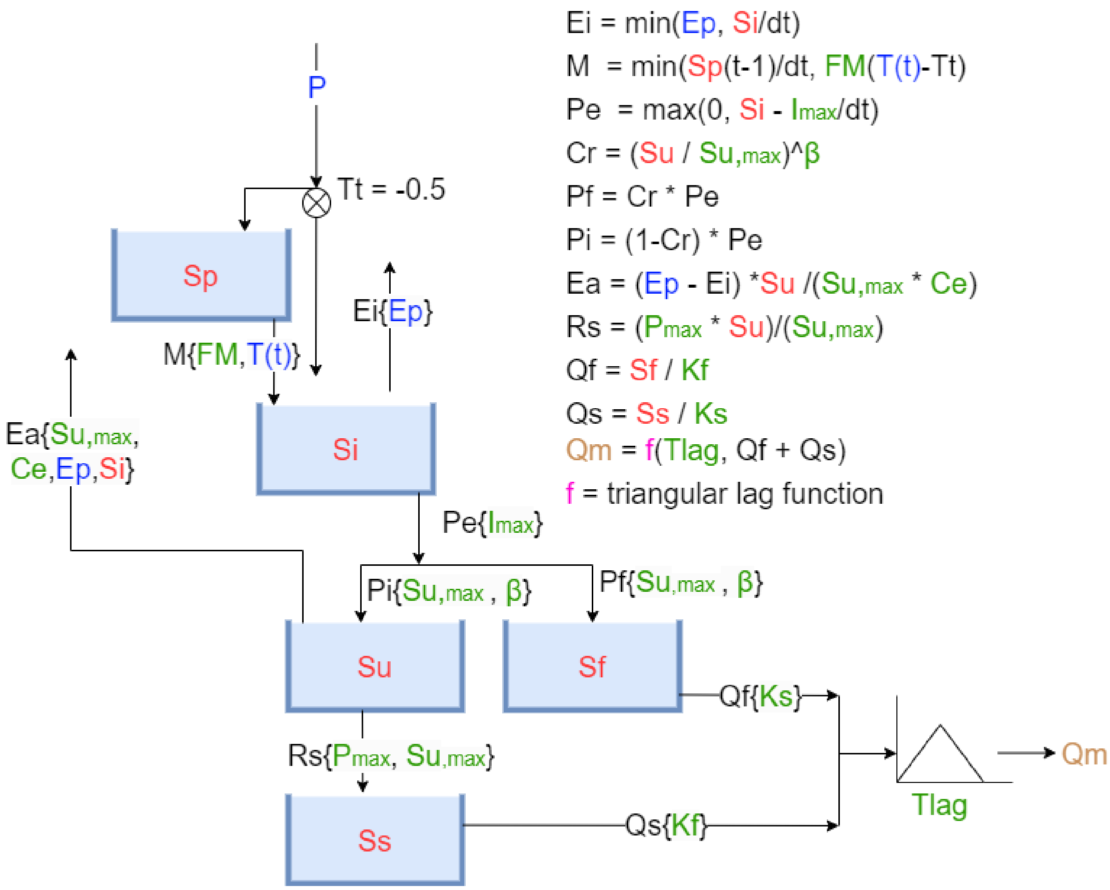


Image from the TU Delft course ENVM1502 - "River Basin Hydrology" by Markus Hrachowitz

4.1 General

First of all, some general python and eWaterCycle libraries need to be imported:

As stated in chapter 3, eWaterCycle provides access to the Caravan dataset, from which a Camel dataset of the catchment of the Wien River is loaded.

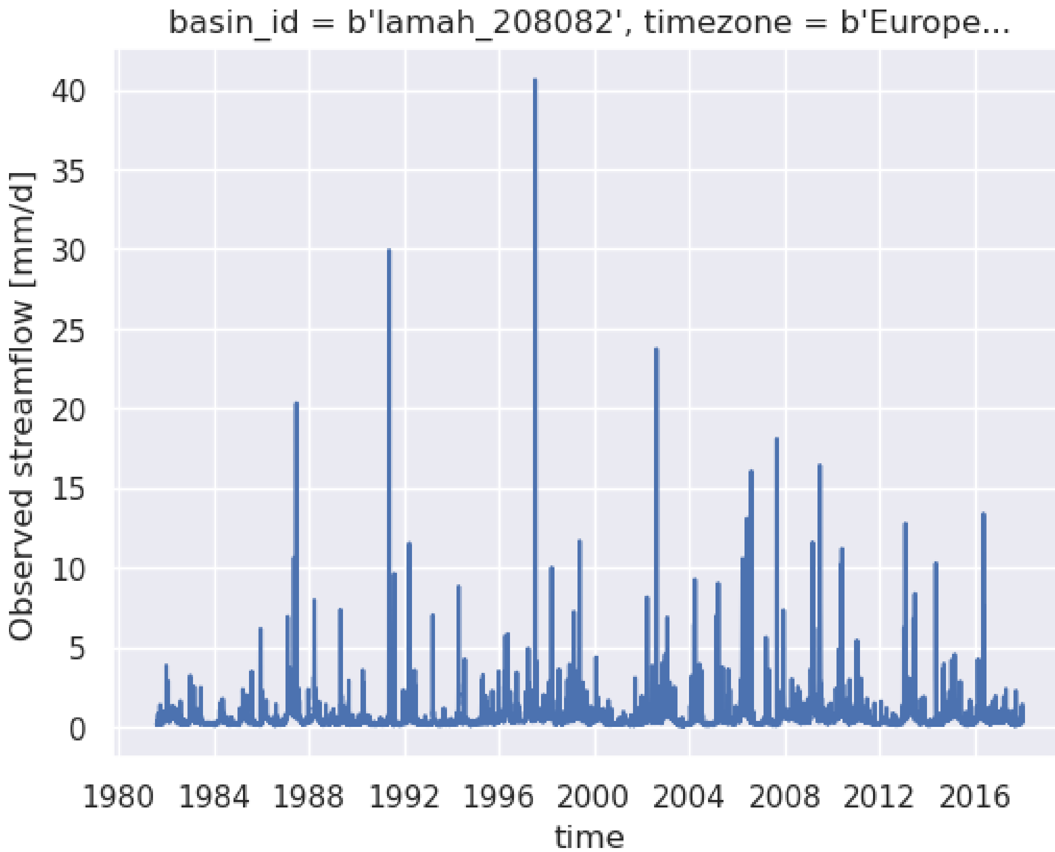
The start and end date of the experiment have to be specified. The start and end date of the calibration have to be specified as well. The period of calibration is chosen to be around 75% of the experiment period. This means that the model is trained on 75% of the observation data, and can be tested on 25% of the observation data, to make sure the model is not only working for the data it was trained on, but on other periods of data as well.

The forcing data can be generated or previously generated data can be loaded.

```
CaravanForcing(
    start_time='1981-08-01T00:00:00Z',
    end_time='2030-12-31T00:00:00Z',
    directory=PosixPath('/home/thirza/forcing/lamah_208082/caravan'),
    shape=PosixPath('/home/thirza/forcing/lamah_208082/caravan/lamah_208082.
 ↪shp'),
    filenames={
        'tasmax': 'lamah_208082_1981-08-01_2030-12-31_tasmax.nc',
        'tas': 'lamah_208082_1981-08-01_2030-12-31_tas.nc',
        'tasmin': 'lamah_208082_1981-08-01_2030-12-31_tasmin.nc',
        'Q': 'lamah_208082_1981-08-01_2030-12-31_Q.nc',
        'pr': 'lamah_208082_1981-08-01_2030-12-31_pr.nc',
        'evspsblpot': 'lamah_208082_1981-08-01_2030-12-31_evspsblpot.nc'
    }
)
```

Above, it can be seen that the forcing data contains precipitation, potential evaporation, discharge and the near-surface temperatures (tas). For this research, only the discharge data is relevant. The discharge data is loaded from the forcing below, and is plotted.

```
[<matplotlib.lines.Line2D at 0x7f26f16205c0>]
```



4.2 Calibration

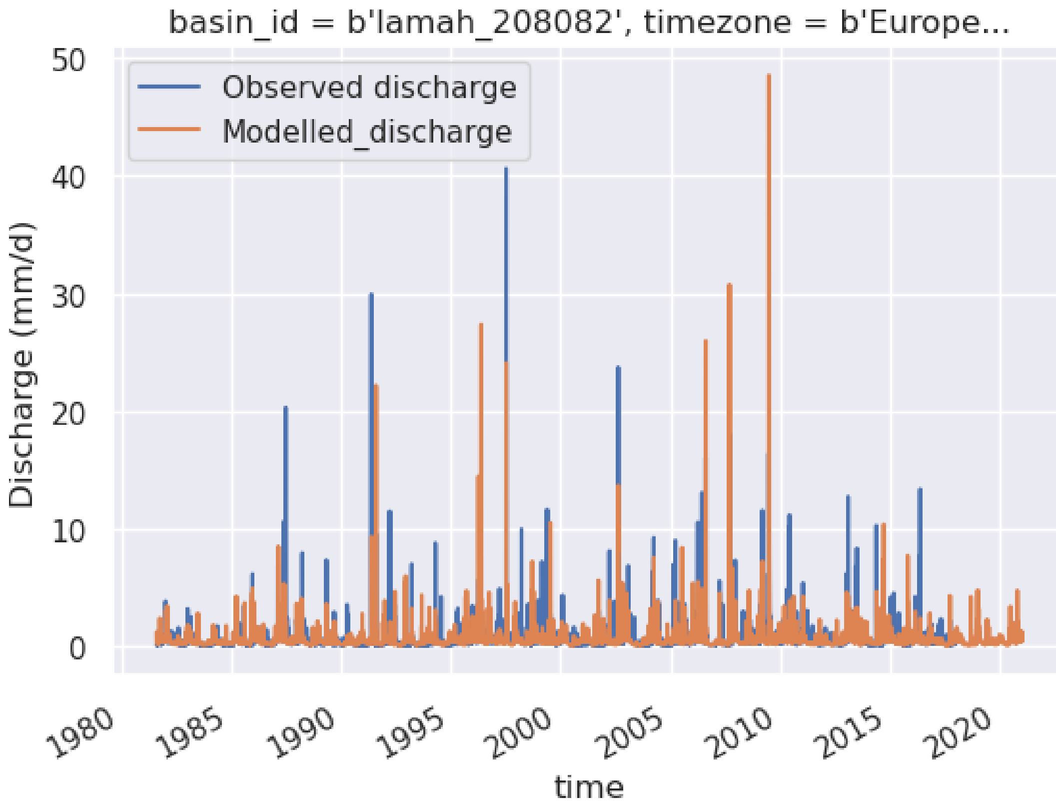
The HBV model contains five stores where the water is stored and nine parameters that control the flow between those stores and in and out of the model. For the storages an array of starting values is specified. The values for the parameters will later be estimated using optimization.

4.2.1 Kling Gupta efficiency

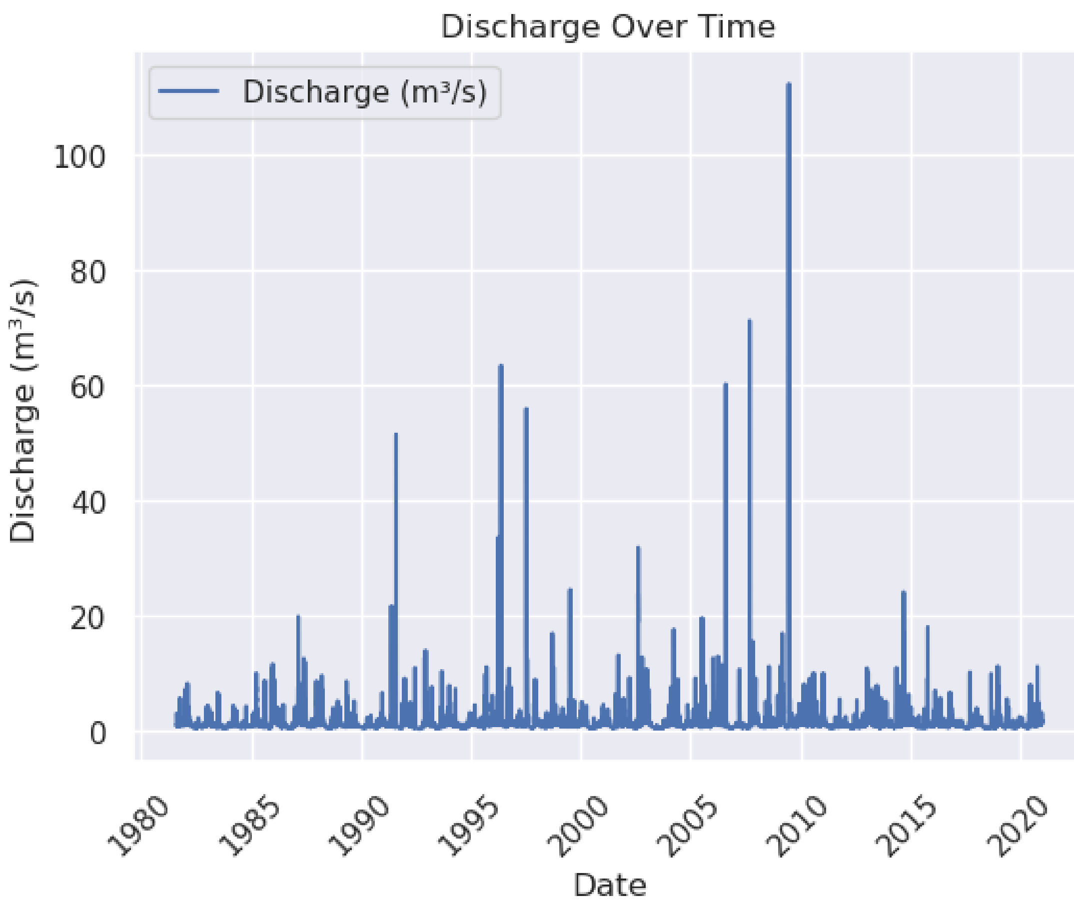
For my research, the height and frequency of the peaks are important, but their timing is less critical. The Kling-Gupta Efficiency is a measure that evaluates how well a model performs by looking at correlation, bias, and variability. By using an altered Kling-Gupta Efficiency in which the correlation is being left out, the timing of the peaks is not being taken into account. This method is useful for predicting the size of peaks and the overall distribution, while being less focused on the exact timing of the peaks.

A good way to predict the best parameter combination is through Nelder-Mead optimization. This optimization method finds the minimum of a function. The result of the Nelder-Mead optimization is the best parameter combination the method found. The Nelder-Mead optimization is run using the Kling-Gupta efficiency.

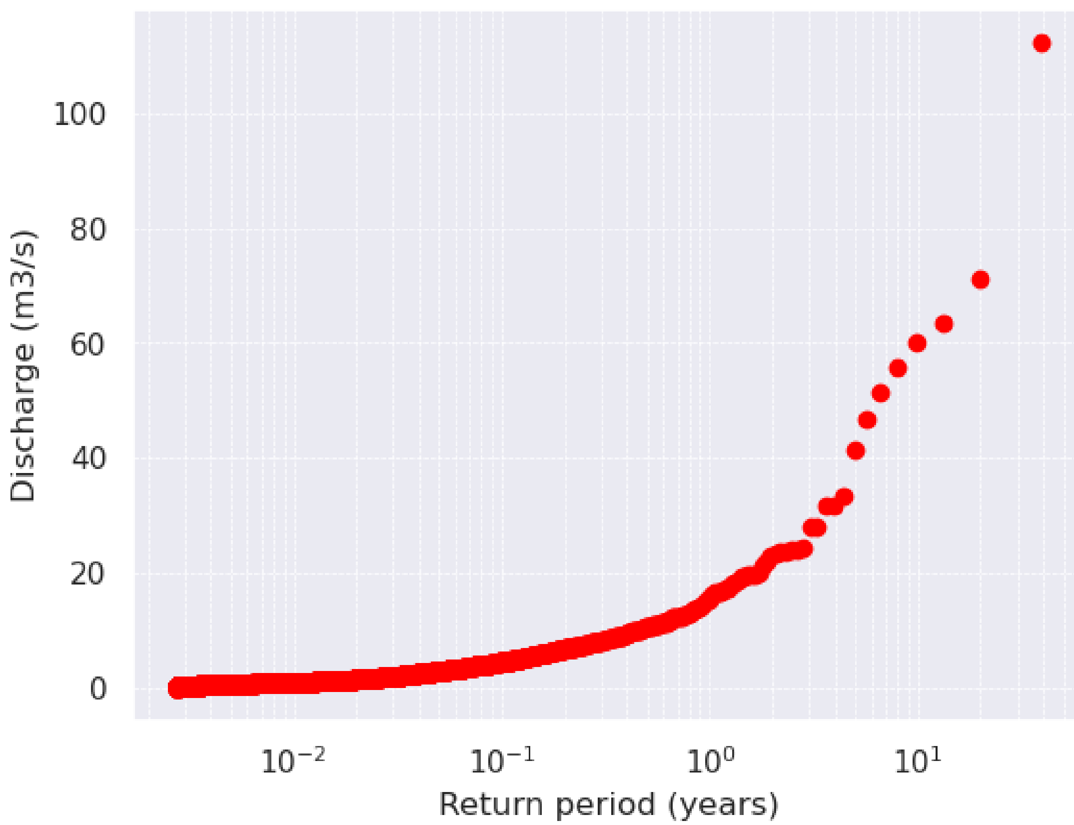
```
Text(0, 0.5, 'Discharge (mm/d)')
```



To be able to compare the model output to the observation data, the model output is converted from mm/day to m3/s as well. This is plotted below.



To be able to evaluate the performence of the model, the extrapolated returnperiods for the modeloutput need to be compared to the extrapolated returnperiods for the observations. The modelled daily discharges are plotted below. The returnperiods still have to be extrapolated.



5 Chapter 4: Future frequency of threshold exceedance under different climate change scenarios

In this chapter the future frequency of threshold exceedance is determined. This is done using different climate change scenarios, which are implemented in the HBV model. The HBV model is calibrated in Chapter 3

6 References

Bergström, S. (1992). THE HBV MODEL - its structure and applications. In SMHI REPORIS HYDROLOGY (p. 32). SMHI.

Compton, K. L., Faber, R., Ermolieva, T. Y., Linnerooth-Bayer, J., & Nachtnebel, H.-P. (2009). Uncertainty and Disaster Risk Management Modeling the Flash Flood Risk to Vienna and Its Subway System (RR-09-002). International Institute for Applied Systems Analysis.

Dore, M. H. I. (2005). Climate change and changes in global precipitation patterns: What do we know? Environment International, 31, 1167–1181. https://www.elsevier.com/locate/envint

Faber, R. (2006). FLOOD RISK ANALYSIS: RESIDUAL RISKS AND UNCERTAINTIES IN AN AUSTRIAN CONTEXT (Door University of Natural Resources and Applied Life Sciences, Vienna).

Faber, R., & Nachtnebel, H. P. (2002). Flood Risk Assessment in Urban Areas: Development and application of a stochastic hydraulic analysis method considering multiple failure types. In J. Linnerooth-Bayer (Ed.), Proceedings Second Annual IIASA-DPRI Meeting, Integrated Disaster Risk Management, Held On 29–31 July 2002, Laxenburg, Austria.

Krone.At. (2024a, september 15). “Landfall” in the city - Dramatic pictures: Vienna in the grip of the floods. Kronen. https://www.krone.at/3526665

Krone.At. (2024b, september 19). Vienna public transport balance sheet - Flood had “unprecedented impact on public transport”. Kronen. https://www.krone.at/3531234

Pollack, G., Gierlinger, S., Haidvogl, G., & Winiwarter, V. (2016). Using and abusing a torrential urban river: the Wien River before and during industrialization. Water History, 8(3), 329–355. https://doi.org/10.1007/s12685-016-0177-7