MASTERARBEIT / MASTER’S THESIS

Titel der Masterarbeit / Title of the Master‘s Thesis

Objective derivation of Climate Indices for the assessment of catchment area sensitive contributions to flood events alongside the Danube

verfasst von / submitted by

Nikta Madjdi, BSc

angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien, 2022/ Vienna 2022

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	A 066 614
Studienrichtung lt. Studienblatt / degree programme as it appears on the student record sheet:	Masterstudium Meteorologie
Betreut von / Supervisor:	Priv.-Doz. Mag. Dr. Christoph Matulla

Abstract

Floods triggered by extreme weather events represent an ever greater challenge for society. Early warning systems are therefore necessary to save human lives and to be able to take protective measures for buildings and infrastructure. Knowledge about flood-triggering precipitation sequences can help to further improve these early warning systems in the future, also with regard to climate change. This work follows the results of Enigl et al., 2019 for the Northern Lowlands in Austria. The aim of this thesis is to identify daily-based precipitation sequences, namely Climate Indices (CIs), triggering floods along the Austrian Danube by refining the Northern Lowlands on a catchment area basis of the Danube tributaries.

The connection between precipitation in the catchment area of the tributary and water level and discharge measurements at hydrological monitoring stations in the tributary is investigated through cross-correlation. The flood events used consist of flood damage events as well as flood measurements at Danube monitoring stations. It is investigated whether differently influenced regions along the Danube can be identified. For these regions, flood-triggering upstream tributaries are determined. For this purpose, cross-correlations between catchment area precipitation and Danube monitoring stations within the region are calculated, as well as station measurements in the tributaries within the week before the flood events are used. From these results, regionally differentiated daily-based precipitation sequences are calculated from gridded precipitation data within the respective catchment areas through EOF analysis. The eigenvectors resulting from the EOF analysis are the sought for CIs. The EOF analysis is calculated for all flood events as well as for damage events and for flood measurements at Danube measuring stations separately.

Precipitation in the catchment area of a tributary can be well described by the water level and discharge measurements of the associated hydrological measuring station, if they are located as close as possible at the inflow to the Danube. A total of 212 flood events were registered in a 1 km buffer around the Danube. Six regions along the Danube can be identified, that are characterised by flood events. For each of these six regions, one to three tributaries were investigated that trigger floods in these regions. Depending on the distance between the tributaries and the regions, their EOF analysis show precipitation maxima on the same day of the flood event up to 3 days before. The statistical significance of the results increases the more flood events are available. The closer the tributary is to the region, the closer the precipitation maximum is on the day of the flood event. The further downstream a region lies, the less likely a tributary has an effect on flood events in this region.

Zusammenfassung

Hochwasser, die durch Extremwetterereignisse ausgelöst werden, stellen eine immer größere Herausforderung für die Gesellschaft dar. Frühwarnsysteme sind daher notwendig um Menschenleben retten und rechtzeitig Maßnahmen zum Schutz von Gebäuden und Infrastruktur ergreifen zu können. Die Kenntnis über hochwasserauslösende Niederschlagsequenzen können dabei helfen, diese Frühwarnsysteme künftig auch im Hinblick auf den Klimawandel weiter zu verbessern. Diese Arbeit folgt den Ergebnissen von Enigl et al., 2019 für das nördliche Flachland (Northern Lowlands) in Österreich. Das Ziel der Arbeit besteht darin, tagesbasierte Niederschlagssequenzen, sogenannte Climate Indices (CIs), die Hochwasser entlang der österreichischen Donau auslösen, zu identifizieren, indem das nördliche Flachland auf Einzugsgebietsbasis der Donau-zubringer verfeinert wird.

Der Zusammenhang zwischen Niederschlag im Einzugsgebiet des Zubringers und Wasserstand- bzw. Abflussmessungen an hydrologischen Messstellen im Zubringer wird mittels Kreuzkorrelation untersucht. Die verwendeten Hochwasserereignisse setzen sich zusammen aus Hochwasserschadereignissen wie auch Hochwassermessungen an Donaumessstationen. Dabei wird untersucht, ob unterschiedlich beeinflusste Regionen entlang der Donau identifiziert werden können. Für diese Regionen werden hochwasserauslösende stromaufwärts liegende Zubringer bestimmt. Es werden dafür sowohl Kreuzkorrelationen zwischen Einzugsgebietsniederschlag und Donaumessstationen innerhalb der Region durchgeführt, als auch über Stationsmessungen in den Zubringern innerhalb der Woche vor dem Hochwasserereignis verwendet. Aus diesen Ergebnissen werden regional differenzierte Niederschlagssequenzen auf Tagesbasis aus gegitterten Niederschlagsdaten innerhalb der betreffenden Einzugsgebiete mittels EOF Analysen berechnet. Die aus den EOF Analysen resultierenden Eigenvektoren sind die gesuchten CIs. Die EOF Analysen werden sowohl für alle Hochwasserereignisse gemeinsam als auch jeweils für Schadereignisse und für Hochwassermessungen an Donaumessstationen durchgeführt.

Der Niederschlag im Einzugsgebiet eines Zubringers lässt sich gut über die Wasserstand- und Abflussmessungen der zugehörigen hydrologischen Messstationen beschreiben, die sich nahe an der Einmündung zur Donau befinden. Insgesamt wurden 212 Hochwasserereignisse in einem 1 km Puffer um die Donau registriert. Es können damit sechs Regionen entlang der Donau identifiziert werden, die von Hochwassern geprägt sind. Für jede dieser sechs Regionen wurden jeweils ein bis drei Zubringer untersucht die Hochwasser in diesen Regionen auslösen. Deren EOF Analysen ergeben je nach Distanz zwischen den Zubringern und den Regionen häufig Niederschlagsmaxima am selben Tag des Hochwasserereignisses bis 3 Tage vorher. Die statistische Aussagekraft der Ergebnisse wird größer, je mehr Hochwasserereignisse zur Verfügung stehen. Je näher der Zubringer zur Region liegt, desto näher liegt das Niederschlagsmaximum am Tag des Hochwassereintritts. Je weiter eine Region stromabwärts liegt, desto unwahrscheinlicher hat ein Zubringer eine Auswirkung auf das Hochwasserereignis in dieser Region.

Contents

List of Figures

List of Tables

List of Abbreviations

BMLRT	**B**undes**M**inisterium für **L**andwirtschaft, **R**egionen und **T**ourismus Federal Ministry of the Republic of Austria for Agriculture, Regions and Tourism
BWV	**B**undes**W**asserbau**V**erwaltung Federal Water Engineering Administration
SPARTACUS	**SPA**tiotemporal **R**eanalysis Da**TA**set for **C**limate in A**US**tria
VIOLA	**VI**olent **O**bserved **L**ocal **A**ssessment
WLV	**W**ildbach und **L**awinen**V**erbauung Austrian Service for Torrent and Avalanche Control
ZAMG	**Z**entral**A**nstalt für **M**eteorologie und **G**eodynamik Central Institute for Meteorology and Geodynamics

Chapter 1

Introduction

Extreme weather events inducing hazards specifically floods have always been a threat to societies. In the past years the public awareness has become greater particularly since the Danube flood in 2002. Since then more flood protective measures have been evaluated, installed and updated along the Danube and prevented damages from floods in the following years (Habersack et al., 2015, Oberösterreichischer Landesrechnungshof, 2014). For example, the "Machland Nord" ("Machland-Damm") project is one of Europe's biggest flood protection projects for the Danube (MDB Machland-Damm Betriebs GmbH, 2008) and has prevented massive damages in 2013 in millions of euros compared to the damages caused by the 2002 Danube flood, thus saving many lives (Habersack et al., 2015, Amt der Oberösterreichischen Landesregierung, 2012, Bilderl, 2017). It is necessary to give early and precise severe weather warnings to the public. Thereby citizens are able to seek shelter and authorities are able to take action in time. In the wake of climate change floods pose a further challenge for society, where regionally differentiated information on catastrophic events become crucial. Determining the weather sequences triggering floods along the Danube can deliver essential information for public decision-makers. Research for the identification of so-called Climate Indices (CIs), which describe weather phenomena triggering hazardous occurences and their intensities, therefore becomes increasingly important.

The linkage of meteorological patterns with hydrological extremes has been investigated in various recent studies for instance in China. Spatio-temporal variations of precipitation patterns through Empirical Orthogonal Function analysis (EOF) have been studied, for example for the basin of Lake Hulun in Northern China (Sun and Lotz, 2020), the Yangtze River basin (Sun et al., 2012) and more in detail for the Poyang Lake basin located in the south bank of the Yangtze River basin (Zhu et al., 2019, Zhu et al., 2020). Their research has been focused on the patterns in precipitation distribution inside the lake and river basins. Frequencies and amplitudes of these precipitation patterns have been examined over different study periods. The results have been linked to hydrological extremes in the past and investigated on correlations with large-scale atmospheric circulations such as the East Asian Summer Monsoon and the Indian Ocean Dipol as well (Sun et al., 2012, Sun and Lotz, 2020, Zhu et al., 2019, Zhu et al., 2020).

With regard to the European Alps, Quadrelli et al., 2001 have studied the linkages between Alpine precipitation variability with the North Atlantic Oscillation (NAO) through EOF analysis as well. For the Austrian part of the Alpine region, Enigl et al., 2019 have unified comprehensive cadasters on weather-induced hazard processes, which have been compiled and maintained by federal authorities. This hazard event data base has been linked with gridded weather observations to determine daily sequences of precipitation totals preceding these damage events. The eigendirections they obtained through EOF analysis are the searched for CIs, representing temporal

precipitation-sequences. These weather-sequences have been examined and allocated to different hazard-categories, including floodings, for three orographically distinct regions in Austria (fig. 1.1) (Enigl et al., 2019).
Following the studies of Enigl et al., 2019 the aim of this thesis is to receive regionally differentiated information on daily based precipitation patterns triggering floods and therefore CIs along the Austrian part of the Danube. The catchment area of the Danube is investigated based on the findings from Enigl et al., 2019 regarding floodings in the region *Northern Lowlands* (fig. 1.1). In order to refine the *Northern Lowlands*, daily sequences of precipitation amounts have to be examined on a smaller scale than previous research. This thesis therefore deals with the catchment areas of the Danube's tributaries.

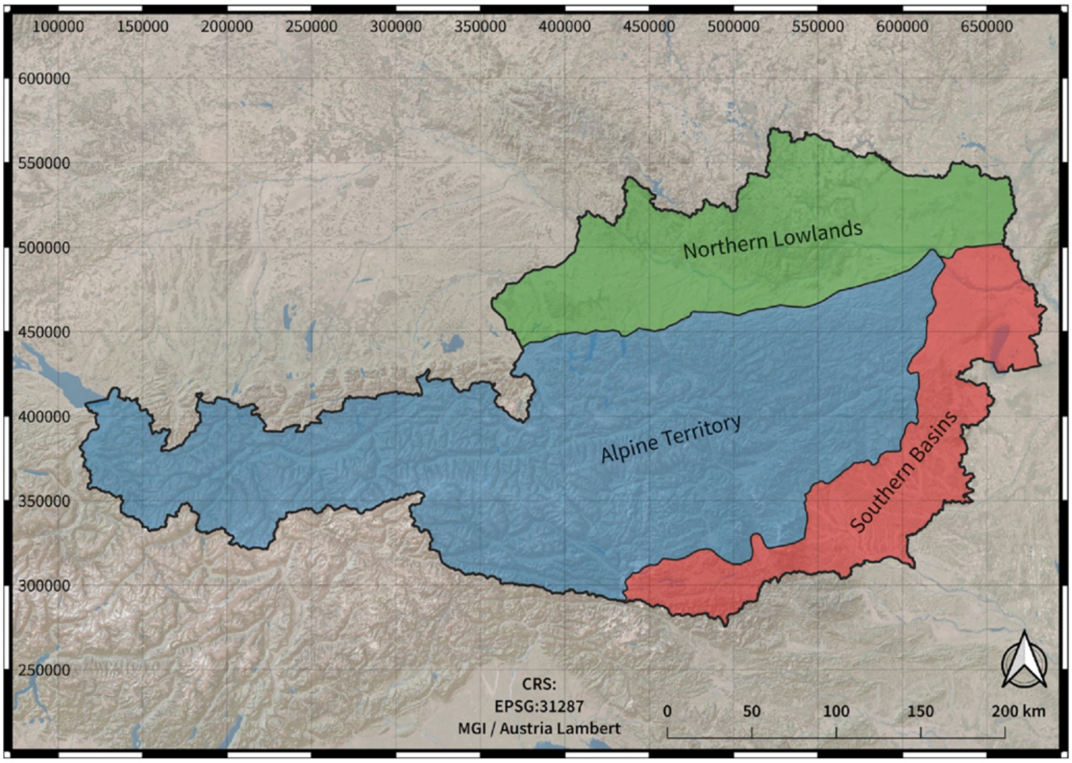


FIGURE 1.1: Research regions from Enigl et al., 2019.

The following research questions arise for this thesis:

1. To what extent is precipitation in the catchment area of a tributary linked to water level and discharge measurements at tributary monitoring stations?
2. Do tributaries exist, which are relevant for inducing floods and flood induced damage events occurring alongside the Danube river in Austria?
3. Is it possible to determine sections or regions along the Danube being differently affected by the Danube's tributaries?
4. What kind of precipitation sequences or patterns inside the tributaries' catchment areas lead to Danube floods and flood damages in the detected regions?

Chapter 2

Data

Meteorological and hydrological data as well as information on damage events are required to answer the aforementioned research questions. This chapter thus deals with available data sets. Firstly the meteorological gridded data is explained, which gives the necessary information on precipitation in Austria, followed by the hydrological terms and symbols relevant for this thesis. Furthermore, hydrological data and their structure, which includes the water networks, catchment areas and hydrological monitoring data, is presented. Lastly the damage event databases compiled by various federal authorities, how they are composed, their similarities and differences to each other, are described in further detail.

2.1 Meteorological data

2.1.1 SPARTACUS

Meteorological data used is SPARTACUS (**SPA**tiotemporal **R**eanalysis Da**TA**set for **C**limate in A**US**tria) by Hiebl and Frei, 2015 and Hiebl and Frei, 2017. This is a gridded observational data set providing daily precipitation sums as well as daily maximum and minimum temperatures in Austria. The spatial resolution of this gridded data set is 1 km x 1 km and covers the time period 1961 until the current previous day. It is kept up to date by the ZAMG, Austria's national meteorological and geophysical service, which is a subordinate agency of the Federal Ministry for Education, Science and Research. This thesis makes use of the precipitation sums recorded from 1961 until 2020.

2.2 Hydrological data

2.2.1 Hydrological terms and symbols

Hydrology deals with water above, on and below the earth's surface, its manifestations, circulation and distribution in space and time, and its properties and interaction with the environment, while hydrometeorology deals with the interactions between atmospheric processes in the water cycle and hydrological processes (Austrian Standards Institute, 2016). Hydrographic terms and symbols used for this thesis are according to the definitions of Austrian Standards Institute, 2016. The following definitions apply in this context:

Definition 2.2.1. (Catchment area) A catchment area is a portion of the land area enclosed by a watershed from which direct surface runoff of precipitation is possible by gravity into a watercourse or other body of water.

Definition 2.2.2. (Discharge Q) Discharge Q is a volume of liquid flowing through a cross-section in a unit of time. The unit is $[\frac{m^3}{s}]$.

Definition 2.2.3. (Water level W) Water level W is the elevation of the free surface of a stream, canal, river, lake or reservoir, relative to a fixed reference point. The unit for the elevation is given in $[cm]$.

Definition 2.2.4. (Mean water level $\overline{W}$ and mean discharge $\overline{Q}$) Mean water level $\overline{W}$ and mean discharge $\overline{Q}$ are the arithmetic mean of water level or discharge during a period of time to be specified.

Definition 2.2.5. (Flood) A flood is water level or discharge that exceeds a limit to be determined. This limit is determined from the water level or flow values and/or the local topographical conditions, for example the lowest (smallest) annual flood of an observation time series.

Definition 2.2.6. (n-annual Flood HWn and HQn) An n-annual flood is a flood whose exceedance probability is equal to the reciprocal of n.
Example: The exceedance probability of a 100-annual flood $= \frac{1}{100} = 0.01 \widehat{=} 1\%$.
In an infinitely long imaginary series of observation years, the n-annual flood is reached or exceeded on average every n years. From this information, the time when this event occurs cannot be determined.

2.2.2 Watercourses

The watercourses of the overall Austrian federal water network have been made available by the Federal Ministry of the Republic of Austria for Agriculture, Regions and Tourism (BMLRT) and the Environment Agency Austria. The watercourses are geospatial linestrings projected in the LAEA Europe coordinate reference system (EPSG:3035).

2.2.3 Catchment areas

Austria's complete watercourse catchment areas also have been provided by the BMLRT and the Environment Agency Austria. The data sets for the catchment areas of the watercourses are geospatial polygons projected in the LAEA Europe coordinate reference system (EPSG:3035). The catchment areas covered by the hydrological monitoring stations also have been provided by the BMLRT. They are available as geospatial polygons aswell, however they are projected in Austria Lambert coordinates (EPSG: 31287).
The catchment area polygons of the watercourses end at the Austrian border, even if some catchment areas extend into neighboring countries, whereas the monitoring station catchment areas include the areas outside of the Austrian borders. In chapter 3 the adjustment of these discrepancies will be discussed.
Within the Austrian national borders the catchment areas are hierarchically subdivided, an explanation is given in the following section.

Hierarchy of catchment areas

Austria's territory lies inside the catchment areas of three major rivers in Europe: Danube, Rhine and Elbe. 96.1 % of Austria's territory lies inside the Danube's catchment area, while 2.8 % and 1.1 % are located inside the Rhine's and Elbe's catchment area, respectively (Bundesministerium für Landwirtschaft, Regionen und Tourismus

(BMLRT), 2021b). In the hierarchy of Austria's watercourse, those three rivers are considered as the three main rivers. Therefore, they are considered as first-order rivers. A tributary that flows into a first-order river is a second-order river. For example, the Inn is a second-order river to the Danube. Therefore, any tributary flowing into the Inn is a third-order river. This can be continued for every single river through assignment to a higher order river.

From this system onward, the catchment area of a river is given a sequential number downstream in order of the inflow of each tributary to the main river. In the data set for the catchment areas of the whole watercourse in Austria, the catchment areas of the Rhine, Danube and Elbe are identified by the sequential numbers 1, 2 and 3, respectively. In this data set, the Inn receives the number '2 8'. The first number corresponds with the Danube's number being first-order and the second number corresponds with the Inn being second-order and a far upstream tributary in Austria. Depending on the river's order and downstream position, the quantity of added numbers and the number itself is determined. Consequently, for every catchment area the first number is the sequential number of the first-order river, then the second number of the second-order river, etc. Selected examples (tbl. 2.1) and an illustration of the hierarchy (fig. 2.1) are given below. Based on this subdivision, one can extract the catchment areas of interest from the watercourse catchment area data set (BMLFUW Abteilung IV/4 Wasserhaushalt HZB, 2014, BMLFUW Abteilung IV/4 Wasserhaushalt HZB, 2011)

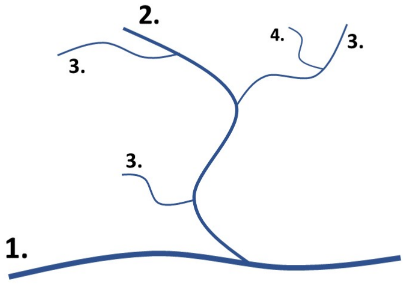


FIGURE 2.1: Illustration of river orders

	Number of the Order			
River	1.	2.	3.	4.
Danube	2			
Inn	2	8		
Enns	2	136		
Salza	2	136	220	
Wien	2	334	6	
Mauerbach	2	334	6	30

TABLE 2.1: Selected examples of the hierarchical structure of the catchment areas

2.2.4 Hydrological monitoring stations

Hydrological data from the Danube and its tributaries have been provided by the BMLRT, which includes data from 50 hydrological monitoring stations for 37 tributaries and from 22 for the Danube (see fig. 2.2 & fig. 2.3). Therefore 72 monitoring stations have been analysed. Depending on the type of monitoring station, either data on water level W $[cm]$ or discharge Q $[\frac{m^3}{s}]$ or both are available on a daily mean basis.

The start of measurements depends on the date of commissioning of the monitoring stations, therefore time periods covered vary by station. Figure 2.4 shows the amount of available data from monitoring stations in relation to the total of 71 stations measuring water level W and 61 measuring discharge Q between 1951 and June 2020. From 1951 until 1976 only 20% to 26% of the monitoring stations have data available. The amount on water level data slightly decreases whereas discharge data increases over this time period. In 1976 especially the amount of water level data increases significantly by 50% reaching 75% of the 71 water level stations available in that year. An explanation for this sharp increase could not be identified. The increase in Q data in 1976 is not as drastic as the one for the W data. However, the availability for both data types increases gradually since then. Between 2011 and 2017 nearly all stations provide measurements. From 2018 onwards the amount of data from monitoring stations decreases sharply. The explanation might be, when the BMLRT provided the data, all the data sets had been quality controlled until 2017 (see Hydrographisches Jahrbuch 2017, Bundesministerium für Landwirtschaft, Regionen und Tourismus (BMLRT) Abteilung I/3 – Wasserhaushalt (HZB), 2021). Since then not all measurements have been quality controlled yet by the BMLRT, therefore the amount of monitoring stations providing data seems to be decreasing. The amount of data from both monitoring station types fluctuates over time, due to the fact that not every station provides a continuous time series of measurements. It is not clear if, for example, a station had to be taken down for maintenance purposes, because it has been damaged, or the measurements taken where defective. Some stations even had measurements only for a very short period of time in comparison to other stations. Figures A.3 and A.4 illustrate this circumstance, showing the data availability over time for each monitoring station.

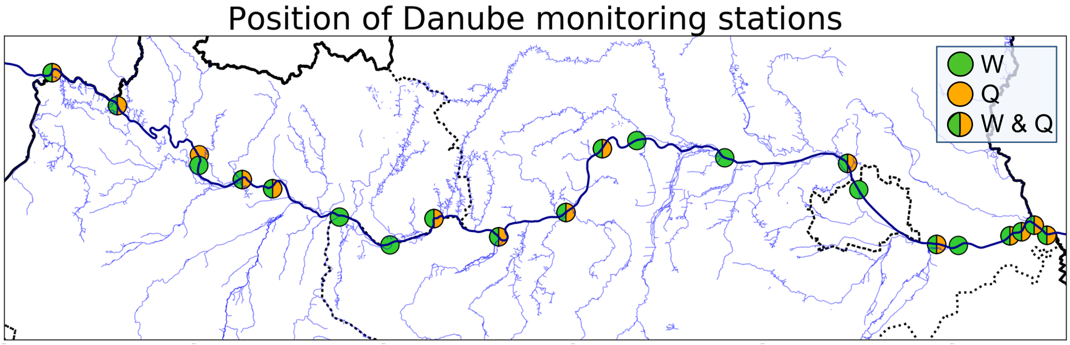


FIGURE 2.2: Location of Danube monitoring stations. In total 22 monitoring stations, which measure either water level W or discharge Q or both, are shown in the figure.

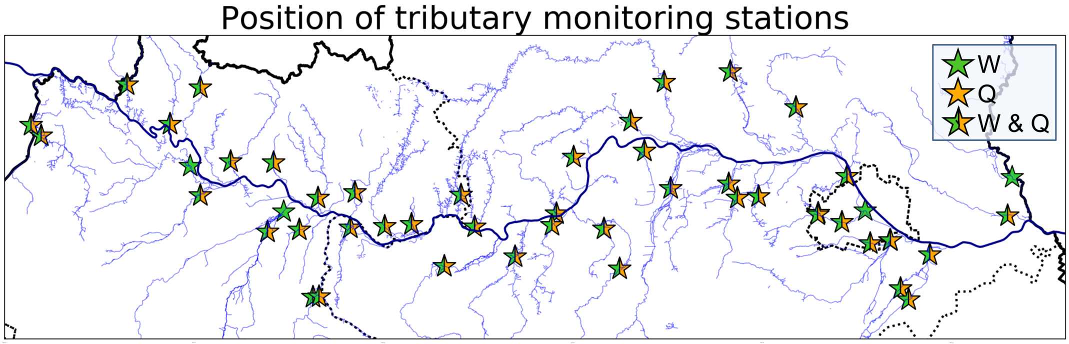


FIGURE 2.3: Location of monitoring stations inside tributaries of the Danube. In total 50 monitoring stations, measuring either water level W or discharge Q or both, are shown in the figure.

The selection of monitoring stations inside the tributaries is based on the representativeness for the tributary and its catchment area. Thus in ideal circumstances it should be located as close as possible to the Danube. As not every tributary is equipped with a monitoring station, the amount of data on water level and discharge from the tributaries is limited. Most of the monitoring stations are located in

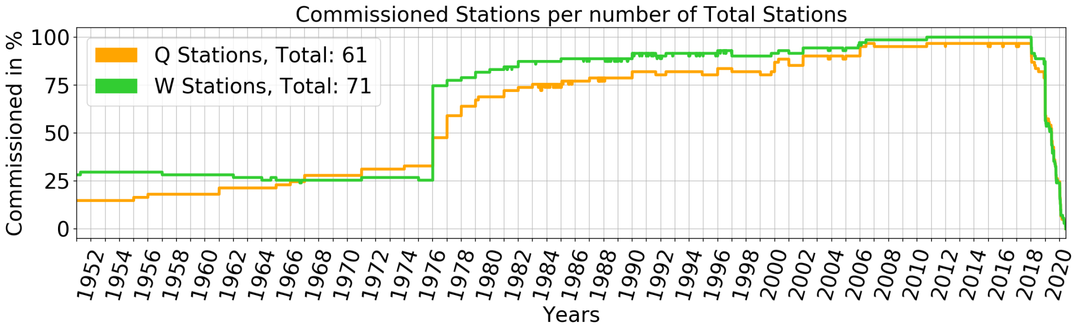


FIGURE 2.4: Monitoring station data available for water level W and discharge Q in relation to the total number of monitoring stations available between 1951 and June 2020 in %.

the immediate vicinity of the Danube. However, in order to obtain as much data as possible, monitoring stations further away from the Danube are also chosen. In cases in which a tributary does not have a station itself, monitoring stations located in its tributaries are included to represent the main tributary (see fig. 2.3). The method to determine the coverage a monitoring station's catchment area provides with respect to the precipitation inside the whole tributaries catchment area is explained in section 3.2.4.

2.3 Damage events

2.3.1 BWV & WLV

The Federal Water Engineering Administration (BWV) and the Austrian Service for Torrent and Avalanche Control (WLV) are subordinate agencies of the BMLRT. One of the tasks of both administrative units includes the collection of hazard-events in Austria that are within their area of competence. The main responsibility of the BWV is the care of all waters, while the WLV is responsible for torrents and avalanches.
The damage events contained in both databases are available as geospatial points and linestrings projected in Austria Lambert coordinates (EPSG: 31287).
Observed flood events and those in which flood protective structures show their effect are digitally documented in the flood database maintained by the BWV since 2013 with the objective to build a national event-database (Kaufmann et al., 2013). This data set has been made available by the BWV with 676 events recorded between 2013 and 2020.
The provided damage events collected by the WLV occurred between 1950 and 2020 and were summarised in the process category *water*. It includes *fluvial sediment transport*, *debris-flow like processes*, *mud flows*, *floods* and *surface water*. The first three processes are distinguished by the amount of solid materials contained inside floods in relation to the flood volume. The first one describes floods with up to one fifth solid materials, the second those with more than one fifth and the third those with more than 50% (Enigl et al., 2019). In total 9059 Events have been recorded to date in this process category for the whole of Austria.

2.3.2 VIOLA

The ZAMG collects damage events caused by extreme weather events in Austria based upon media reports in the VIOLA database (**VI**olent **O**bserved **L**ocal **A**ssessment)

(Zentralanstalt für Meteorologie und Geodynamik (ZAMG), 2019). Thereby registered events date back until 1948.

Similar to the WLV database structure, the VIOLA database collects damage events from different types of categories including wind, snow, avalanches, heat/drought, glides, flows and falls as well as floods and flash floods. In this thesis the category *floods* triggered by continuous rainfall with 524 recorded events is used.

These damage events are available as geospatial polygons projected in Austria Lambert coordinates (EPSG: 31287). These polygons might represent the general area or more specific locations in which a damage event happened, depending on the level of specificity of the description from media reports. Possible location descriptions could be for instance a small town, a city, a district or a general area in Austria. In some cases a whole state of Austria is recorded to be affected by a damage event. Thus, the polygon sizes and shapes vary greatly depending on the available reports. The larger the polygon, the more difficult it is to determine the exact location of the damage compared to the exact coordinate locations given by WLV and BWV data.

Chapter 3

Methods

This chapter deals with the methods used, specifically the processing and analysis of the hydrological and meteorological data sets discussed in chapter 2, to determine the precipitation patterns in the catchment areas of the Danube's tributaries. Every single step in this process corresponds with the order of the chapter's sections.

3.1 Data processing

3.1.1 Unification of information on tributaries and Danube monitoring stations

Firstly, it is necessary to have an easy accessible overview on information about the tributaries as well as the Danube. A comprehensive database in Austria providing the necessary information for all rivers could not be found. The process of gathering these information involved many institutions and literature research. Data availability is sparse regarding $\overline{W}$, $\overline{Q}$ and catchment area sizes for the tributary monitoring stations. The same problems has arisen for the mean and statistical expected values for the Danube monitoring stations. Therefore, many different sources where used to gather as much information as possible. The sources used are listed in the tables 3.1 and 3.2.

Tributaries
Bundesministerium für Landwirtschaft, Regionen und Tourismus (BMLRT), 2021a
Bundesministerium für Landwirtschaft, Regionen und Tourismus (BMLRT) Abteilung I/3 – Wasserhaushalt (HZB), 2021
Anderwald et al., 1995a
Anderwald et al., 1995b
Anderwald et al., 1995c
Anderwald et al., 1996
Anderwald et al., 1997a
Anderwald et al., 1997b
Anderwald, 2001
Bachura et al., 1992
Kainz, 1986
BMLFUW Abteilung IV/4 Wasserhaushalt HZB, 2011
BMLFUW Abteilung IV/4 Wasserhaushalt HZB, 2014

TABLE 3.1: Table of sources used to create the table of information for the tributaries and their monitoring stations

Danube
Bundesministerium für Landwirtschaft, Regionen und Tourismus (BMLRT), 2021a
Bundesministerium für Landwirtschaft, Regionen und Tourismus (BMLRT) Abteilung I/3 – Wasserhaushalt (HZB), 2021
Bayerisches Landesamt für Umwelt, 2021
Land Oberösterreich (Amt der Oberösterreichischen Landesregierung Abteilung Wasserwirtschaft), 2021
Land Niederösterreich (Amt der Niederösterreichischen Landesregierung - Abteilung Landesamtsdirektion), 2021
viadonau - Österreichische Wasserstraßen-Gesellschaft mbH, 2012
viadonau - Österreichische Wasserstraßen-Gesellschaft mbH, 2021

TABLE 3.2: Table of sources used to create the table of information for the Danube monitoring stations

Eventually, as much information as possible has been gathered for the tributaries and for the Danube inside two Excel mastertables. The two tables can be expanded any time to increase the amount of information for further usage.
Following information has been gathered for each **tributary**:

- river name
- hierarchical number
- catchment area size

If monitoring stations are present, the table also includes:

- station names
- station IDs
- river names in which the stations are located, if it considers a third-order tributary
- $\overline{W}$ and $\overline{Q}$ depending on monitoring types
- if available, catchment area sizes covered by monitoring stations

The following data has been collected for **Danube monitoring stations**:

- hierarchical number (here every station has the number 2)
- station names
- station IDs
- position of monitoring stations in river kilometers
- $\overline{W}$ and $\overline{Q}$ depending on monitoring types
- if available, statistical expected values for flood water levels ($HW1$ to $HW100$) and flood discharge ($HQ1$ to $HQ100$)

Parts of the information tables could not be filled, because the data was partially not publicly available. If $\overline{W}$ and $\overline{Q}$ could not be found through literature sources, they were replaced by calculating $\overline{W}$ and $\overline{Q}$ from available monitoring station data. This means that for the time period available for the monitoring station data the mean value has been calculated.
An extract of each of the two tables can be seen in fig. A.1 and fig. A.2.

3.1.2 Further data set preparations

Firstly the data sets discussed in chapter 2 have to be processed for further usage. For this thesis the programming language python (Python Software Foundation, 2022a) has been used with the following packages:
`numpy`, `pandas`, `geopandas`, `shapely`, `xarray`, `rioxarray`, `netCDF4`, `timeit`, `datetime`, `matplotlib`, `sklearn`, `scipy` and `eofs` (Python Software Foundation, 2022b).
The first step is the coordinate transformations to Austria Lambert coordinates (EPSG: 31287). Thereby the projections are equal and the data sets are comparable, especially the positions of damage events in relation to the tributaries, the Danube, their monitoring stations and the catchment areas.
Secondly, the time series data sets for the monitoring stations are merged into one pandas data set, because they are initially available separately as .csv files for each station. With this step it becomes easier to compare measurements of each station.
Thirdly, through the hierarchy number of the tributaries the associated catchment areas are selected and merged into polygons describing the whole catchment area of the tributaries of first order. An example can be seen in fig. 3.1.

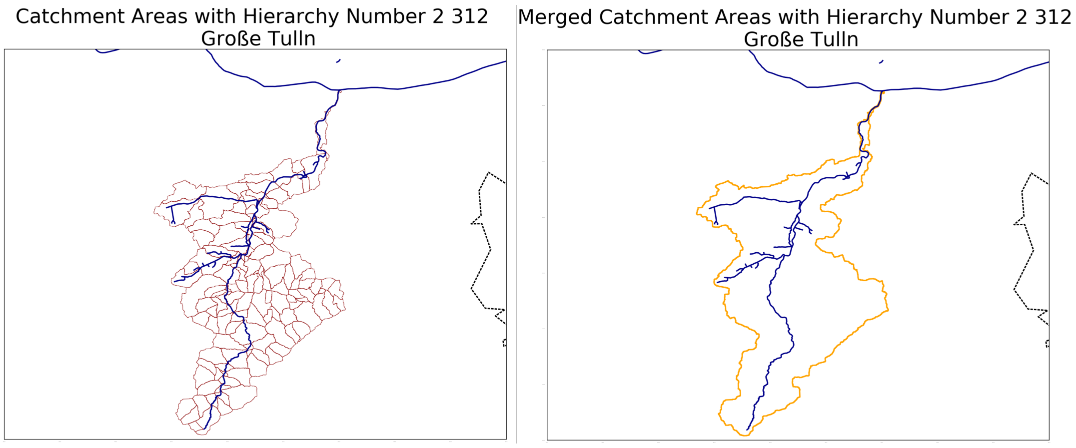


FIGURE 3.1: Merging of catchment areas with the same hierarchy number of a first order tributary. The Danube tributary's name is Große Tulln and has the hierarchy number 2 312. Left: catchment area polygons in red before merging. Right: whole catchment area polygon in yellow after merging.

Three monitoring station catchment areas are clipped at the Austrian border, because these reached beyond in comparison to the whole catchment areas of the tributaries, as described in chapter 2. With this step better comparisons are possible between the tributary's and the station's catchment area.
Lastly the damage and flood events have to be filtered for the area of interest, meaning as close as possible to the Danube. Due to the different kinds of data bases available, the approach differs depending on the data base, as can be seen in the next section.

3.1.3 Filtering events in and around the Danube

BWV & WLV

Considering that the events from BWV and WLV events are not exactly located inside the Danube, a 1 km buffer around the Danube is used to filter the flood events for the area of interest.

VIOLA

Due to the fact that most of the polygons are to broad to actually identify the exact location of the damage event, the following approach has been used.
First the polygons which represent the Austrian states Upper Austria, Lower Austria and Vienna have been filtered from the overall events, which borders intersect with the 1 km buffer. The next step is to use the existing mean and statistical expected values from the Danube monitoring stations, which were summarized in the Danube information table, to identify the monitoring stations inside these polygons, which reach one of these thresholds on the target day the VIOLA damage event has been registered. The first threshold for a Danube monitoring station is $\overline{W} + \sigma_W$ or $\overline{Q} + \sigma_Q$, with standard deviations σ_W and σ_Q calculated from the whole time series available for the measurement type for this station. The next thresholds are $HW1$ to $HW100$ or $HQ1$ to $HQ100$. If one of these thresholds has been reached, the coordinates of the monitoring station are used as the damage position for the polygon. If more than one monitoring station have exceeded a threshold, the coordinates of the easternmost monitoring station alongside the Danube is used. The easternmost is taken, because the further east, the further downstream the selected monitoring station lies. This gives the opportunity to consider more tributaries upstream of the station's location.

Danube monitoring stations

Thirdly every Danube monitoring station is checked, if they exceeded their specified statistical expected value of HW10 or HQ10 depending on the type of monitoring station and data availability. These monitoring stations exceeding their HW10 or HQ10 values respectively are classified as events as well. These values are considered as a threshold for endangered agricultural areas and objects or properties without sufficient flood protective measures (Bundesministerium für Nachhaltigkeit und Tourismus (BMNT), 2018). It is ensured, that HW10 and HQ10 flood events are not identical to the VIOLA events to avoid duplicate events.

3.2 Analysis of damage and flood events

The next step after the data processing is the analysis of damage and flood events to obtain the results presented in chapter 4 and discussed in chapter 5. The following has been done with the prepared data:

3.2.1 Grouping into regions

In order to further analyse the damage events, the first step is to group the events into distinct regions, in which the frequency of registered events were the greatest along the Danube. These groups are found through hierarchical clustering, the specific technique used is agglomerative hierarchical (Nielsen, 2016). Euclidean distance is used as the distance between any two event data points and each new subset distance is determined with the Ward linkage function, which allows variance minimisation, as described in Nielsen, 2016. This has been implemented with the `AgglomerativeClustering` submodule from pythons package `sklearn` (Python Software Foundation, 2022b). The resulting dendogram gives information on the clusters, that can be formed from the event data.

3.2.2 Tributaries upstream of an event

After grouping of the events, the next step is the identification of tributaries upstream of the events locations. Since very few events are actually located inside the Danube river, the method for each event works as follows:

1. Finding the nearest point on the Danube to the events location.
2. Splitting the Danube at the nearest point into an upstream and downstream part.
3. Intersecting the tributaries with the upstream part of the Danube, hence obtaining the tributaries flowing into the Danube before the events location. These are the ones of interest.

This is done with the python shapely module, specifically the `nearest_points` and `split` packages, as well as the in-built function `intersects`.
If for example an event lies in a catchment area or right next to a tributary, which has not been selected as an upstream tributary, because it flows downstream of the nearest point into the Danube, this tributary has also been included. Each case has been treated individually in order to decide, if an extra tributary has to be included because of this circumstance.

3.2.3 Precipitation fields

With the known upstream tributaries, their catchment area's polygons are used to clip the precipitation field from SPARTACUS. This was done with the python `rioxarray` module. For the following calculations the mean precipitation over the catchment areas was used. This method helps to compare the different catchment area sizes of the tributaries.

3.2.4 Cross-Correlation and determination of important tributaries

Cross-correlation is calculated as described in Shumway and Stoffer, 2017:
The cross-covariance function with two time series x_t and y_t is defined as:

$$\gamma_{xy}(h) = cov(x_{t+h}, y_t) = E[(x_{t+h} - \mu_x), (y_t - \mu_y)] \tag{3.1}$$

being a function of lag h, where t represents time and μ_x and μ_y being the mean of the time series x_t and y_t respectively.
The cross-correlation function of x_t and y_t is defined as:

$$\rho_{xy}(h) = \frac{\gamma_{xy}(h)}{\sqrt{\gamma_x(0)\gamma_y(0)}} = \frac{\gamma_{xy}(h)}{\sqrt{\sigma_x \sigma_y}} \tag{3.2}$$

with σ_x and σ_y being the standard deviations of the time series x_t and y_t respectively.

Linkage between precipitation and monitoring station's catchment area

Cross-correlations between the precipitation amounts inside the tributaries' catchment areas and the tributaries' monitoring station measurements are calculated. This is done in order to determine whether, when and to what extent the influence of precipitation falling in the catchment area is reflected in the amplitude of the measured values of the measuring station.

Determination of important tributaries

The next step is to receive the tributaries most important for floods in the Danube regions. Therefore 2 different approaches were used:

1. Cross-correlations between the precipitation fields from the tributaries and the Danube monitoring stations were calculated. Statistical expected values of the Danube monitoring stations are used as thresholds for the station data and precipitation data used for the calculations. Statistical expected values used as thresholds are primarily HW10 and HQ10, if available. If these values are not available for a particular station, higher expected values such as HW30 and HQ30 are used as well. Data from the target day, where a threshold has been exceeded, until 7 days prior are used for the cross-correlation calculations. The highest correlation at a specific lag in days for each tributary is used to rank the tributaries from highest to lowest correlation.

2. For each event inside a region the number of exceeded thresholds at monitoring stations of upstream tributary from the target day until 7 days prior are counted. A monitoring station's threshold is $\overline{W} + \sigma_W$ and/or $\overline{Q} + \sigma_Q$, with standard deviations σ_W and σ_Q calculated from the whole time series available for the measurement type.

Both of these approaches are used, meaning the highest ranked tributaries from cross-correlation and tributaries, where their monitoring stations exceeded most often for a specific region are assessed. Based on the results from both approaches, the tributaries were selected for further investigations.

3.2.5 EOF analysis

In order to obtain the Climate Indices (CIs) for a specific region and tributary EOF analysis is used. In time-series analysis empirical orthogonal function analysis (EOF) is an important multivariate statistical technique widely used in the atmospheric sciences. This statistical technique is elaborately described in both Peixoto and Oort, 1992 and Wilks, 2006 and is used here as the basis for further analysis.
Temporal EOF analysis is used to determine the precipitation patterns inside catchment areas of the selected tributaries for the investigated regions. Firstly a catchment area's mean precipitation is calculated. For the EOF analysis the anomaly of the mean precipitation is calculated. The precipitation anomalies for the date of occurrence of the event (target day, 'TD') and during the preceding week were used. The considered 8-day sequence is in accordance to Enigl et al., 2019. Different investigation periods from various studies concerning duration and change of large-scale weather characteristics in continental and Central Europe were elaborately discussed. It is concluded, that an 8-day analysis covers the threat process' development well enough.
Three different sample sizes are used for the EOF Analysis for each detected region:

- Based on the damage events from WLV, BWV and VIOLA
- Based on the exceeded HW10 and HQ10 of the Danube monitoring stations
- Based on both damage events and Danube monitoring stations

The matrix used for the calculation has to be structured as follows:
Since the date of an event n is known, the precipitation anomaly pr inside the catchment area of the tributary to be investigated is calculated for that target day TD and the seven days prior to the target day (TD-1,..., TD-7), thus eight mean precipitation values are obtained for an event n.
For each investigated tributary all events X downstream of the tributary's inflow are taken into account using the above mentioned approach for their TD respectively. Therefore one obtains an array of X row vectors forming an $X \times 8$ matrix E with rows where $n = 1, ..., X$ and eight columns from TD to TD-7, as shown in equation 3.3.

$$E = \begin{pmatrix} pr_{TD,1} & pr_{TD-1,1} & \cdot \quad \cdot \quad \cdot & pr_{TD-7,1} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ pr_{TD,n} & & & \cdot \\ \cdot & & & \cdot \\ pr_{TD,X} & pr_{TD-1,X} & \cdot \quad \cdot \quad \cdot & pr_{TD-7,X} \end{pmatrix} \tag{3.3}$$

With this matrix the EOF analysis is used to determine the precipitation patterns inside a tributary triggering these examined events. This is done with the python's `eofs` module. From this analysis the first three components are kept to account for 80% of simulated variance. The sought-for CIs are represented by the eigenvectors resulting from the EOF analysis.

Chapter 4

Results & Discussion

Results presented in this chapter are ordered in the same way the steps were conducted, described in the method's chapter 3. Each detected region along the Danube river and their respective results is elaborately discussed in this chapter.

4.1 Filtered events and regions

After filtering the damage events from the different databases in a 1 km buffer around the Danube as well as flood measurements from Danube monitoring stations as described in section 3.1.3, table 4.1 gives an overview of the total number of events available for analysis. 58 damage events have been located in this area. Including the events from HQ10 and HW10 exceedances, 212 events have been identified in total next to or inside the Danube.

data set	**number of events**
BWV	7
WLV	27
VIOLA	24
HW10	71
HQ10	83
	212

TABLE 4.1: Number of damage and flood events per data set after filtering the events in a 1 km buffer around the Danube. BWV, WLV and VIOLA are the damage event databases. While HW10 and HQ10 describe flood events registered at Danube monitoring stations, where measurements exceeded its statistical value for 10-yearly flood water levels or discharge respectively. For further information on the different databases see sections 2.2.4 and 2.3.

In fig. 4.1 the location of those events is depicted, while fig. 4.2 gives an overview on the number of registered events per year. Both figures are broken down by event data set.

The damage events have happend in some cases at the same location, due to the monitoring station events registering flood events at the same location but at different times. On the other hand, flood and damage events occurred at some locations very close to each other, which makes it slightly difficult to distinguish them in fig. 4.1. In fig. 4.2 the major flood events in the Austrian part of the Danube can be identified, as can be seen in the maxima in 2002 and 2013 as well as 1965, 1981 and 1991. Furthermore, the amount of damage events increases over the years. The reasons are on one hand that not all damage events registered have been digitised yet regarding the BWV events. While on the other hand damage events are also in different databases from other sources, which are not easily accessible.

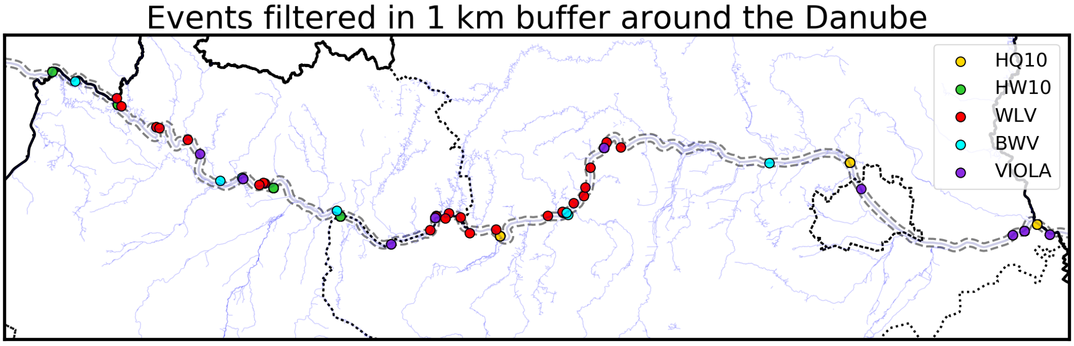


FIGURE 4.1: Filtered Events around the Danube using a 1 km buffer (grey lines). Orange point: HQ10, green point: HW10, red point: WLV, blue point: BWV, violet point: VIOLA

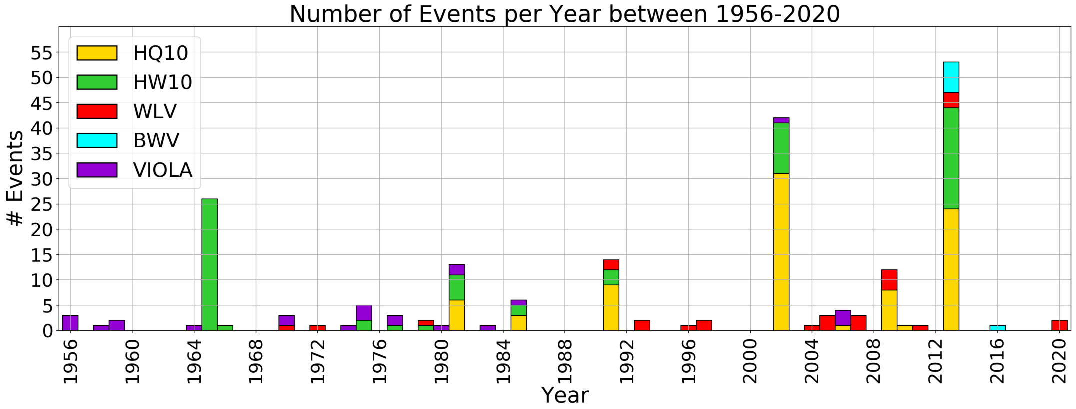


FIGURE 4.2: Number of events registered per year and data set. Orange bar: HQ10, green bar: HW10, red bar: WLV, blue bar: BWV, violet bar: VIOLA

With this information, the next step was to cluster the events into groups as explained in chapter 3. The dendogram resulting from hierarchical clustering is shown in fig. 4.3. The cutting line for receiving a certain number of clusters does not need to be at a constant height. The dendogram allows one to choose different heights for cutting to obtain more or less clusters Nielsen, 2016. Using different clustering methods such as K-Means clustering can give additional information on the possible number of clusters. However they are used for guidance than as a decision criterion. The objective is the appropriate analysis of the events along the Danube in reasonably sized clusters and receiving differentiated information. For this reason the cutting line has been made at six clusters. They form the regions to be investigated, seen in fig. 4.4. The regions have been given the following names from west to east:

- Schärding
- Linz/Linz Land
- Machland/Ybbs

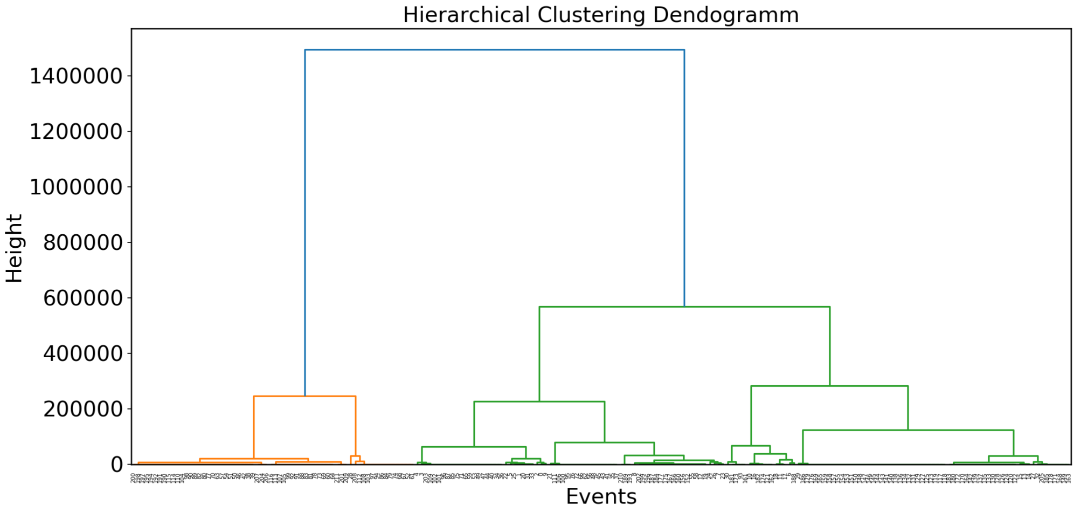


FIGURE 4.3: Hierarchical clustering dendogram for clustering the events along the Danube.

- Wachau/Kienstock
- Korneuburg/Vienna
- Bruck an der Leitha

One change has been made regarding the hierarchical clustering, which calculated the regions Linz/Linz Land and Machland/Ybbs. The monitoring station events from Mauthausen were counted in the hierarchical clustering to Linz/Linz Land and not Machland/Ybbs. Since Mauthausen is counted to the Machland region in various sources regarding flood protection measures ((MDB Machland-Damm Betriebs GmbH, 2008), (Amt der Oberösterreichischen Landesregierung, 2012), (Oberösterreichischer Landesrechnungshof, 2014), (Frank, 2018)), for the purpose of this thesis, this monitoring stations events were included in the Machland/Ybbs region instead.

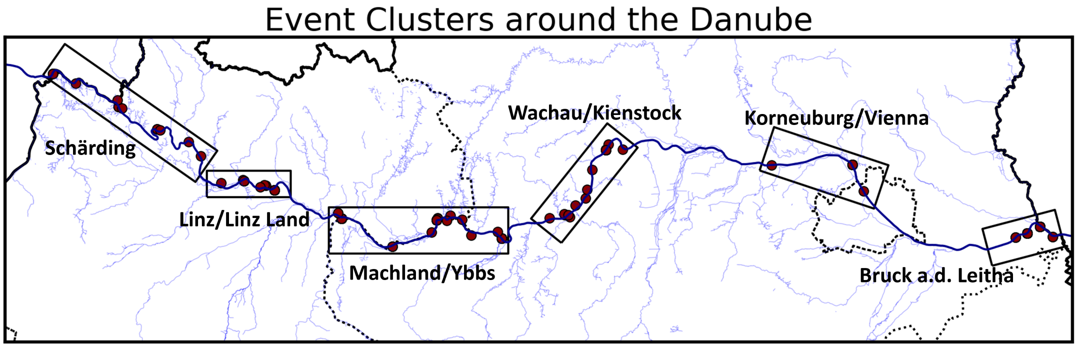


FIGURE 4.4: Regions found after visual and hierarchical clustering. Darkred points: Events.

4.2 Precipitation coverage through tributary monitoring stations

Through cross-correlation calculation the effect of precipitation inside a catchment area on the measurements of tributary monitoring stations is analysed. Two examples, where the first monitoring station lies close to a tributary's inflow and the second lies further upstream of a tributary, are given in fig. 4.5 and 4.6.

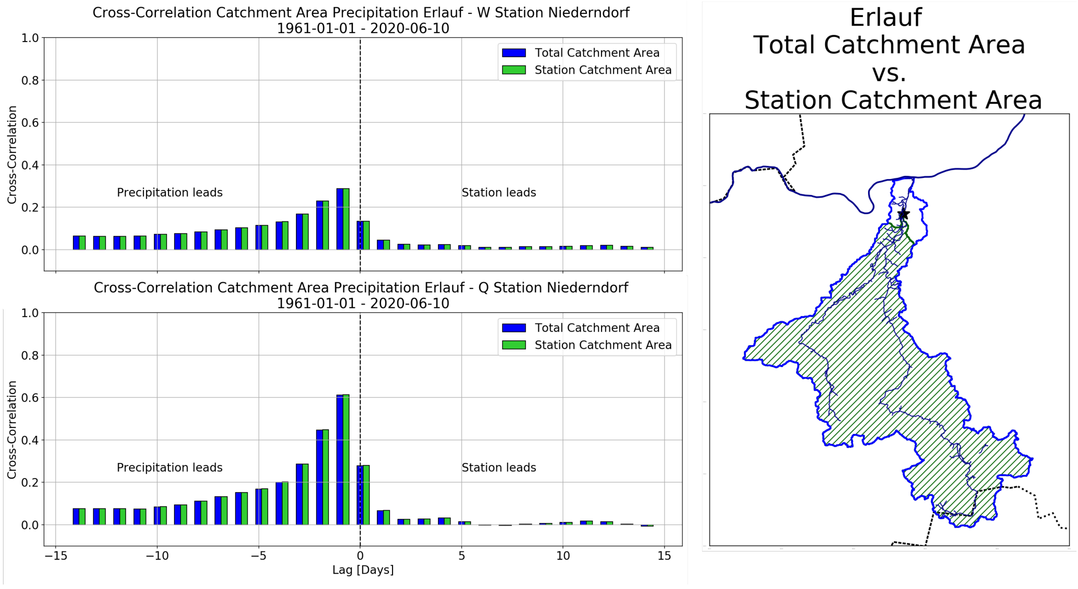


FIGURE 4.5: Cross-correlation comparison between the total catchment area of the Erlauf and the station catchment area of the station Niederndorf in the Erlauf.
Left figures: Cross-correlation between precipitation inside the total (blue bars) or station catchment area (green bars) and W (upper left figure) or Q (lower left figure) monitoring station data, respectively.
Right figure: Comparison of catchment area sizes. Black star: position of the monitoring station Niederndorf. Size of the Erlauf's total catchment area (blue polygon): 631.48 m^2. Size of the station catchment area (green hatched polygon): 604.9 m^2. 95.79% of the total catchment area are covered by the monitoring station.

The results show, that the more the size of a monitoring station's catchment area is similar to the tributary's catchment area, the higher the correlation is with the tributary's catchment area's precipitation (compare fig. 4.5 and fig 4.6). If Q data is used, higher correlations are available than with W data. This is the case for both types of catchment area coverage by the monitoring stations. Cross-correlation with a station catchment area that is considerably smaller than the total catchment area gives slightly higher values. This might be, because less grid points give higher mean precipitation values over the catchment area, resulting in higher cross-correlation.
All four cross-correlations in fig. 4.5 and fig 4.6 show a maximum at lag = -1. This means, that when precipitation is registered inside the catchment area, the effect in monitoring station measurements can be seen the day after. No difference can be observed when different catchment areas or different measurements are used. These calculations with other tributaries produce similar results.
Precipitation can be described through W and Q well enough, under the premise, that the monitoring station is located as close as possible at the inflow to the Danube.

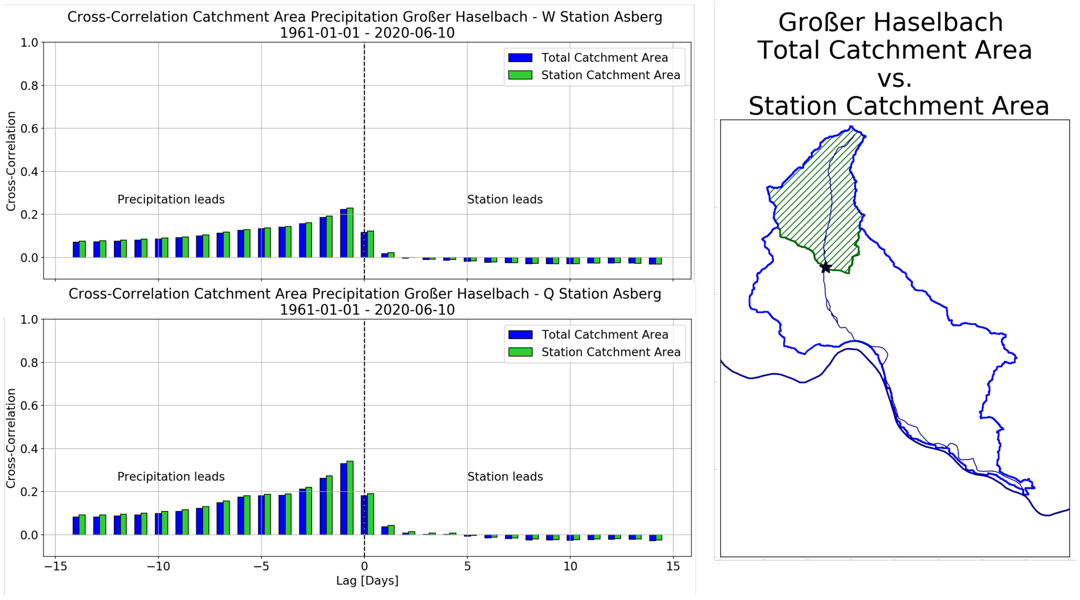


FIGURE 4.6: Cross-Correlation comparison between the total catchment area of the Großer Haselbach and the station catchment area of the station Asberg in the Großer Haselbach.
Left figures: Cross-correlation between precipitation inside the total (blue bars) or station catchment area (green bars) and W (upper left figure) or Q (lower left figure) monitoring station data, respectively. Right figure: Comparison of catchment area sizes. Black star: position of the monitoring station Asberg. Size of the Großer Haselbach's total catchment area (blue polygon): 119.6 m^2. Size of the station catchment area (green hatched polygon): 27.9 m^2. 23.33% of the total catchment area are covered by the monitoring station.

4.3 EOF analysis

The following EOF analysis has been done for the regions mentioned above. The figures 4.7 through 4.23 depict these analysis in a standardized layout: The top row presents a section of Austria showing the investigated region (black rectangle), the events inside the region (darkred points) and the investigated tributaries with names in the legend (red, green and yellow) and their catchment area outline (grey lines). The 2nd through 4th rows present the Climate Indices (CIs) from the EOF analysis for the investigated tributaries, where the outline colors correspond to the color of the tributary in the top row respectively. For each row from left to right it is illustrated the simulated variance in % including error margins and the first to third EOF with simulated variance for each EOF, showing the precipitation characteristics in the catchment area of the tributary respectively.

4.3.1 Schärding

In total 16 events were located inside the region Schärding, which are made up of 8 damage events and 8 monitoring station events. The two approaches described in section 3.2.4 have been conducted for the analysis of the region. The number of exceeded thresholds $\overline{W} + \sigma_W$ and/or $\overline{Q} + \sigma_Q$ of tributary monitoring stations from the target day ('TD') until 7 days prior to an event showed, that nearly exclusively stations inside the Inn's catchment area have recorded in total 80 W and 112 Q exceedances.

In table 4.2 the cross-correlation of the Inn with Danube monitoring stations is shown. Precipitation in the Inn's catchment area has the highest correlation with the monitoring stations in the Danube inside the Schärding region, Achleiten and Engelhartszell respectively. All other tributaries in this region either do not have any monitoring station or their monitoring station did not record any exceedances. All other tributaries' catchment areas, which have high cross-correlations with the Danube monitoring stations, are in relation to the Inn very small. The Inn will almost always outplay the other small streams because of its size.
Therefore for the Schärding region the following tributary has been analysed:

- Inn

Monitoring Station	HWn/HQn	Tributary	Cross-Corr.	lag (Days)
Achleiten	HW10	Inn	0.87	-2
	HQ10	Inn	0.87	-2
Engelhartszell	HW10	Inn	0.79	-2

TABLE 4.2: Maximum Cross-Correlation values at specific lag in days between tributary and Danube monitoring stations in the region Schärding having a statistical expected value for $\geq$ HW10 or HQ10.

In figure 4.7 the EOF analysis of all events in this region, meaning HQ10, HW10 and damage events (WLV, BWV, VIOLA), is depicted, while figure 4.8 describes the EOF analysis for damage events only and figure 4.9 for monitoring station events only, respectively.

All events

In the case, where all 16 events are used for the EOF-Analysis (fig. 4.7) the first EOF for the Inn reached 50 simulated variance, indicating that the first EOF explaines a majority of precipitation characteristics for these events. The error margin for the simulated variance of each leading pattern is extensive due to the fact that very few events have been registered in this region.
For the Inn the first EOF's temporal pattern in figure 4.7 shows an increase starting from TD-6 until a maximum on TD-2 with a decrease until the damage occurrence. While the second EOF's pattern with 26% simulated variance suggests that with a maximum on TD-7 precipitation decreases to a minimum until TD-3 from where we have an increase in precipitation amounts on TD-2 and TD-1 and decreasing precipitation on TD itself. Pertaining the third EOF's temporal pattern with only 16% simulated variance presents a slight increase until TD-3 and a sharp maximum on TD-1 and slightly less precipitation on TD.

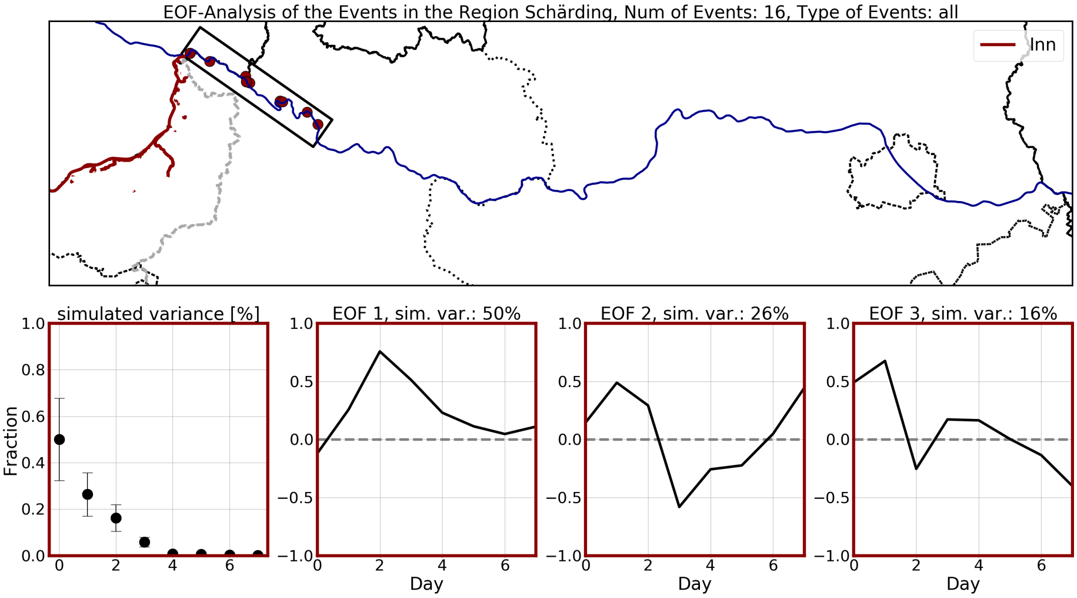


FIGURE 4.7: EOF Analysis of the region Schärding. All events, meaning monitoring stations and damage events, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Damage events

Significant differences can be seen for the Inn if compared to the results of the EOF analysis with only damage events used (fig. 4.8). The first EOF shows a maximum on TD and TD-1 with simulated variance of 61%. Whereas the second EOF depicts precipitation over a longer period of time from TD-4 until TD-1. The third EOF's pattern suggesting maxima on TD-6, TD-2 and on TD while significant decreases are shown on the days in between.

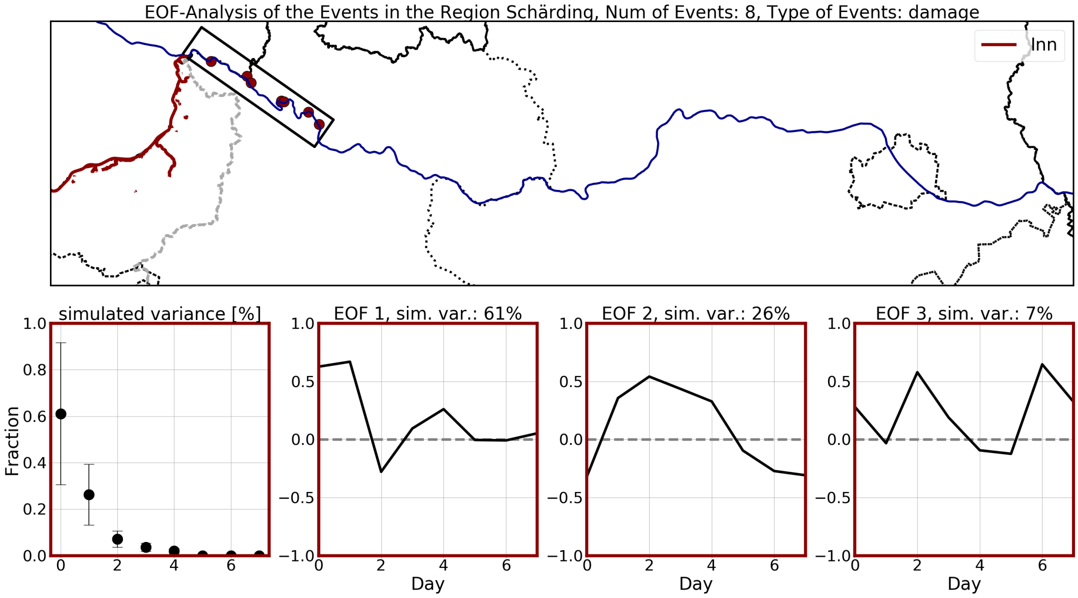


FIGURE 4.8: EOF Analysis of the region Schärding. Damage events from WLV, BWV and VIOLA, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Monitoring station events

From the EOF analysis when only monitoring station events are considered (fig. 4.9) the first leading pattern shows two maxima, at first at the beginning of the preceding week and again with increasing precipitation from TD-2 until one day before the events occurrence. On the other hand the second EOF's pattern shows a sharp maximum in TD-1 and also significant precipitation on the TD itself. In comparison the third leading pattern gives two distinct maxima at TD-4 and TD-2 significantly less precipitation in the rest of the days.

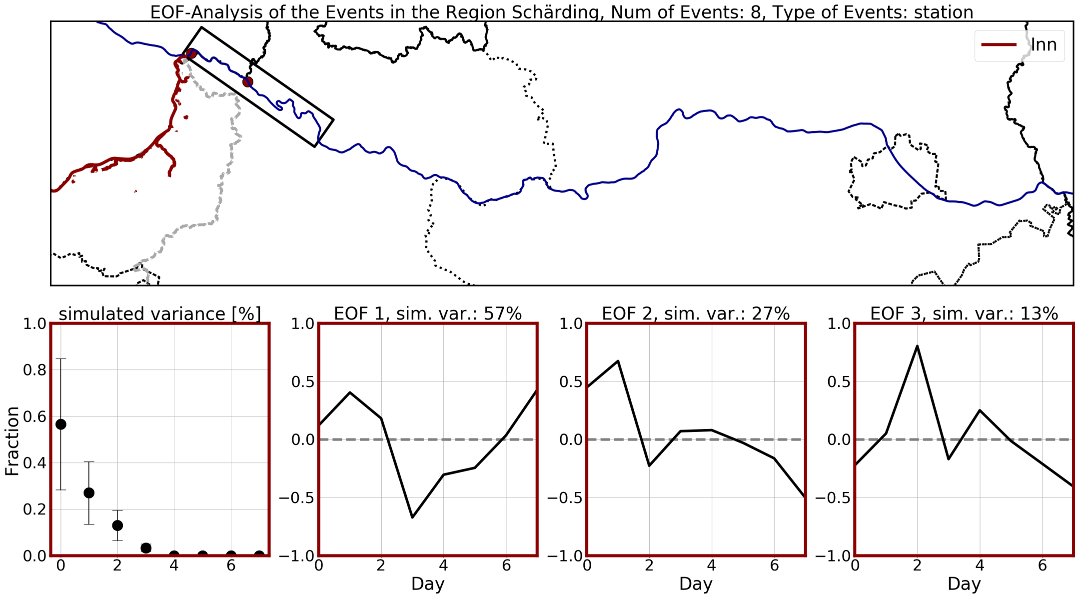


FIGURE 4.9: EOF Analysis of the region Schärding. Monitoring station events, where HQ10 or HW10 were exceeded, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

4.3.2 Linz/Linz Land

In the region Linz/Linz Land 28 events were registered, 6 of which were damage events and 22 were monitoring station events. The two approaches described in section 3.2.4 have been conducted for the analysis of the region. The number of exceeded thresholds $\overline{W} + \sigma_W$ and/or $\overline{Q} + \sigma_Q$ of tributary monitoring stations from the target day ('TD') until 7 days prior to an event showed, that the Inn, Innbach and Große Rodl showed the highest number of exceedances. In the Inn's catchment area were in total 213 W and 166 Q, for the Innbach in total 140 W and 85 Q and for the Große Rodl in total 68 W and 145 Q exceedances registered.

In table 4.3 the cross-correlation of these three tributaries with Danube monitoring stations is shown. The Inn had the highest correlation with the monitoring stations in the Danube inside the Linz/Linz Land region, Wilhering and Linz respectively. The Innbach is ranked fifth for Wilhering and eighth for Linz. However a great discrepancy is seen with the Große Rodl being ranked last out of 28 tributaries for Wilhering and third for Linz. But due two the high number of exceedances of the Große Rodl's monitoring station, this tributary is investigated as well.

Therefore, for the Linz/Linz Land region the following tributaries have been selected:

- Inn
- Innbach
- Große Rodl

In figure 4.10 the EOF analysis of all events in this region, meaning HQ10, HW10 and damage events (WLV, BWV, VIOLA), is depicted, while figure 4.11 and 4.12 describe the EOF analysis for damage events only and monitoring station events only, respectively.

Monitoring Station	HWn/HQn	Tributary	Cross-Corr.	lag (Days)
Wilhering	HW10	Inn	0.77	-2
		Innbach	0.66	-1
		Große Rodl	0.60	-1
Linz	HW10	Inn	0.51	-2
		Innbach	0.31	-7
		Große Rodl	0.34	-7

TABLE 4.3: Maximum Cross-Correlation values at specific lag in days between tributary and monitoring stations in the region Linz/Linz Land having a statistical expected value for $\geq$ HW10 or HQ10.

All events

This region is also under the influence of the Inn, though if the first EOF's temporal pattern with all events used (fig. 4.10) is compared to the Inn's first for the region Schärding (fig. 4.7), the maximum precipitation occurs one day earlier namely on TD-1 than in Schärding, despite being further downstream to the inflow of the Inn. This could be due to the fact that a larger number of events occured in the Linz/Linz Land region and therefore a larger sample is available for the calculation of the EOFs. Futhermore the first and second leading EOF's of all three tributaries are similar to each other (see fig. 4.10). The first EOF's temporal pattern for the three tributaries show a maximum on TD-1. Precipitation amounts increase in the Inn's catchment area from TD-4 until TD-1 with a slight decrease on the TD itself. While the Inn has only one maximum, the other two tributaries have an equally pronounced or stronger second maximum on TD-6. Similarly the second EOF's pattern for all three catchment areas has an increase in precipitation until a maximum on TD-3 and a decrease afterwards. The Inn's third leading pattern differs from the other two tributaries Innbach and Große Rodl with a peak at TD-4 and at TD-1 until TD. The Innbach has a constant rise in precipitation until the flood occurrence as well as the Große Rodl with a maximum on TD-1 and a very slight decrease on the TD.

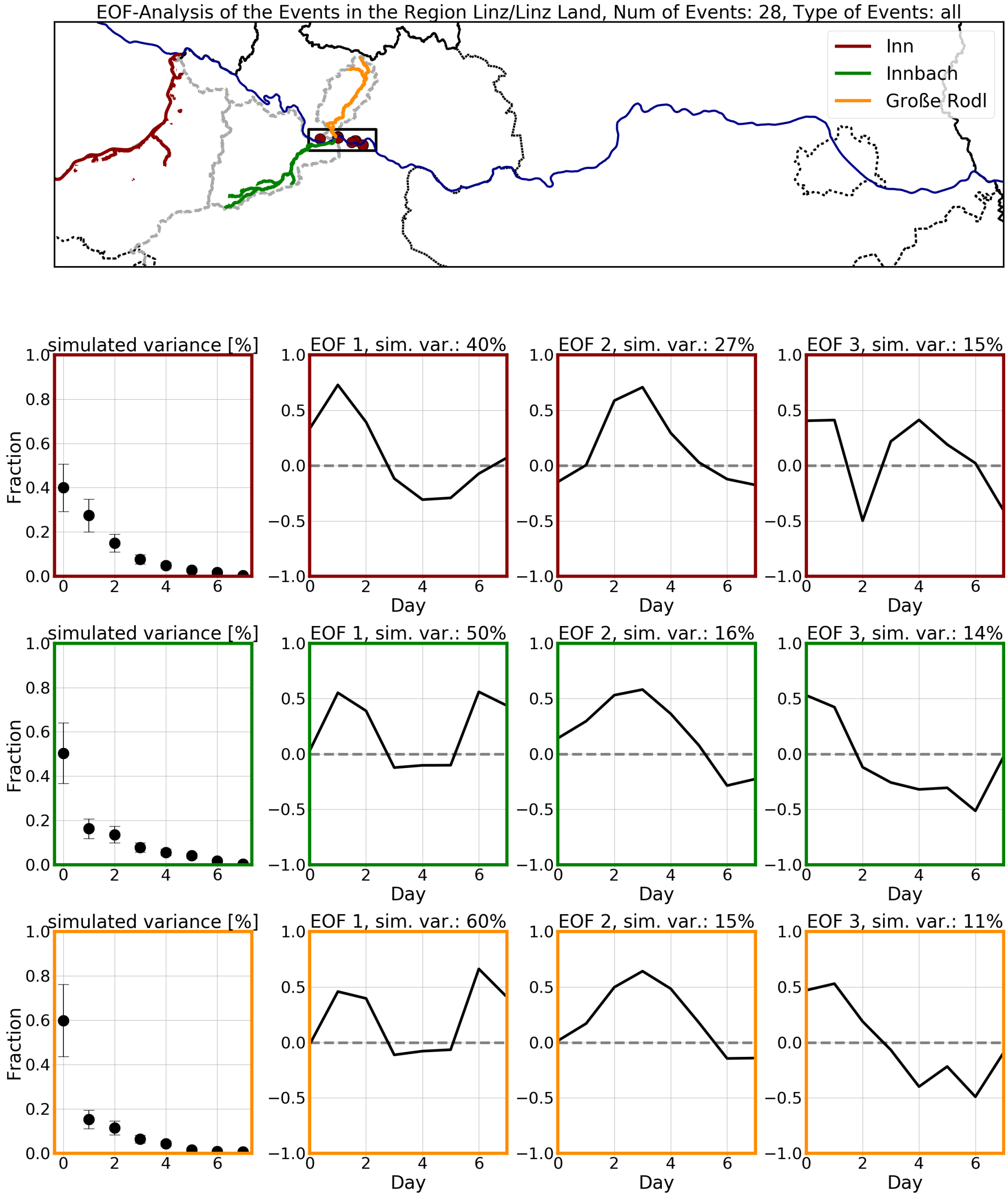


FIGURE 4.10: EOF Analysis of the region Linz/Linz Land. All events, meaning monitoring stations and damage events, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Damage events

Comparing the number of events recorded in damage databases and by monitoring stations, the difference is significant. More than 3.5 times as many events were registered by monitoring station than damage events. Regarding the EOF analysis in this context, the first leading patterns with damage events simulate more variance in the data than those with all events or only monitoring station events (compare fig. 4.11 to fig. 4.10 & fig. 4.12), except for the Große Rodl's first EOF pattern with only damage events, where the simulated variance is less than those of the other to sample sizes. Due to the fact that only 6 damage events are available, their EOF analysis is only representative to a limited extent, as can bee seen in the error margins for the simulated variances of each tributaries' first leading EOF pattern (fig. 4.11).

In both EOF analysis with damage events or monitoring station events respectively, the first three leading patterns of all three tributaries are similar to each other as well (compare fig. 4.11 and fig. 4.12).

As seen in fig. 4.11 the Inn has a maximum on TD-1 in the first leading pattern with damage events. The second leading pattern's maximum shows an increase in precipitation until TD-2, while the third EOF's pattern of the damages events shows a broad maximum between TD-5 and TD-3 and a less pronounced maximum on TD-1.

Regarding the patterns for the Innbach and Große Rodl, in the case with damage events the first leading patterns for both show an increase in precipitation from TD-3 until the TD with a maximum on TD-1 for the Innbach while the Große Rodl has two maxima at TD-2 and TD (green and yellow diagrams in fig. 4.11). The second leading patterns for both tributaries are similar to the second leading pattern for the Inn (see fig. 4.11). Similarities can be seen in the shape of the third EOF's pattern to the pattern of the Inn, however the pattern for the Große Rodl has a more pronounced maximum on TD-1. Furthermore the third leading patterns of all three tributaries in this case only account for less than 10% of the simulated variance, hence they carry less importance.

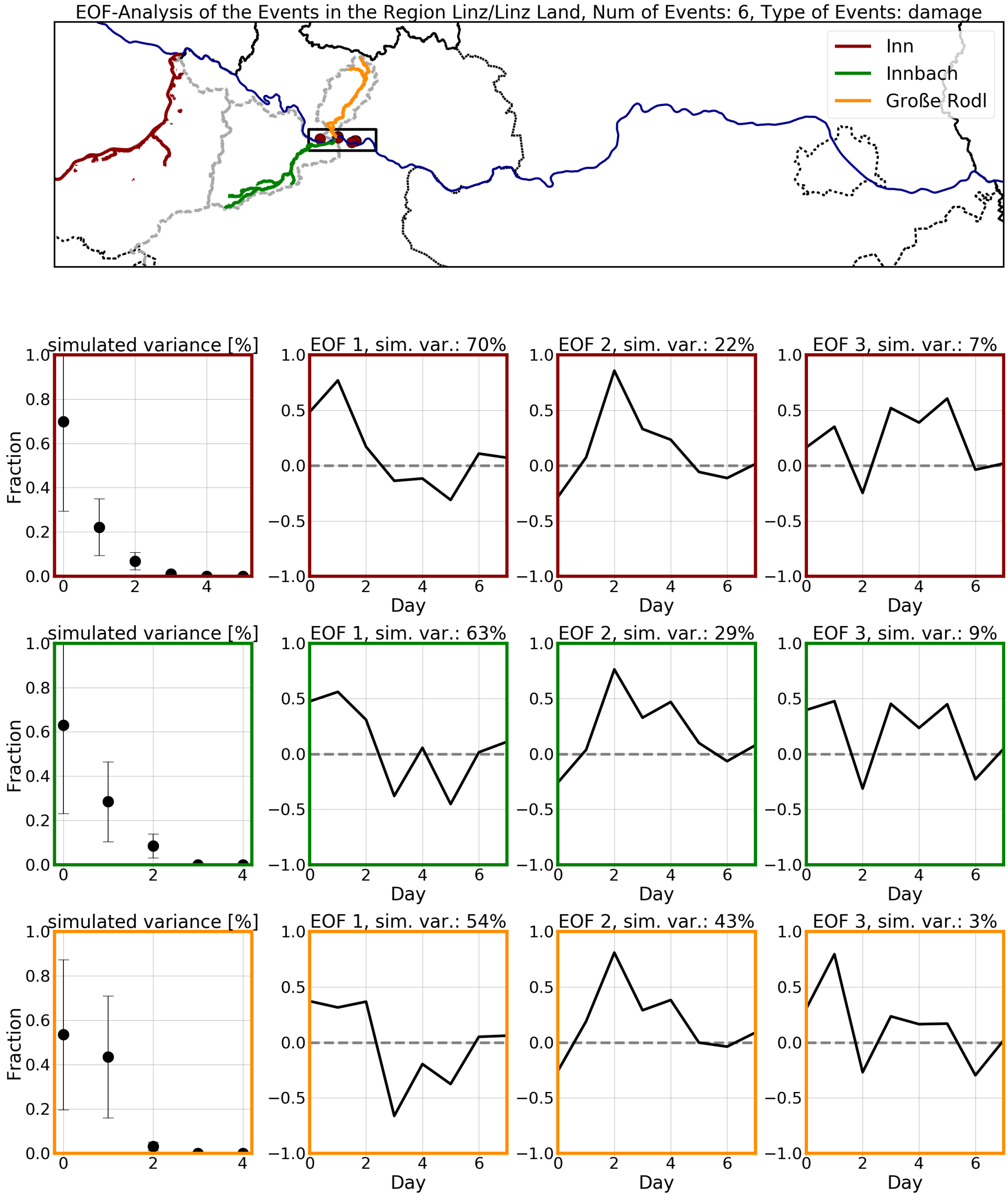


FIGURE 4.11: EOF Analysis of the region Linz/Linz Land. Damage events from WLV, BWV and VIOLA, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Monitoring station events

It can be seen that the Inn's first precipitation pattern with monitoring station events has a broader maximum at TD-2 and TD-1 (fig. 4.12). Moreover the shapes of the second and third leading patterns in both cases with damage or monitoring station events are similar to each other. The second leading pattern's maximum shifts to an increase until TD-3 derived from monitoring station events, thereby explaining the smoothed out curve seen in the second EOF's pattern when all events were used (compare with fig. 4.10). If monitoring station events are used, the third leading pattern changes to a more distinct yet slighter maximum at TD-4 and a greater maximum at TD-1.

On the other hand the first EOF's pattern using monitoring stations for the Innbach and Große Rodl, both tributaries have two maxima at TD-6 and TD-1 and no precipitation on the TD itself (green and yellow diagrams in fig. 4.12). As described for the EOF analysis with damage events, the same circumstance occurs with monitoring station events for the second leading patterns for both tributaries, where they are similar to the second leading pattern for the Inn. When looking at the third leading pattern with monitoring station events, the patterns for both Innbach and Große Rodl show an increase until a maximum at TD-1, but only account for 12% or 11% of variance respectively.

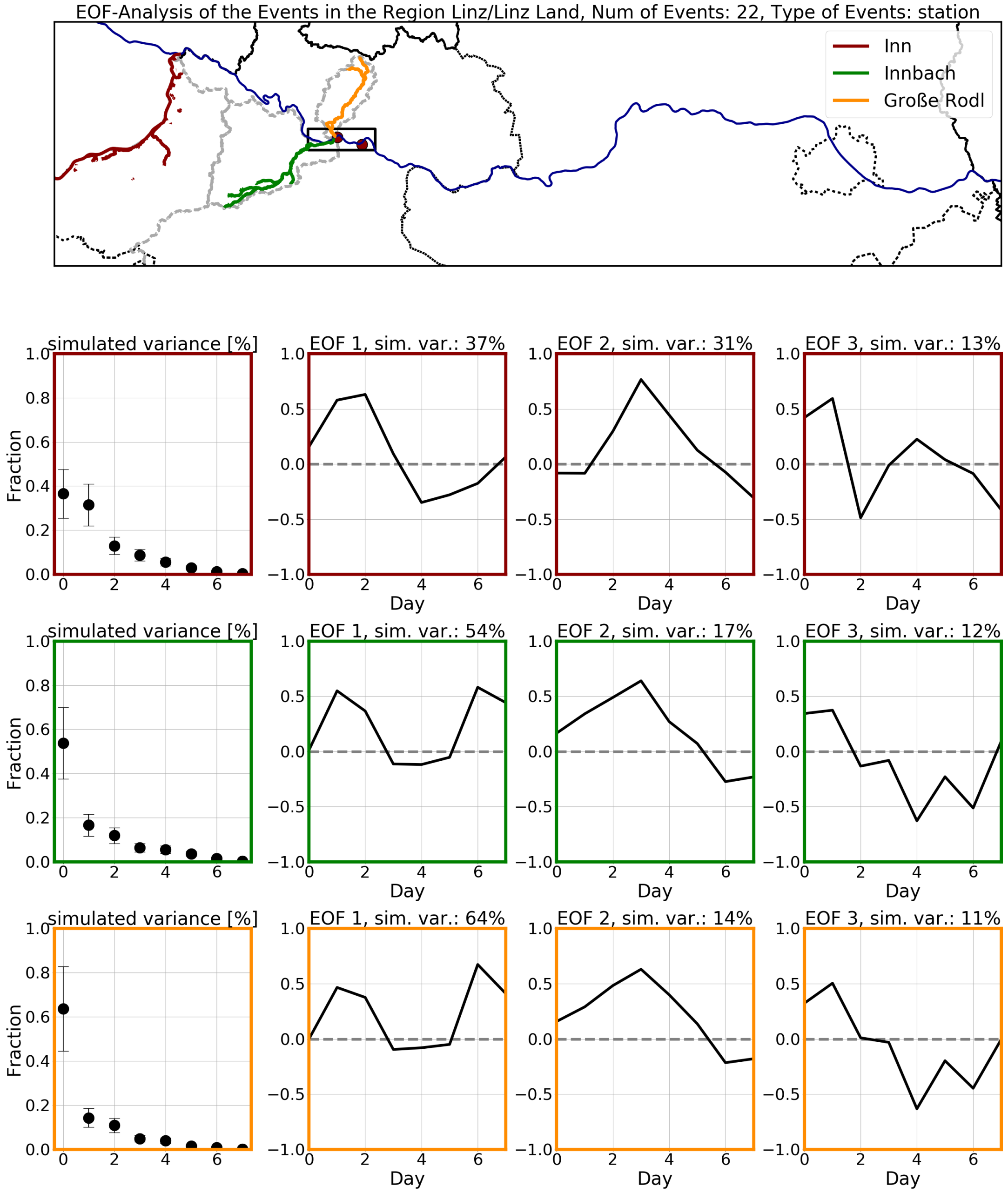


FIGURE 4.12: EOF Analysis of the region Linz/Linz Land. Monitoring station events, where HQ10 or HW10 were exceeded, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

4.3.3 Machland/Ybbs

This region has the highest number of events registered with 72 events, consisting of 13 damage events and 59 monitoring station events. The two approaches described in section 3.2.4 have been conducted for the analysis of the region. The number of exceeded thresholds $\overline{W} + \sigma_W$ and/or $\overline{Q} + \sigma_Q$ of tributary monitoring stations from the target day ('TD') until 7 days prior to an event showed, that the Inn, Enns and Traun showed the highest number of exceedances. In the Inn's catchment area were in total 471 W and 466 Q, for the Traun in total 516 W and 230 Q and for the Enns in total 468 W and 582 Q exceedances registered. They have the greatest catchment areas of all Danube tributaries directly flowing into the investigated Danube part in Austria.

In table 4.4 the cross-correlation of these three tributaries with Danube monitoring stations in this region is shown. These three tributaries often shared in the cross-correlation ranking for the three monitoring stations with available HQ10 or HW10 thresholds, being Mauthausen, Grein and Ybbs an der Donau. The Inn's cross-correlation is ranked 13. at the Ybbs an der Donau station. However the Inn is still one of the top three tributaries in this region when considering the previous mentioned results.

From this findings, the following three tributaries have been selected for the Machland/Ybbs region:

- Inn
- Traun
- Enns

Monitoring Station	HWn/HQn	Tributary	Cross-Corr.	lag (Days)
Mauthausen	HW10	Inn	0.58	-2
		Traun	0.62	-2
		Enns	0.57	-2
Grein	HW10	Inn	0.69	-2
		Traun	0.70	-2
		Enns	0.70	-2
	HQ10	Inn	0.73	-3
		Traun	0.72	-2
		Enns	0.75	-2
Ybbs an der Donau	HW30	Inn	0.83	-2
		Traun	0.81	-2
		Enns	0.86	-2
	HQ10	Inn	0.68	-3
		Traun	0.74	-2
		Enns	0.74	-2

TABLE 4.4: Maximum Cross-Correlation values at specific lag in days between tributary and monitoring stations in the region Machland/Ybbs having a statistical expected value for $\geq$ HW10 or HQ10.

In figure 4.13 the EOF analysis of all events in this region, meaning HQ10, HW10 and damage events (WLV, BWV, VIOLA), is depicted, while figure 4.14 and 4.15 describe the EOF analysis for damage events only and monitoring station events only respectively.

All events

Regarding the EOF analysis where all event categories are used (fig. 4.13), the shape of the first three leading EOFs of all three tributaries show many similarities. The first leading EOF presents a precipitation increase from TD-4 until TD-1 for the Inn and Traun or until TD-2 for the Enns, although the Enns is located closer to the region. Interestingly the second leading pattern simulates nearly as high of the variance as the first. All three tributaries show a maximum at TD-3 with an increase from TD-7 or TD-6. The Traun has a broader maximum including TD-2. Two maxima are visible in the third leading EOF for all three tributaries. TD-4 and TD-1 are the maxima calculated for the Inn's catchment area, while an increase until TD-3 and TD-1 and TD for the Traun has been determined. In contrast, for the Enns the first maximum is between TD-4 and TD-3 and the second maximum at TD-1.

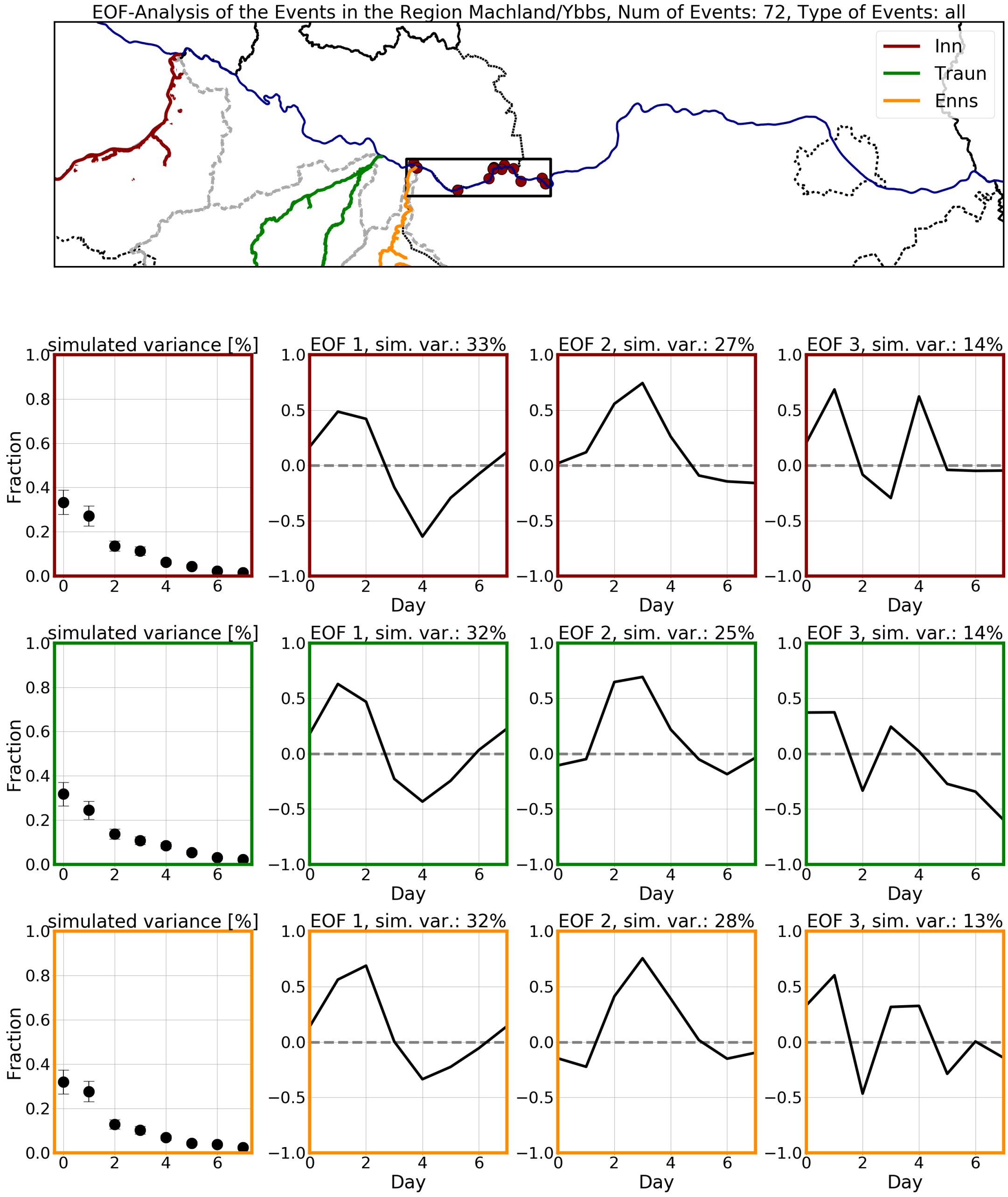


FIGURE 4.13: EOF Analysis of the region Machland/Ybbs. All events, meaning monitoring stations and damage events, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Damage events

A similar picture emerges when analysing the first leading patterns using exclusively damage events (fig. 4.14). The first leading EOF for all three tributaries shows increasing precipitation from TD-5 until a maximum at TD-1. The second leading pattern shows constant rainfall from TD-7 until TD-2 for the Inn and Enns, TD-3 for the Traun. Both Traun and Enns have a maximum at TD-1 in the third leading pattern in comparison to the Inn having a maximum at TD-5 and a less significant second maximum at TD-1.

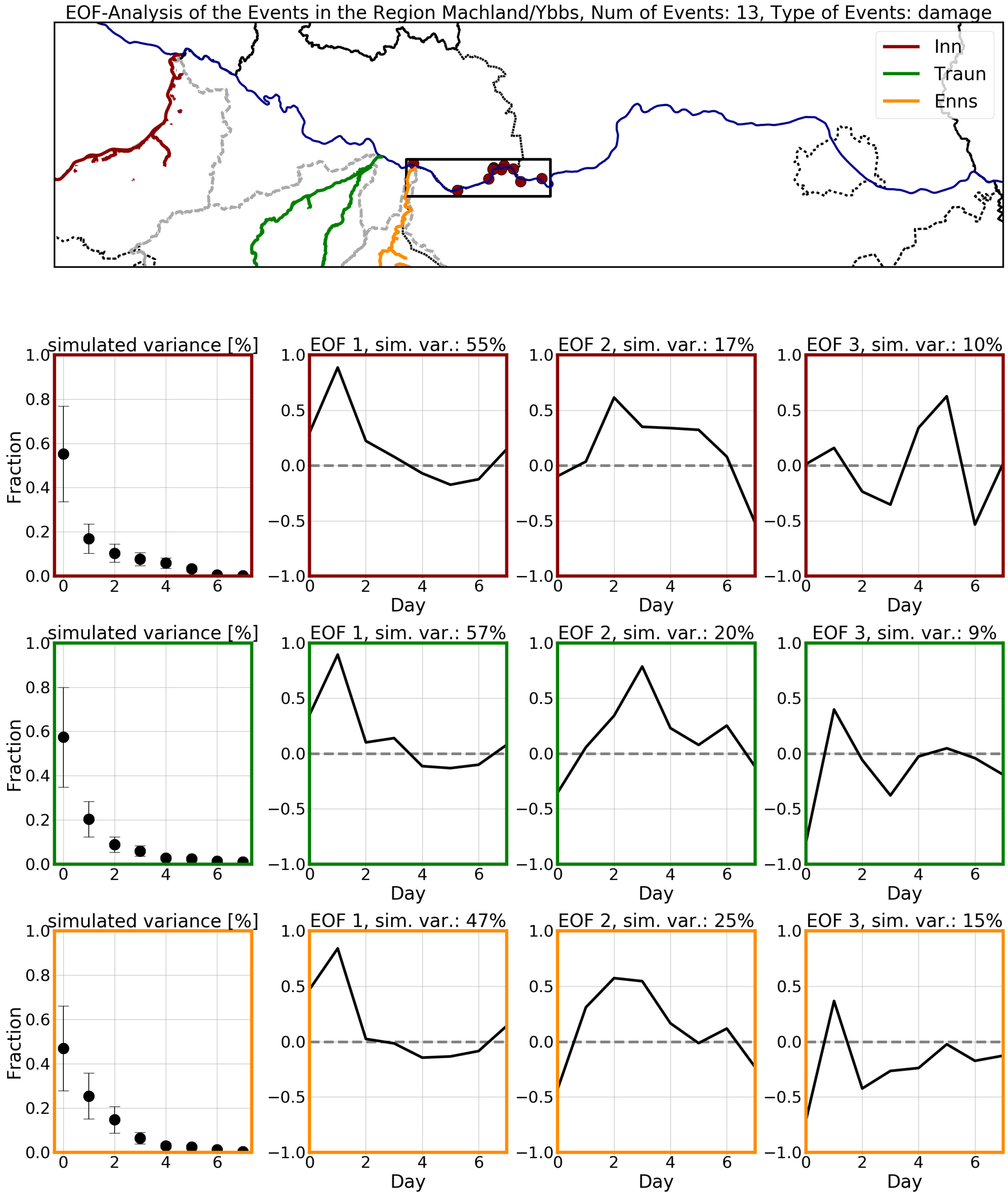


FIGURE 4.14: EOF Analysis of the region Machland/Ybbs. Damage events from WLV, BWV and VIOLA, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Monitoring station events

Lastly the monitoring station events give a slightly different picture (fig. 4.15). All three tributaries have in their first leading pattern an increase from TD-4 until TD-2. The maximum shifts to TD-3 for all three in the second leading EOF's pattern. For the Inn the third leading pattern gives two maxima at TD-4 and from TD-2 to TD-1, while the Enns has three maxima increasing over time at TD-6, TD-4 and TD-1. On the other hand the Traun shows an increasing precipitation amount until the date of event occurrence.

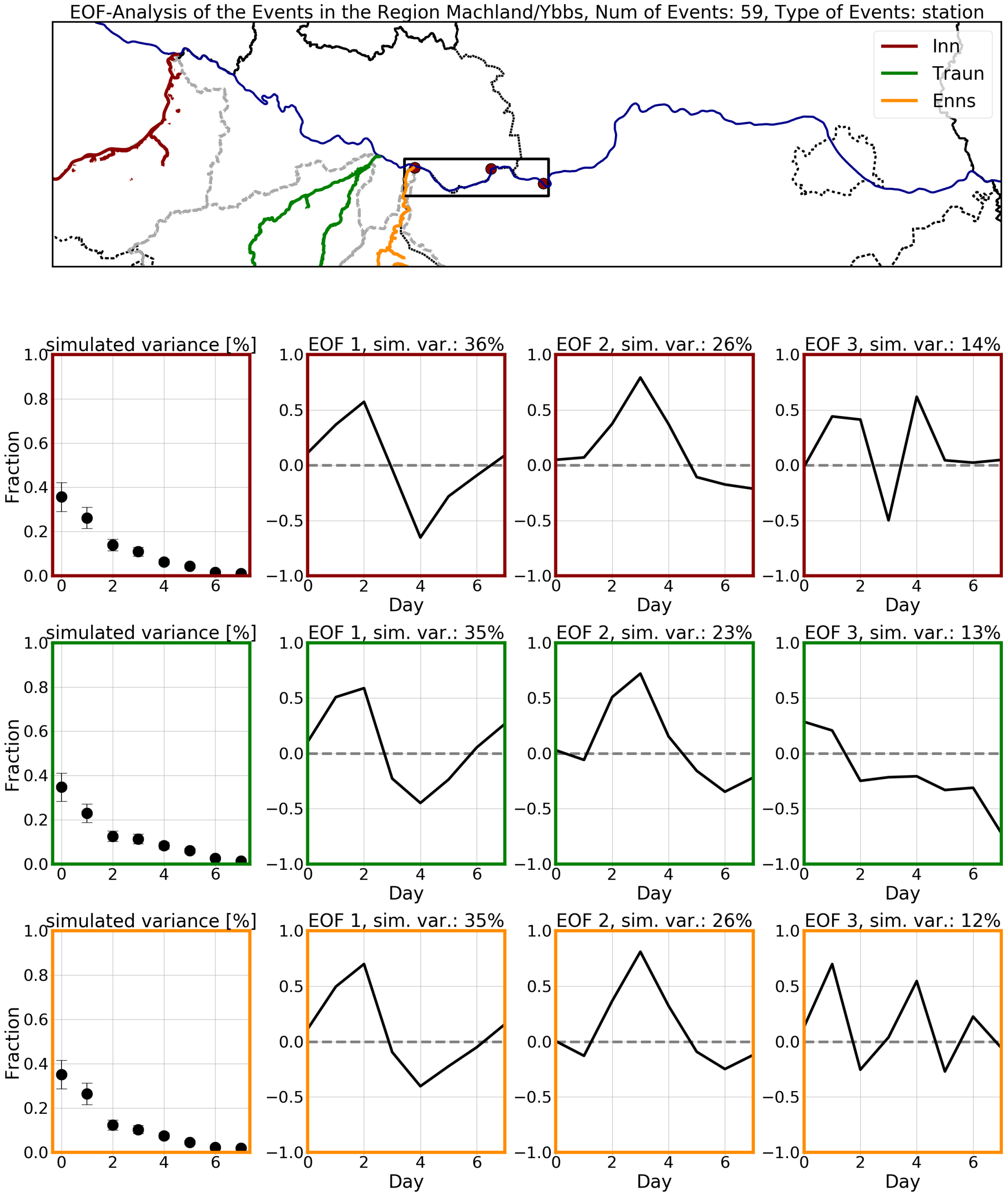


FIGURE 4.15: EOF Analysis of the region Machland/Ybbs. Monitoring station events, where HQ10 or HW10 were exceeded, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

4.3.4 Wachau/Kienstock

Inside the region Wachau/Kienstock 30 events were registered with 13 damage events and 17 monitoring station events. The two approaches described in section 3.2.4 have been conducted for the analysis of the region. The number of exceeded thresholds $\overline{W} + \sigma_W$ and/or $\overline{Q} + \sigma_Q$ of tributary monitoring stations from the target day ('TD') until 7 days prior to an event showed, that the Traun, Enns and Ybbs showed the highest number of exceedances. Inside the Traun's catchment area monitoring stations registered in total 277 W and 115 Q, the Enns' stations in total 214 W and 243 Q and the Ybbs' station in total 142 W and 124 Q exceedances.
In table 4.5 the cross-correlation of these three tributaries with Danube monitoring stations in this region, being Melk and Kienstock, is shown. The Enns and Traun were first and second for both HW30 thresholds, while the Ybbs was eighth. However, the Ybbs together with the Enns and Traun were the top three tributaries for Kienstock's HQ10 threshold.
For the Wachau/Kienstock region the following three tributaries have been selected:

- Traun
- Enns
- Ybbs

Monitoring Station	HWn/HQn	Tributary	Cross-Corr.	lag (Days)
Melk	HW30	Traun	0.74	-2
		Enns	0.76	-2
		Ybbs	0.70	-2
Kienstock	HW30	Traun	0.74	-2
		Enns	0.76	-2
		Ybbs	0.69	-2
	HQ10	Traun	0.73	-2
		Enns	0.73	-2
		Ybbs	0.73	-2

TABLE 4.5: Maximum Cross-Correlation values at specific lag in days between tributary and monitoring stations in the region Wachau/Kienstock having a statistical expected value for $\geq$ HW10 or HQ10.

In figure 4.16 the EOF analysis of all events in this region, meaning HQ10, HW10 and damage events (WLV, BWV, VIOLA), is depicted, while figure 4.17 and 4.18 describes the EOF analysis for damage events only and monitoring station events only, respectively.
As seen in the EOF analysis of the Machland/Ybbs region (fig. 4.13-4.15), the shape of the patterns described by the first three leading EOFs for all three tributaries show many similarities (compare fig. 4.16-4.18).

All events

For the EOF analysis using all events in this region it is noticeable, that the simulated variance by both the first and second EOF for all tributaries lie in the range of 27-30%, suggesting that the first leading precipitation pattern is not the dominating pattern triggering the flood events in this region (fig. 4.16). All three tributaries' first

EOF patterns have the maximum in precipitation on TD-1 in common, where the increase in precipitation begins three days prior to the events occurrence. However the broader maximum for the Ybbs shows high precipitation amounts occurring on TD-2 as well compared to those of the Traun and Enns. In contrast the second leading pattern shows an increase from TD-5 until a maximum at TD-2 for the Traun and Enns, while the Ybbs has the maximum at TD-3. The third EOF's pattern for the tributaries features 2 maxima, specifically all of them have one at TD-3 and more pronounced at TD itself or TD-1 for the Ybbs.

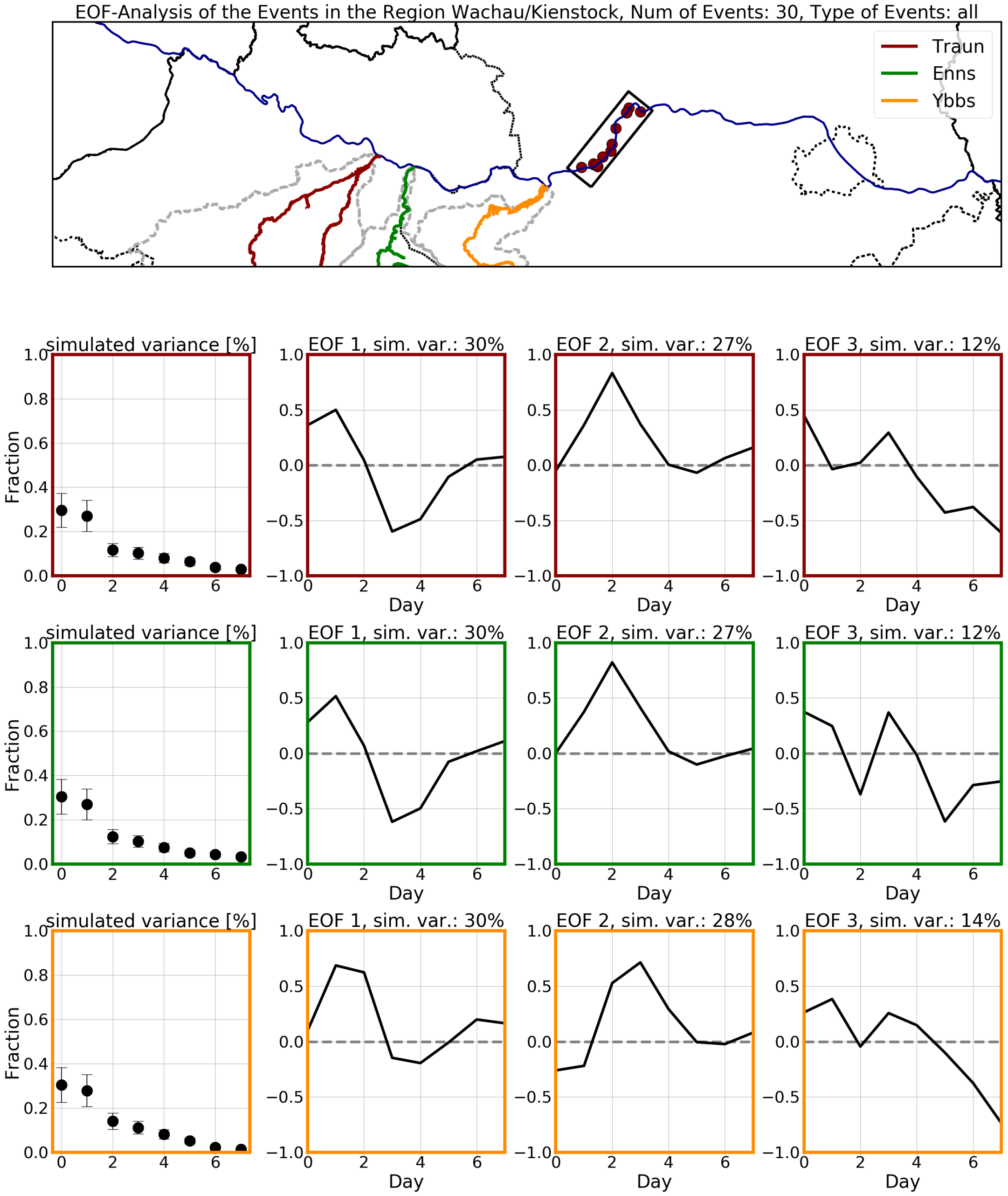


FIGURE 4.16: EOF Analysis of the region Wachau/Kienstock. All events, meaning monitoring stations and damage events, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Damage events

13 out of 30 events have been registered as damage events. Therefore the error when calculating the first leading EOF pattern grows larger due to the smaller amount of flood events used, as can bee seen in the error bars regarding the simulated variances for the three tributaries in figure 4.17. Regarding the first leading pattern, the precipitation pattern for the Traun catchment area differs from the Enns and Ybbs. The Traun's pattern shows a continuous increase in precipitation from TD-3 to a maximum at the TD, while the precipitation increase peaks at TD-1 for the Enns and Ybbs. However the second EOF's leading pattern indicates a sharp maximum on TD-1 for the Traun and Enns and a less pronounced peak on TD-3 and TD-1 for the Ybbs. In comparison, the third EOF's pattern presents a maximum at TD-2, though the Traun and Enns have high amounts of precipitation on TD-3 as well.

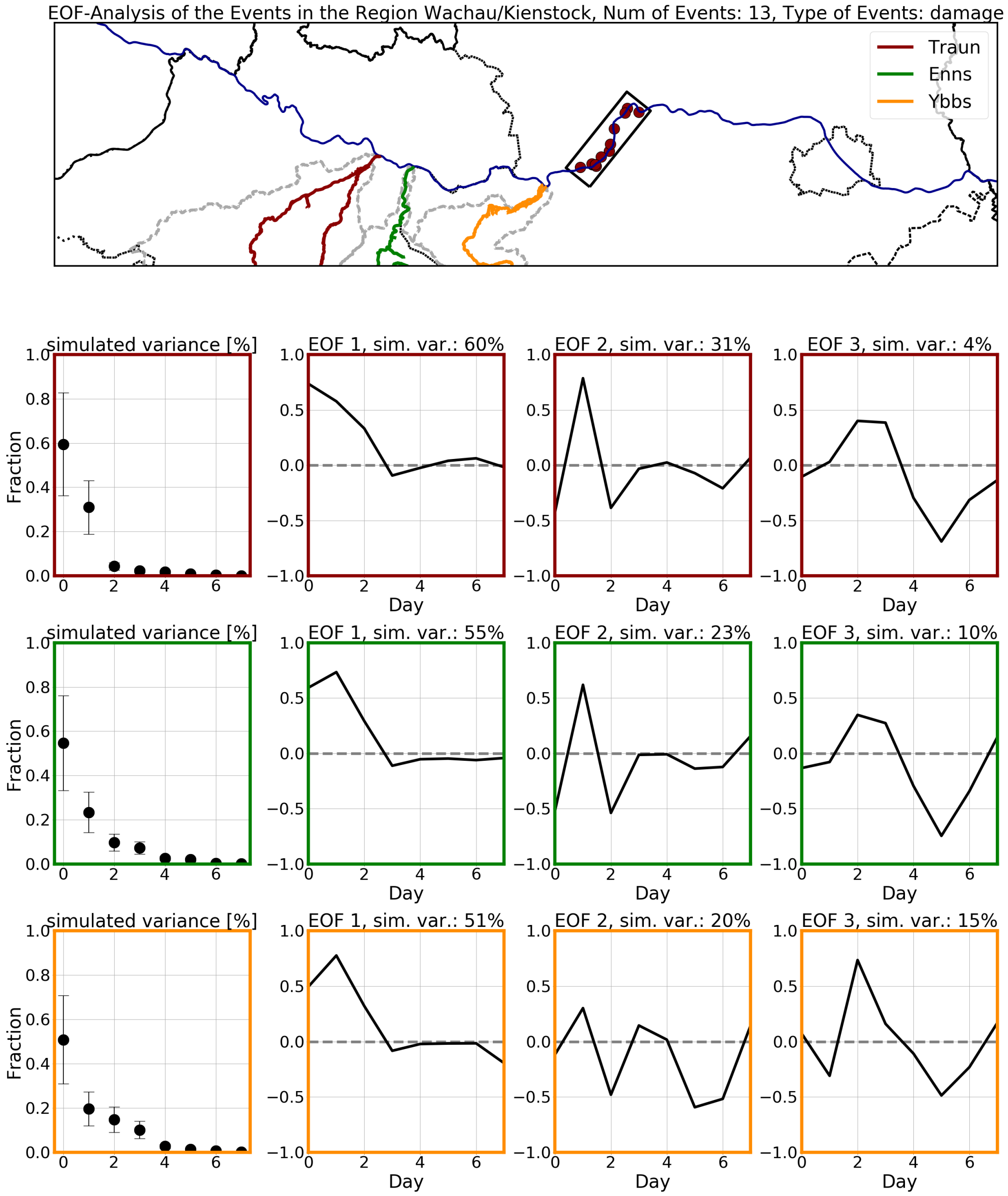


FIGURE 4.17: EOF Analysis of the region Wachau/Kienstock. Damage events from WLV, BWV and VIOLA, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Monitoring station events

When only monitoring station's flood events are considered (see fig. 4.18), the number of events rises to 17 out of 30 events leading to a smaller yet still visible range in error for the EOF analysis. The results for these event type differs greatly to the results with just damage events. It is apparent in the first leading precipitation pattern, that the maximum shifts from TD-2 to TD-1 when the catchment area lies further downstream in relation to the region. The Traun is located further upstream than the Enns and Ybbs and the maximum is at TD-2, with a nearly equal maximum on TD-1 as well, while the Enns presents the shift in the maximum slightly to TD-1. Eventually the Ybbs being the furthest tributary downstream indicates a strong maximum on TD-1. The same can bee seen in the second EOF's leading pattern, where the Traun and Enns show a maximum on TD-3, while the Ybbs presents a maximum in precipitation on TD-2. Lastly, the third leading pattern for the Traun shows two maxima at TD-5, and TD-1, while the Enns has high precipitation amounts at TD-5 as well as at TD-2. However, the Ybbs shows a steady increase in precipitation with the start of the week prior to the event until TD-1.

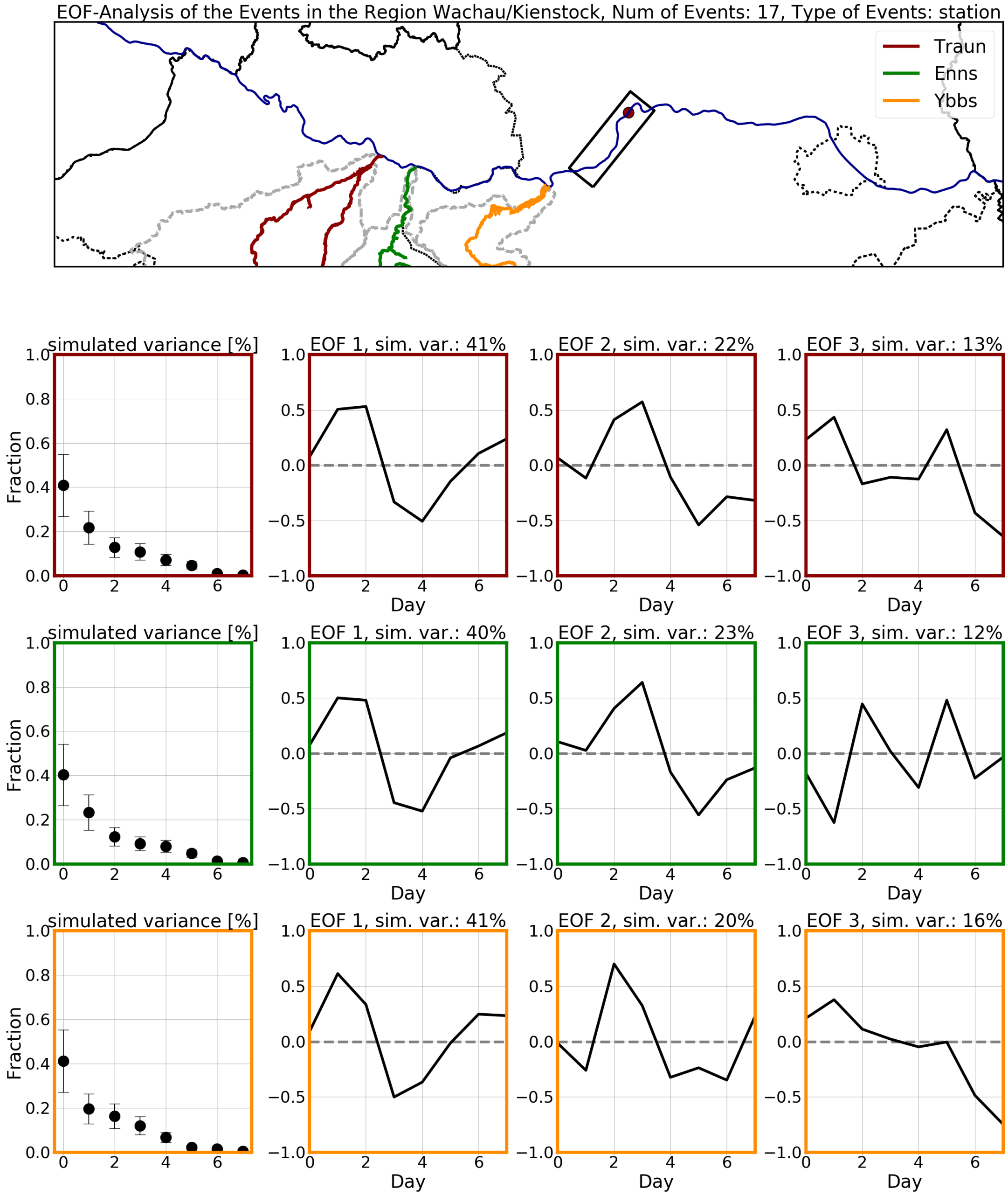


FIGURE 4.18: EOF Analysis of the region Wachau/Kienstock. Monitoring station events, where HQ10 or HW10 were exceeded, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

4.3.5 Korneuburg/Vienna

In this region 15 events were registered, consisting of 2 damage events and 13 monitoring station events. The two approaches described in section 3.2.4 have been conducted for the analysis of the region. The number of exceeded thresholds $\overline{W} + \sigma_W$ and/or $\overline{Q} + \sigma_Q$ of tributary monitoring stations from the target day ('TD') until 7 days prior to an event showed, that the Enns, the Große Tulln and the Kleine Tulln showed the highest number of exceedances. Inside the Enns' catchment area monitoring stations registered in total 148 W and 153 Q, the Große Tulln's stations in total 60 W and 62 Q and the Kleine Tulln's station in total 66 W and 55 Q exceedances.
In table 4.6 the cross-correlation of these three tributaries with Danube monitoring stations in this region, being Korneuburg and Wien (Nußdorf), is shown. The Kleine Tulln and Große Tulln were first and second for both of Korneuburg station's thresholds, while the Enns was eighth for HQ10 and fourth for HW30. However, the Enns was first for the Wien (Nußdorf) HW30 threshold, while the Kleine Tulln ranked sixth and Große Tulln ranked ninth.
Hence, for the Korneuburg/Vienna region the following three tributaries have been selected:

- Enns
- Große Tulln
- Kleine Tulln

Monitoring Station	HWn/HQn	Tributary	Cross-Corr.	lag (Days)
Korneuburg	HW30	Enns	0.65	-3
		Große Tulln	0.67	-2
		Kleine Tulln	0.71	-2
	HQ10	Enns	0.65	-3
		Große Tulln	0.67	-2
		Kleine Tulln	0.67	-2
Wien (Nußdorf)	HW30	Enns	0.68	-3
		Große Tulln	0.62	-2
		Kleine Tulln	0.63	-2

TABLE 4.6: Maximum Cross-Correlation values at specific lag in days between tributary and monitoring stations in the region Korneuburg/Vienna having a statistical expected value for $\geq$ HW10 or HQ10.

In figure 4.19 the EOF analysis of all events in this region, meaning HQ10, HW10 and damage events (WLV, BWV, VIOLA), is depicted, while figure 4.20 describes the EOF analysis for just monitoring station events.
Very few events have been registered in this region, 13 out of 15 events were monitoring station events and just two events were registered damage events. Therefore an EOF analysis with only two events is not productive, hence there are not three but two different EOF analysis (see fig. 4.19 & 4.20). Concerning the simulated variance, it can bee seen, that the variance fraction described by the first leading EOF's patterns decreases when only monitoring station events are used. Whereas the second leading pattern's simulated variances increase. The extent of the error margins for the described variances can be explained by the lack of events recorded in this

region. Hence the need for more events arises for increased reliability in the precipitation patterns.
Since the Große Tulln and Kleine Tulln lie next to each other, their EOF analysis in both instances show many similarities than those for the Enns. The further downstream the regions are, the less important the tributaries far upstream, such as the Inn or the Traun, are to the flood situations inside this regions. This goes for the regions Korneuburg/Vienna region and the Bruck a. d. Leitha.

All events

Regarding the EOF-Analysis with all event categories (fig. 4.19), the precipitation patterns appear similar for all three tributaries, though the shift in the maximum is apparent when analysing the first leading pattern. While the Enns shows a maximum at TD-2 with an increase starting from TD-4, the other two's maximum shifted to a slightly greater maximum at TD-1, with still high amounts on TD-2 and increase beginning at TD-4 as well. The shift is also recognisable in the second and third leading patterns. Two maxima can be seen in the second EOF's leading patterns for the tributaries. While the Enns has the first at TD-5 and TD-1, the other two have theirs at TD-4 and on TD. However the third leading EOF gives slightly earlier maximums at the beginning of the preceeding week. with the Enns having two maximums at TD-6 and TD-3, while the Kleine Tulln and Große Tulln have theirs at TD-5 and TD-2.

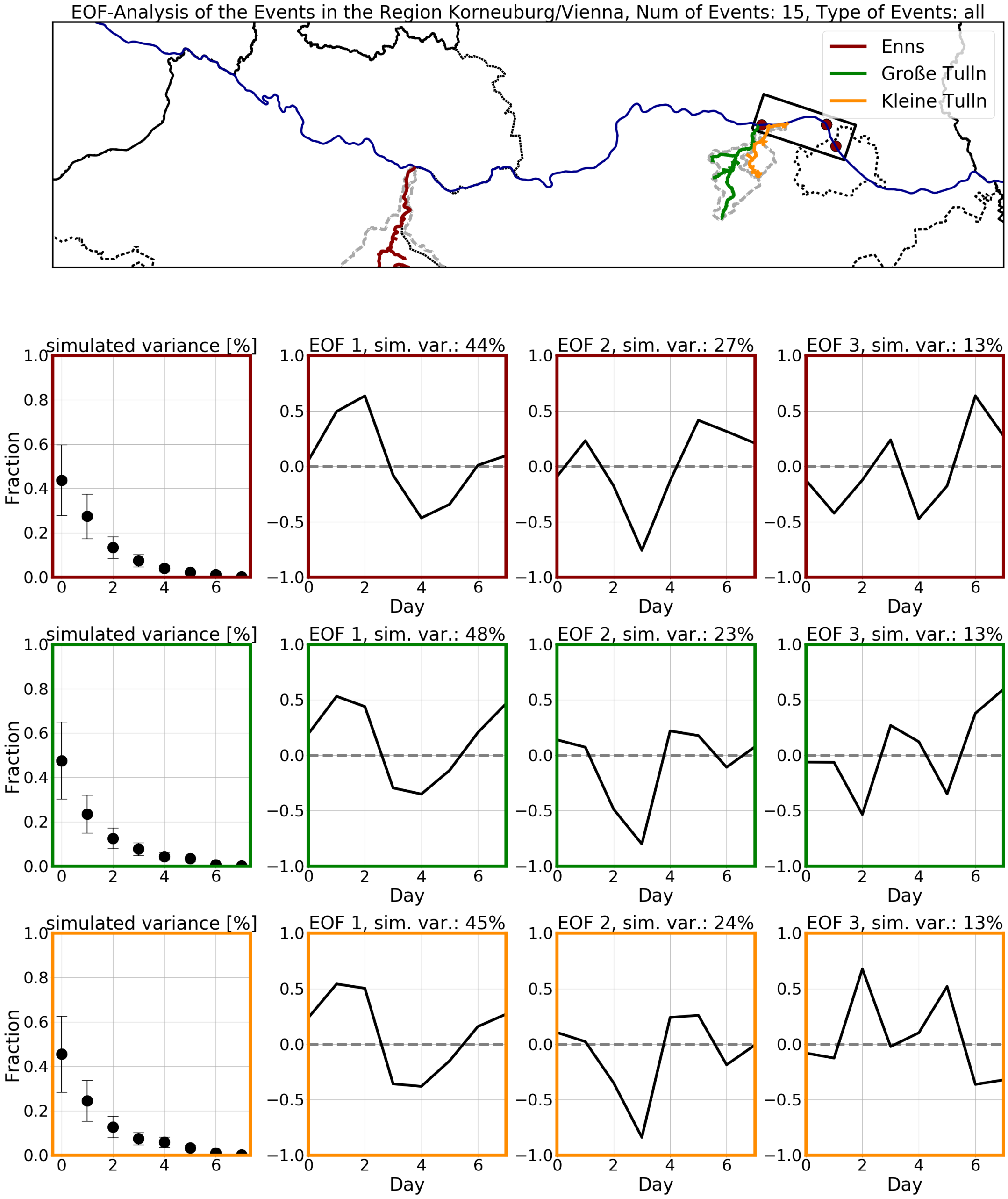


FIGURE 4.19: EOF Analysis of the region Korneuburg/Vienna. All events, meaning monitoring stations and damage events, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Monitoring station events

Due two the fact that nearly all events located in this region are made up of monitoring station events, the EOF analysis with only those events does not differ substantially regarding the pattern shapes to the EOF analysis with all event categories (compare 4.19 & 4.20). One difference is discernible to before being the shift in maximum for both Kleine and Große Tulln from TD-1 to TD-2, because the two damage events probably affect this shift in maximum.

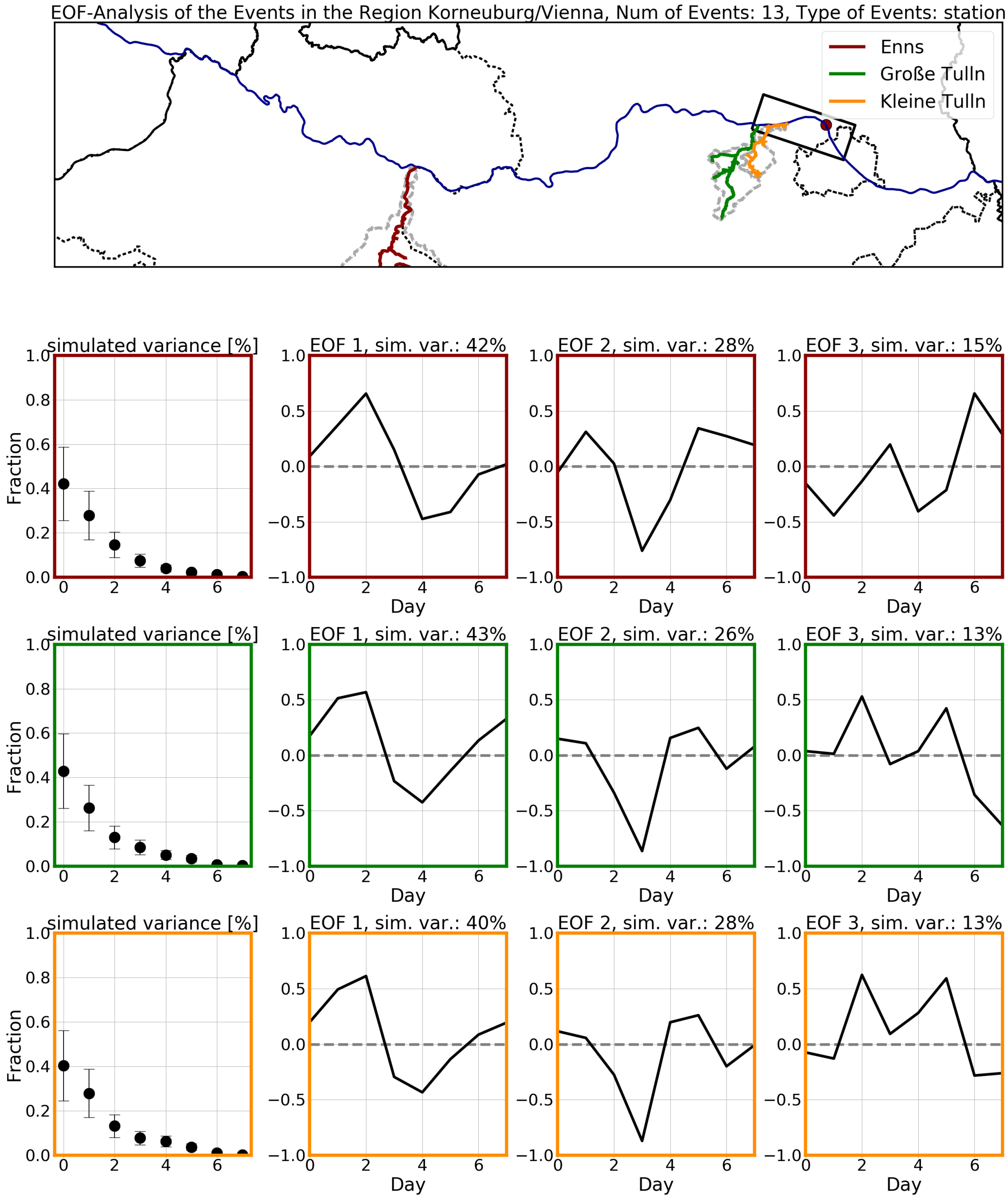


FIGURE 4.20: EOF Analysis of the region Korneuburg/Vienna. Monitoring station events, where HQ10 or HW10 were exceeded, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

4.3.6 Bruck an der Leitha

Inside the region Bruck an der Leitha 45 events were registered, of which 10 were damage events and 35 were monitoring station events. The two approaches described in section 3.2.4 have been conducted for the analysis of the region. The number of exceeded thresholds $\overline{W} + \sigma_W$ and/or $\overline{Q} + \sigma_Q$ of tributary monitoring stations from the target day ('TD') until 7 days prior to an event showed, that the Enns, the Kleine Tulln and the Wien showed the highest number of exceedances. Inside the Enns' catchment area monitoring stations registered in total 397 W and 432 Q, the

Kleine Tulln's stations in total 181 *W* and 149 *Q* and the Wien's station in total 123 *W* and 150 *Q* exceedances.

In table 4.6 the cross-correlation of these three tributaries with Danube monitoring stations in this region, being Hainburg an der Donau, Thebnerstraßl and Wolfsthal, is shown. The Kleine Tulln was ranked first at all stations with HW30 thresholds, while being second or eighth at Hainburg an der Donau and Thebnerstraßl with HQ10 thresholds, respectively. Consistently at ranked forth is the Enns, except at Wolfsthal, where the Enns is second. The Wien is first at the HQ10 threshold of Thebnerstraßl and most often ranked sixth and ninth at the other monitoring stations.

From this results, for the Bruck an der Leitha region the following three tributaries have been selected:

- Enns (397 W, 432 Q)
- Kleine Tulln(181 W, 149 Q)
- Wien (123 W, 150 Q)

Monitoring Station	HWn/HQn	Tributary	Cross-Corr.	lag (Days)
Hainburg an der Donau	HW30	Enns	0.60	-4
		Kleine Tulln	0.65	-3
		Wien	0.60	-2
	HQ10	Enns	0.63	-3
		Kleine Tulln	0.62	-3
		Wien	0.61	-3
Thebnerstraßl	HW30	Enns	0.62	-4
		Kleine Tulln	0.67	-3
		Wien	0.60	-3
	HQ10	Enns	0.61	-3
		Kleine Tulln	0.62	-3
		Wien	0.62	-3
Wolfsthal	HW30	Enns	0.61	-4
		Kleine Tulln	0.63	-3
		Wien	0.57	-3

TABLE 4.7: Maximum Cross-Correlation values at specific lag in days between tributary and monitoring stations in the region Bruck an der Leitha having a statistical expected value for ≥ HW10 or HQ10.

In figure 4.21 the EOF analysis of all events in this region, meaning HQ10, HW10 and damage events (WLV, BWV, VIOLA), is depicted, while figure 4.22 & 4.23 describe the EOF analysis for damage events only and monitoring station events only, respectively.

In total 45 events have been registered in this region, however the damage events make up for 10 events. With the high number of total events the error margin for the simulated variance of the first leading EOF analysis is clearly lower than when the event categories are analysed separately (compare 4.21 to 4.22 & 4.23). The precipitation patterns calculated through the EOF analysis follow similar shapes for all tributaries.

All events

As can be seen in the EOF analysis for all events in figure 4.21 the shift in maximum is apparent regarding all three leading patterns due to the locations of the tributaries' inflows being further downstream. The maximum shifts from TD-3 for the Enns to TD-2 for the Kleine Tulln as well as for the Wien. It is discernible, that the maximum tends to TD-1 regarding the Wien's first leading pattern. For the second leading pattern the maximum shifts from the Enns at TD-4 to TD-3 when reaching the Wien. In comparison two maximums are given by the third EOF's leading pattern. The Enns shows a maximum once at TD-6 and at TD-3, the same goes for the Kleine Tulln. Yet the Wien has the maxima shifted to TD-5 and TD-2.

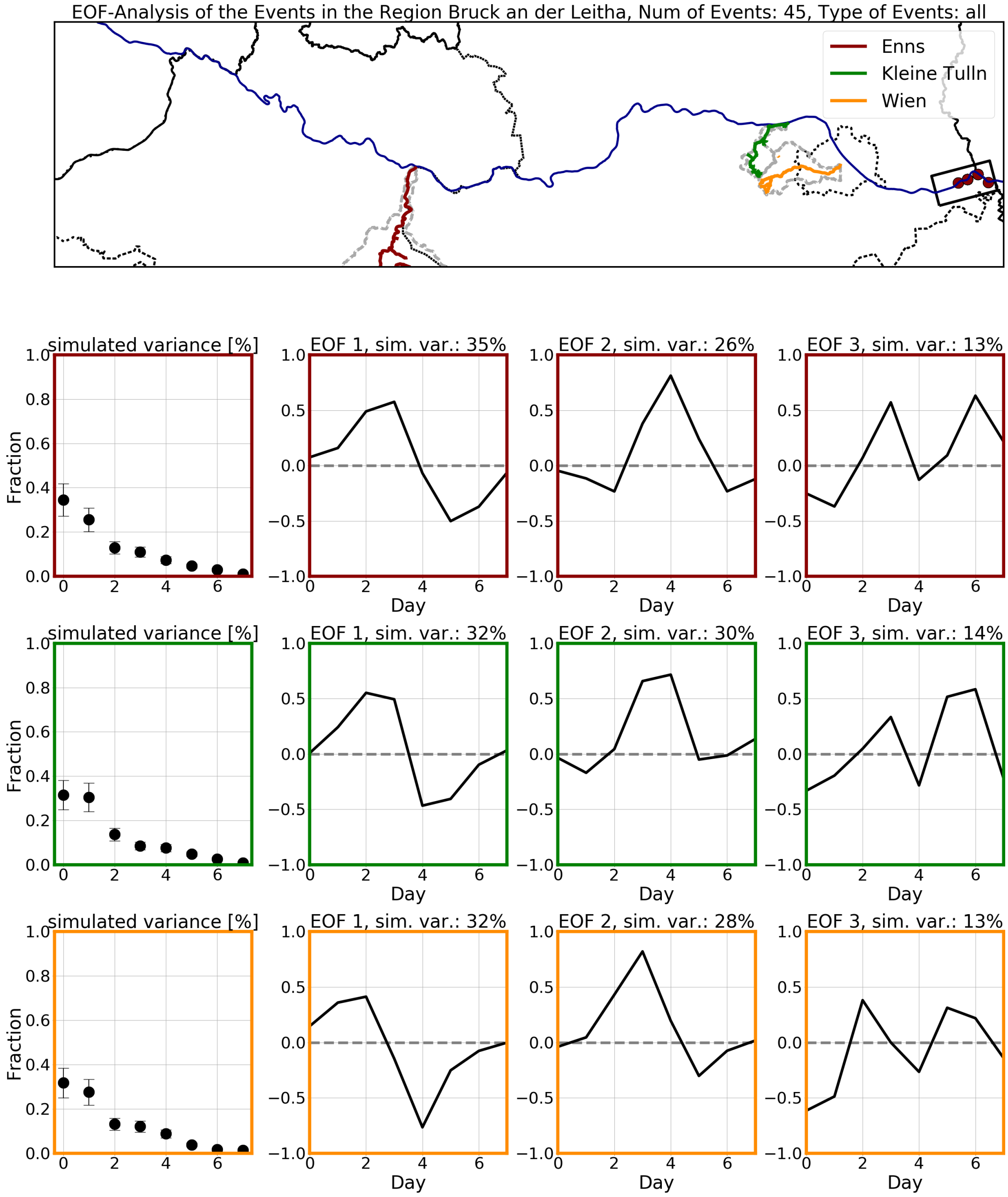


FIGURE 4.21: EOF Analysis of the region Bruck an der Leitha. All events, meaning monitoring stations and damage events, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Damage events

Error margins especially for the first leading EOF when only damage events are considered become greater than before, as can be seen in figure 4.22. Every tributary investigated present a strong maximum at TD-1. However the further downstream the tributary the more precipitation is likely at TD itself. Regarding the second leading pattern, the Enns this time shows precipitation rising from TD-4 until TD-1 with the maximum at TD-2. However, the two other tributaries have two maxima at TD-3 and on TD. The third leading pattern suggests a different pattern. A single maximum on TD-2 for the Enns can bee seen while the Kleine Tulln and Wien show rising precipitation amounts through out the preceding week with a maximum on TD-2 as well.

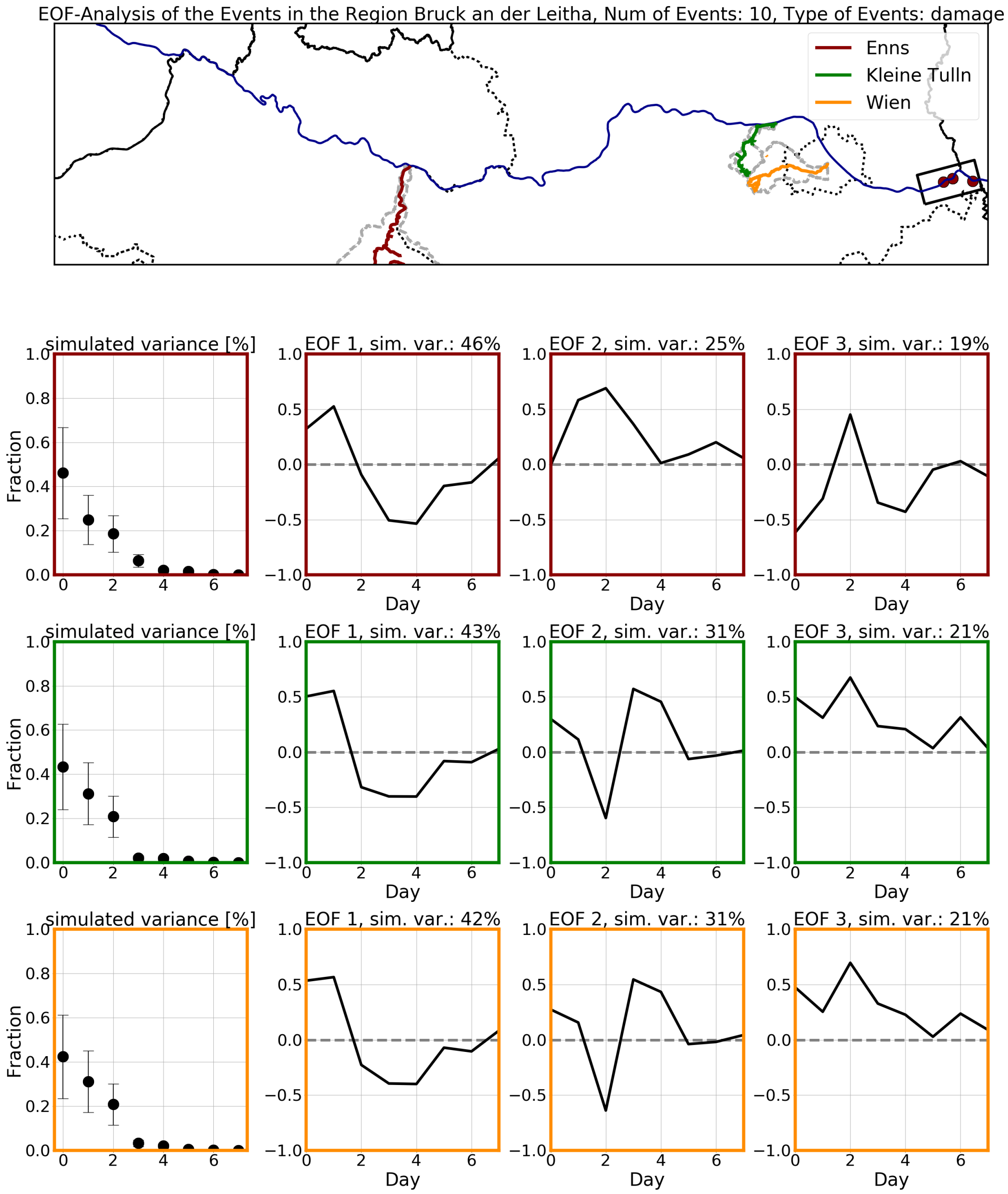


FIGURE 4.22: EOF Analysis of the region Bruck an der Leitha. Damage events from WLV, BWV and VIOLA, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

Monitoring station events

If only monitoring station events are considered, the amount of events available is 35, therefore the error margin decreases drastically seen in figure 4.23. All three tributaries' first leading pattern in this case present a maximum at TD-3 and once again a slight shift towards TD-2 when reaching the Wien, where the difference is just slightly discernable. This shift is also recognisable in the second leading patterns, where the maximum lies at TD-4 for all three tributaries. Though the amount of precipitation rises slightly at TD-3 when reaching the furthermost downstream tributary. As for the third EOF's leading pattern, the Enns shows two maximums namely at TD-5 and TD-2. The Kleine Tulln and the Wien do not show as pronounced maximums as the Enns. A very slight maximum on TD is shown for Kleine Tulln. However, the Wien shows a smaller maximum on TD-4 and a slightly greater maximum on TD-2 with comparable precipitation amounts on TD as the Kleine Tulln.

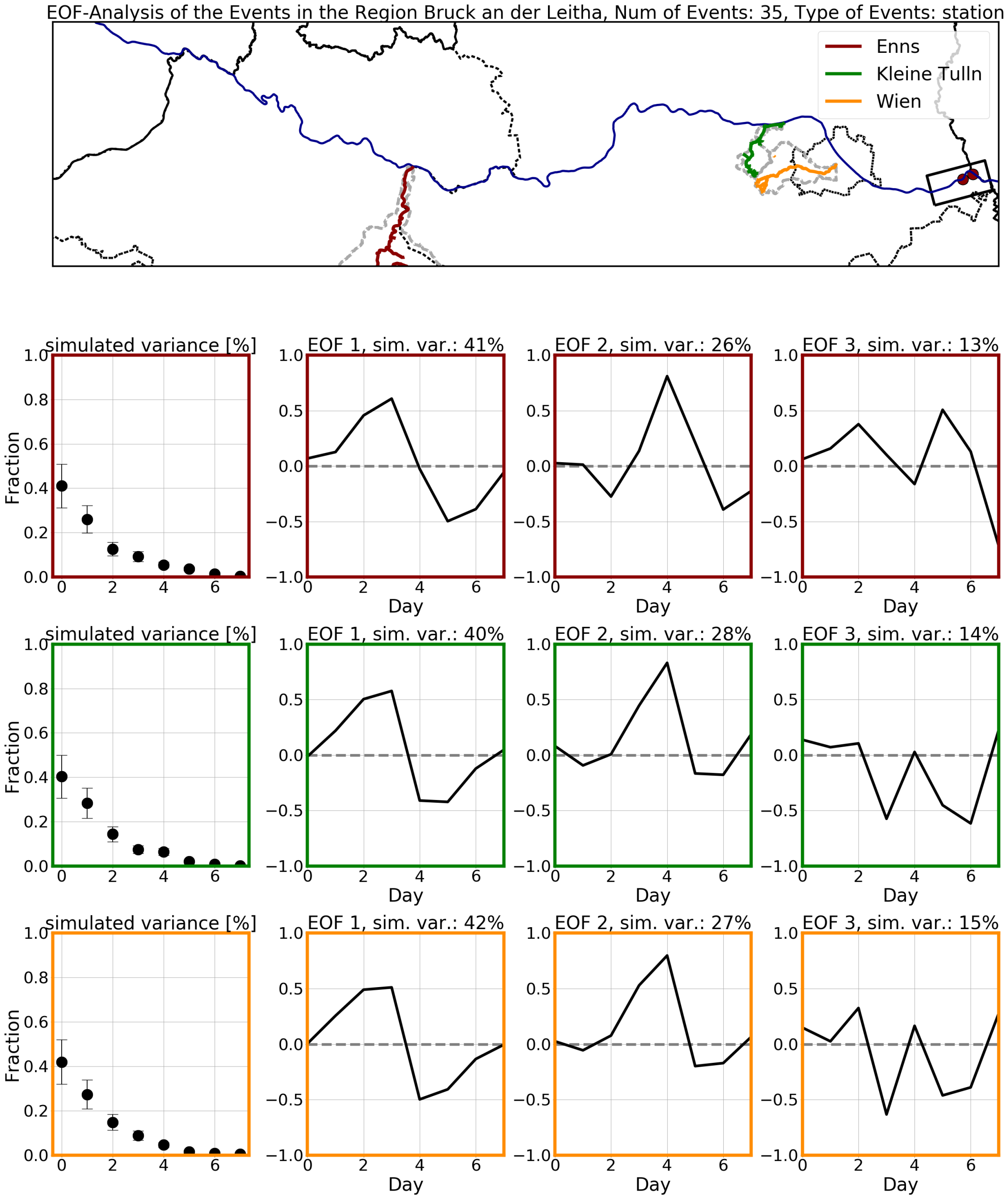


FIGURE 4.23: EOF Analysis of the region Bruck an der Leitha. Monitoring station events, where HQ10 or HW10 were exceeded, were analysed. Note: An extensive explanation elaborating the content of all panels can be found in the text at the beginning of section 4.3.

4.3.7 Regional Comparison

After the analysis of each region seperately, one can compare the regions with each other. It has become evident, that the Inn plays a major role for the three regions located mostly in Upper Austria. The regions Schärding, Linz/Linz Land and Machland/Ybbs have been impacted the most by the Inn. The more downstream the region lies, the more other big streams have a greater influence in the regions. From the Machland/Ybbs region onward the Enns has become more important. It step by step replaces the role of the Inn in the eastern Danube. For the regions Wachau/Kienstock, Korneuburg/Vienna and Bruck an der Leitha the Enns is the dominant tributary. The precipitation patterns of the biggest streams Inn, Traun and Enns shift slightly with each region further downstream up to one or two days. However the CIs derived from the first leading EOF pattern themselves are almost the same for each region and each investigated tributary. The EOF's first leading pattern almost always shows one significant precipitation maximum between the target day and until three days in advance.

Chapter 5

Conclusion

In this thesis the aim was to receive regionally differentiated information on daily based precipitation patterns, so called Climate Indices (CIs), triggering floods along the Austrian part of the Danube.

Firstly, the linkage between precipitation inside the catchment area of a tributary to water level W and discharge Q measurements at tributary monitoring stations has been investigated. It can be concluded, that precipitation can be described through W and Q well enough, under the premise, that the monitoring station is located as close as possible at the inflow to the Danube. However, there are only few monitoring stations available close to the inflow to the Danube. Catchment area sizes of monitoring stations often differ significantly in size compared to the total catchment area. Currently a lot of monitoring stations do not cover the precipitation falling inside the total catchment area of a tributary. For future investigations it is necessary to use measurements of monitoring station, which accurately represent the precipitation inside the total catchment area. Ideally they should be located next to the inflow to the Danube, which is unfortunately not always the case.

Regarding floods along the Danube, at first only damage events from Enigl et al., 2019 and Zentralanstalt für Meteorologie und Geodynamik (ZAMG), 2019 were used to determine regions often affected by floods. When only damage events are considered in this calculations, consisting of WLV, BWV and VIOLA data sets, the number of events available is 58. This number seemed too low to receive accurate results with low variance. Hence the number of events had to be raised with measurements of monitoring stations where at least 10-yearly flood water levels $HW10$ or discharge $HQ10$ were exceeded. With this implementation the number of events available is 212, whereby the EOF analysis from which the CIs are derived for the regions can be more feasible and statistically more robust. Nevertheless the number of events is still significantly lower than the 666 events Enigl et al., 2019 had available for calculating the precipitation patterns triggering floods in the Northern Lowlands.

In total 6 differently affected regions have been found along the Danube. Overall it is clear, that all three leading EOF precipitation patterns when using all events available are composed of the leading patterns calculated from both event types separately. The results are differently weighted depending on the amount of events available in the particular event category. Also the more events are available, the better the first EOF can describe the processes triggering the events occurring in the region. Thereby error margins became significantly smaller the more events were used.

From the results seen in chapter 4, it is evident, that at least one of the three tributaries with the largest catchment area inside the Austrian border, being Inn, Traun and Enns, have an influence on the regions detected alongside the Danube. The Inn shows its importance for the Schärding, Linz/Linz Land and Machland/Ybbs region through having high correlations with the Danube monitoring stations. The same applies for Traun being important for the regions Machland/Ybbs and Wachau/ Kienstock. Besides, the Enns influences the regions Machland/Ybbs, Wachau/ Kienstock, Korneuburg/Vienna and Bruck a.d. Leitha.

Furthermore it can be deduced, that if the distance between a tributary and a region becomes greater, the later the effects of the precipitation falling into the tributaries catchment area can be perceived in the region resulting in a flood event. This effects can also be perceived in the lag with highest cross-correlations shifting to later lags depending on the downstream position of the Danube monitoring stations. For example, the maximum precipitation derived from the EOF's patterns for the Enns shows a shift by a day if the region and hence the event lies farther east and therefore further downstream respectively. While the Enns tends towards having a maximum at TD-1 or TD-2 for the Machland/Ybbs and Wachau/Kienstock the shift to TD-3 can be seen when reaching the region Bruck a.d. Leitha, which lies downstream of the Danube. However this does not completely apply for the Inn, due to the Inns high mean discharge of 727 $\frac{m^3}{s}$ in comparison to the mean discharge of the Traun and Enns (135 and 204 $\frac{m^3}{s}$ respectively). Water amounts are rapidly transported, arriving sooner at regions further downstream of the Danube, partially one day after high amounts of precipitation fell inside its catchment area in comparison than when precipitation falls in the Traun's and Enns' catchment area. Therefore maximums at TD-1 have been determined for the Schärding and Linz/Linz Land region.

Due to lack of availability, in future research the contribution of snowmelt can be implemented as well as hydrological precipitation-discharge models. Furthermore, the currently calculated precipitation patterns with the approach of using flood induced damage events, a greater database as well as more different damage event databases can further improve the calculated CIs.

The methods used in this thesis can be applied for any other river if monitoring stations and damage data is available. With this approach it could become possible to better determine future flood events through precipitation patterns. Thereby, one can enhance extreme weather warnings for the public, which can be crucial in the wake of climate change.

Acknowledgements

First of all thanks to my thesis supervisor Dr. Christoph Matulla for his ideas, creativity, scientific discussions and constructive feedback during the years writing this thesis.

I want to thank Katharina Enigl MSc for her great support, patience and advices over the past years. The many conversations with her gave me the motivation to keep going and to finish this thesis.

Thank you to the ZAMG and the experts of BMLRT for providing me with the data sets for this research project.

A great thank you goes to my family for their continuous support and trust throughout my whole life and many years of study.

Lastly, my deepest gratitude goes to my fiancé Max for his love, encouragement and support throughout all these years and for always being there for me.

Bibliography

Amt der Oberösterreichischen Landesregierung (Aug. 2012). *Jahrhundertbauwerk Machlanddamm: Europas größtes Hochwasserschutzprojekt in Rekordzeit fertig. Feierliche Eröffnung am 25. August. Information zur Pressekonferenz*. Amt der Oberösterreichischen Landesregierung.

Anderwald, Peter (Jan. 2001). *Traun-Enns Platte. Gewässerschutzbericht 24/2001*. Amt der Oberösterreichischen Landesregierung Abteilung Umweltschutz, Unterabteilung Gewässerschutz.

Anderwald, Peter et al. (1995a). *Aschach und Dürre Aschach, Untersuchungen zur Gewässergüte. Stand 1992-1994, Gewässerschutz Bericht 9/1995*. Amt der Oberösterreichischen Landesregierung Unterabteilung Gewässerschutz.

Anderwald, Peter et al. (1995b). *Pram, Untersuchungen zur Gewässergüte. Stand 1992-1994, Gewässerschutz Bericht 8/1995*. Amt der Oberösterreichischen Landesregierung Unterabteilung Gewässerschutz.

Anderwald, Peter et al. (1995c). *Trattnach und Innbach, Untersuchungen zur Gewässergüte. Stand 1992-1994, Gewässerschutz Bericht 11/1995*. Amt der Oberösterreichischen Landesregierung Unterabteilung Gewässerschutz.

Anderwald, Peter et al. (1996). *Kleine Gusen, Große Gusen und Gusen, Untersuchungen zur Gewässergüte. Stand 1992-1995, GewässerschutzBericht 13/1996*. Amt der Oberösterreichischen Landesregierung Abteilung Umweltschutz, Unterabteilung Gewässerschutz.

Anderwald, Peter et al. (1997a). *Kleine Mühl, Steinerne Mühl und Große Mühl, Untersuchungen zur Gewässergüte. Stand 1992-1996, Gewässerschutz Bericht 16/1997*. Amt der Oberösterreichischen Landesregierung Unterabteilung Gewässerschutz.

Anderwald, Peter et al. (1997b). *Ranna, Osterbach, Pesenbach und Große Rodl, Untersuchungen zur Gewässergüte. Stand 1993-1996, Gewässerschutz Bericht 17/1997*. Amt der Oberösterreichischen Landesregierung Unterabteilung Gewässerschutz.

Austrian Standards Institute (Mar. 2016). *Hydrology — Hydrographic terms and symbols — Additional provisions. concerning ÖNORM EN ISO 772, Ausgabe 2016-03-01*. Austrian Standards Institute 2016.

Bachura, Bohumil et al. (1992). *Traun, Untersuchungen zur Gewässergüte. Stand 1991, Gewässerschutz Bericht 1/1992*. Amt der Oberösterreichischen Landesregierung Unterabteilung Gewässerschutz.

Bayerisches Landesamt für Umwelt (2021). *Hochwassernachrichten Bayern*. `https://www.hnd.bayern.de/pegel/jaehrlichkeiten/donau_bis_passau`. [Last access 1-February-2021].

Bilderl, Barbara (2017). *Die Jahrhunderthochwässer 2002 und 2013 im Vergleich: Wie hat sich das Hochwassermanagement an der Donau verändert?* Wien.

BMLFUW Abteilung IV/4 Wasserhaushalt HZB (Oct. 2011). *Flächenverzeichnis der österreichischen Flussgebiete. Ennsgebiet. Beiträge zur Hydrographie Österreichs, Heft Nr. 61*. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft.

— (Dec. 2014). *Flächenverzeichnis der Flussgebiete. Donaugebiete von der Enns bis zur Leitha. Beiträge zur Hydrographie Österreichs Heft 62*. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft.

Bundesministerium für Landwirtschaft, Regionen und Tourismus (BMLRT) (2021a). *eHYD-Hydrographische Daten*. https://ehyd.gv.at/. [Last access 25-January-2021].

— (2021b). *Flusseinzugsgebiet und Flussgebietseinheit*. https://info.bmlrt.gv.at/themen/wasser/gewaesserbewirtschaftung/feg_fge.html. [Last access 24-November-2021].

Bundesministerium für Landwirtschaft, Regionen und Tourismus (BMLRT) Abteilung I/3 – Wasserhaushalt (HZB) (2021). *Hydrographisches Jahrbuch - Teil der WISA Familie*. https://wasser.umweltbundesamt.at/hydjb/index.xhtml. [Last access 25-January-2021].

Bundesministerium für Nachhaltigkeit und Tourismus (BMNT) (May 2018). *eHYD — Aktuelle Hydrographische Daten*. Bundesministerium für Nachhaltigkeit und Tourismus (BMNT).

Enigl, Katharina et al. (July 2019). "Derivation of canonical total-sequences triggering landslides and floodings in complex terrain". In: *Advances in Water Resources* 129, pp. 178–188. DOI: 10.1016/j.advwatres.2019.04.018. URL: https://doi.org/10.1016/j.advwatres.2019.04.018.

Frank, Fabian Georg (2018). *Ensembles of flooding occurrences driven by different pathways of mankind until 2100 and decision theory for forward-planning sustainable protection*. eng. Wien.

Habersack, Helmut et al. (Sept. 2015). *Hochwasserdokumentation Donau 2013. Ereignissdokumentation*. Bundesministerium für Verkehr, Innovation und Technologie (bmvit).

Hiebl, Johann and Christoph Frei (Feb. 2015). "Daily temperature grids for Austria since 1961—concept, creation and applicability". In: *Theoretical and Applied Climatology* 124.1-2, pp. 161–178. DOI: 10.1007/s00704-015-1411-4. URL: https://doi.org/10.1007/s00704-015-1411-4.

— (Mar. 2017). "Daily precipitation grids for Austria since 1961—development and evaluation of a spatial dataset for hydroclimatic monitoring and modelling". In: *Theoretical and Applied Climatology* 132.1-2, pp. 327–345. DOI: 10.1007/s00704-017-2093-x. URL: https://doi.org/10.1007/s00704-017-2093-x.

Kainz, Erich (Feb. 1986). *The Fish-Stock of the Haselbach (Upper Austria)*. Aus der Bundesanstalt für Fischereiwirtschaft in Scharfling/Mondsee.

Kaufmann, Andreas et al. (2013). *Leitfaden zur Erfassung und Dokumentation von Hochwasserereignissen in der Hochwasser-Fachdatenbank*. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft-Sektion VII Wasser.

Land Niederösterreich (Amt der Niederösterreichischen Landesregierung - Abteilung Landesamtsdirektion) (2021). *Wasserstandsnachrichten und Hochwasserprognosen*. https://www.noe.gv.at/wasserstand. [Last access 1-February-2021].

Land Oberösterreich (Amt der Oberösterreichischen Landesregierung Abteilung Wasserwirtschaft) (2021). *Hydrographischer Dienst Oberösterreich*. https://hydro.ooe.gv.at. [Last access 1-February-2021].

MDB Machland-Damm Betriebs GmbH (2008). *Machlanddamm*. https://machlanddamm.at/start/. [Last access 25-January-2021].

Nielsen, Frank (2016). "Hierarchical Clustering". In: *Introduction to HPC with MPI for Data Science*. Springer International Publishing, pp. 195–211. DOI: 10.1007/978-3-319-21903-5_8. URL: https://doi.org/10.1007/978-3-319-21903-5_8.

Oberösterreichischer Landesrechnungshof (Sept. 2014). *Hochwasserschutz Machland Nord. LRH-Bericht Initiativprüfung*. Oberösterreichischer Landesrechnungshof.

Peixoto, José P. and Abraham H. Oort (1992). *Physics of climate*. eng. New York, NY: Springer. ISBN: 0883187116.

Python Software Foundation (2022a). *Python*. https://www.python.org/. [Last access 2-January-2022].

— (2022b). *Python Package Index (PyPI*. https://pypi.org/. [Last access 2-January-2022].

Quadrelli, Roberta et al. (Aug. 2001). “Observed winter Alpine precipitation variability and links with large-scale circulation patterns”. In: *Climate Research - CLIMATE RES* 17, pp. 275–284. DOI: 10.3354/cr017275.

Shumway, Robert H. and David S. Stoffer (2017). *Time Series Analysis and Its Applications*. Springer International Publishing. DOI: 10.1007/978-3-319-52452-8. URL: https://doi.org/10.1007/978-3-319-52452-8.

Sun, Zhandong and Tom Lotz (May 2020). “Linking meteorological patterns shift to hydrological extremes in a lake watershed across the mid-high latitude transition region”. In: 34.8, pp. 1121–1134. DOI: 10.1007/s00477-020-01822-z. URL: https://doi.org/10.1007/s00477-020-01822-z.

Sun, Zhandong et al. (Aug. 2012). “Precipitation patterns and associated hydrological extremes in the Yangtze River basin, China, using TRMM/PR data and EOF analysis”. In: 57.7, pp. 1315–1324. DOI: 10.1080/02626667.2012.716905. URL: https://doi.org/10.1080/02626667.2012.716905.

viadonau - Österreichische Wasserstraßen-Gesellschaft mbH (Sept. 2012). *Kennzeichnende Wasserstände der österreichischen Donau. KWD 2010*. viadonau.

— (2021). *DoRIS - Donau River Information Services*. https://www.doris.bmk.gv.at/fahrwasserinformation/pegelstaende-und-prognosen/hochwasserprognosen. [Last access 1-February-2021].

Wilks, Daniel S (2006). *Statistical Methods in the Atmospheric Sciences: An Introduction*. eng. International geophysics series. Burlington: Elsevier Science & Technology. ISBN: 0127519661.

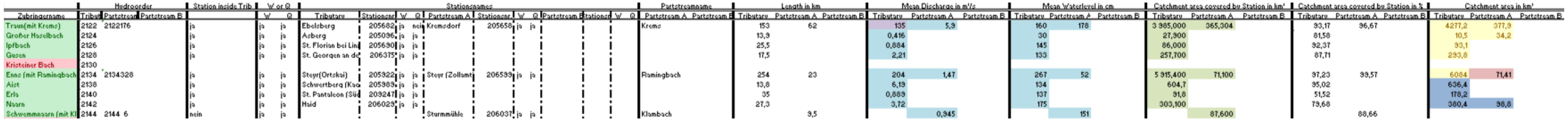
Zentralanstalt für Meteorologie und Geodynamik (ZAMG) (2019). *VIOLA*. https://www.zamg.ac.at/cms/de/klima/klimaforschung/datensaetze/viola. [Last access 23-August-2021].

Zhu, Hua et al. (Aug. 2019). “Spatiotemporal Variations of Summer Precipitation and Their Correlations with the East Asian Summer Monsoon in the Poyang Lake Basin, China”. In: *Water* 11, p. 1705. DOI: 10.3390/w11081705. URL: https://doi.org/10.3390/w11081705.

Zhu, Hua et al. (Sept. 2020). “Regional Characteristics of Long-Term Variability of Summer Precipitation in the Poyang Lake Basin and Possible Links with Large-Scale Circulations”. In: *Atmosphere* 11.10, p. 1033. DOI: 10.3390/atmos11101033. URL: https://doi.org/10.3390/atmos11101033.

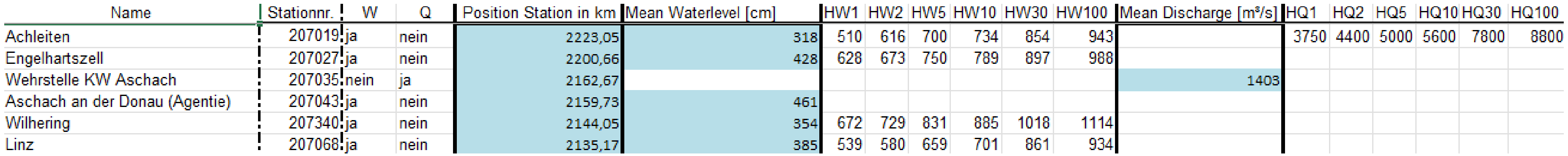
Appendix A

Additional Figures



	Hydroorder			Station inside Trib	W or Q		Stationsnames												Partstreamname		Length in km			Mean Discharge in m^3/s			Mean Waterlevel in cm			Catchment area covered by Station in km^2			Catchment area covered by Station in %			Catchment area in km^2		
Zubringername	Tribut	Partstrean	Partstream B		W	Q	Tributary	Stationsnr	W	Q	Partstream A	Stationsnr	W	Q	Partstream B	Stationsnr	W	Q	Partstream A	Partstream B	Tributary	Partstream A	Partstream B	Tributary	Partstream A	Partstream B	Tributary	Partstream A	Partstream B	Tributary	Partstream A	Partstream B	Tributary	Partstream A	Partstream B	Tributary	Partstream A	Partstream B
Traun(mit Krems)	2122	2122176		ja	ja	ja	Ebelsberg	205682	ja	nei	Kremsdorf	205658	ja	ja					Krems		153	62		135	5,9		160	178		3 985,000	365,304		93,17	96,67		4277,2	377,9	
Großer Haselbach	2124			ja	ja	ja	Asberg	205096	ja	ja											13,9			0,416			30			27,900			81,58			10,5	34,2	
Ipfbach	2126			ja	ja	ja	St. Florian bei Lin	205690	ja	ja											25,5			0,884			145			86,000			92,37			93,1		
Gusen	2128			ja	ja	ja	St. Georgen an de	206375	ja	ja											17,5			2,21			133			257,700			87,71			293,8		
Kristeiner Bach	2130																																					
Enns (mit Ramingbach	2134	2134328		ja	ja	ja	Steyr(Ortskai)	205922	ja	ja	Steyr (Zollamt	206599	ja	ja					Ramingbach		254	23		204	1,47		267	52		5 915,400	71,100		97,23	99,57		6084	71,41	
Aist	2138			ja	ja	ja	Schwertberg (Ka	205989	ja	ja											13,8			6,19			134			604,7			95,02			636,4		
Erla	2140			ja	ja	ja	St. Pantaleon (Süd	209247	ja	ja											35			0,889			137			91,8			51,52			178,2		
Naarn	2142			ja	ja	ja	Haid	206029	ja	ja											27,3			3,72			175			303,100			79,68			380,4	98,8	
Schwemmnaarn (mit Kl	2144	2144 6		nein	ja	ja					Sturmmühle	206037	ja	ja					Klambach			9,5			0,945			151			87,600			88,66				

FIGURE A.1: Extract of the mastertable for the tributaries giving information on each tributary.



Name	Stationnr.	W	Q	Position Station in km	Mean Waterlevel [cm]	HW1	HW2	HW5	HW10	HW30	HW100	Mean Discharge [m³/s]	HQ1	HQ2	HQ5	HQ10	HQ30	HQ100
Achleiten	207019	ja	nein	2223,05	318	510	616	700	734	854	943		3750	4400	5000	5600	7800	8800
Engelhartszell	207027	ja	nein	2200,66	428	628	673	750	789	897	988							
Wehrstelle KW Aschach	207035	nein	ja	2162,67								1403						
Aschach an der Donau (Agentie)	207043	ja	nein	2159,73	461													
Wilhering	207340	ja	nein	2144,05	354	672	729	831	885	1018	1114							
Linz	207068	ja	nein	2135,17	385	539	580	659	701	861	934							

FIGURE A.2: Extract of the mastertable for the Danube monitoring stations.

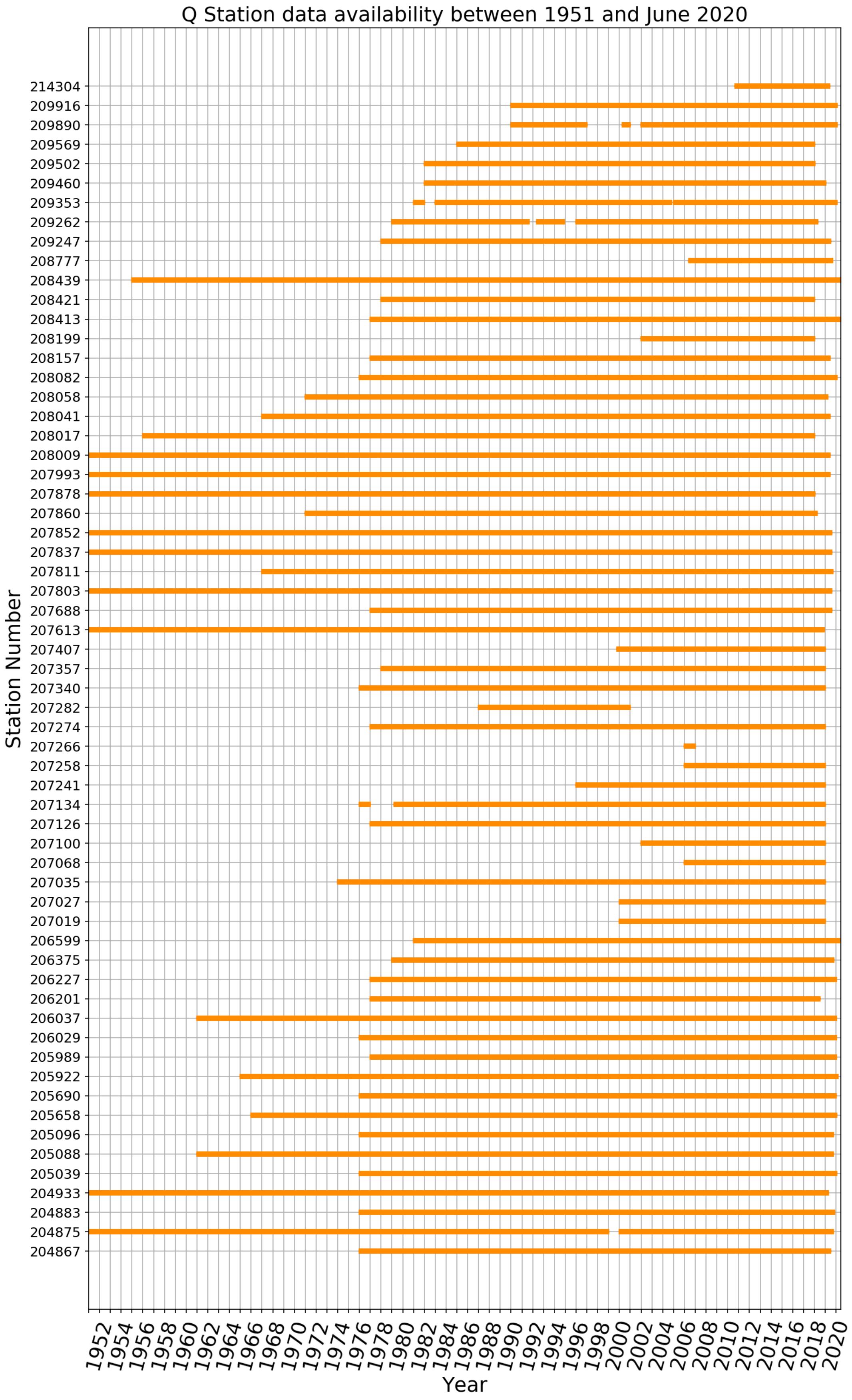


FIGURE A.3: Discharge Q data availability of the selected monitoring stations in the Danube and inside the tributaries near to the inflow to the Danube.

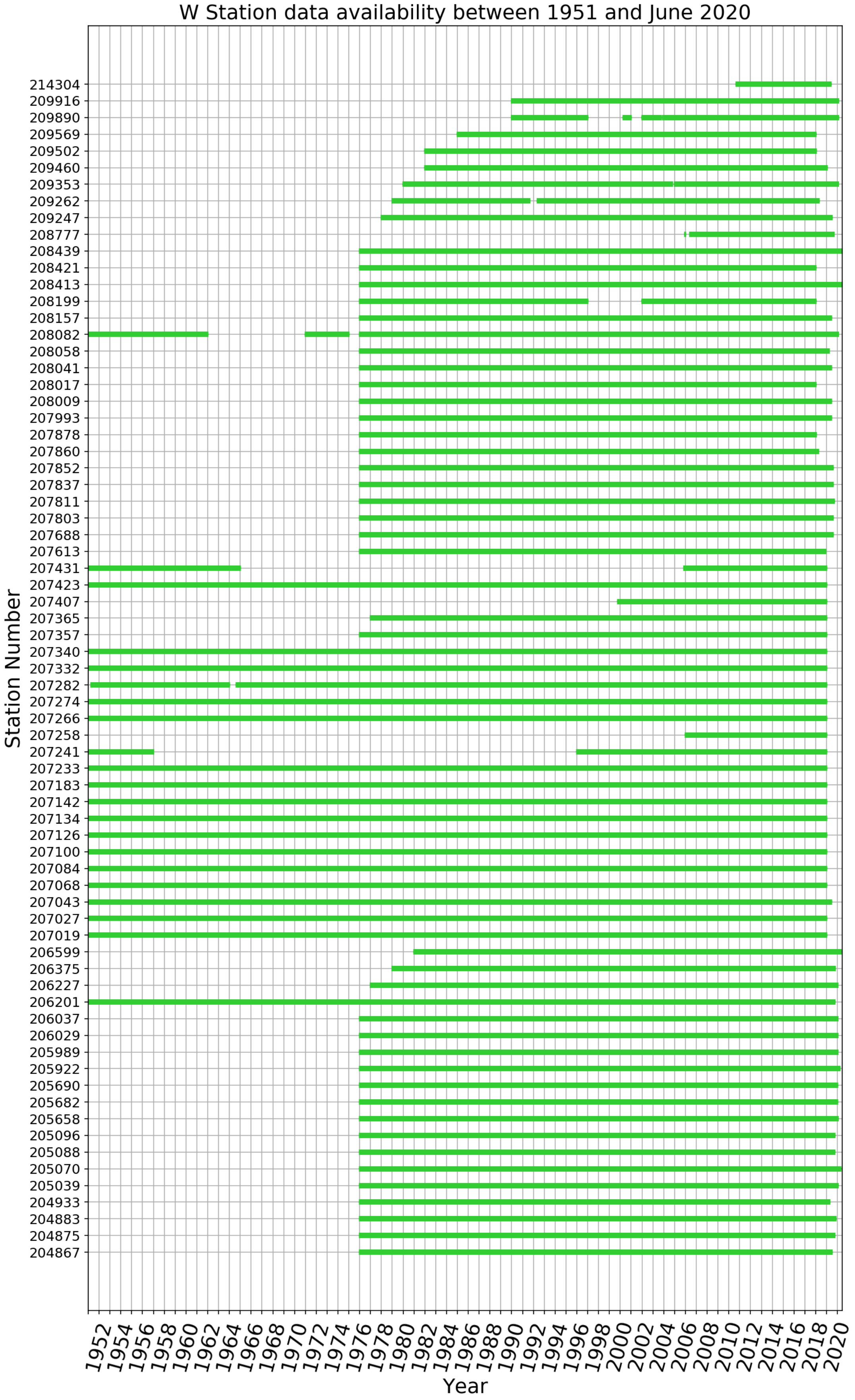


FIGURE A.4: Waterlevel W data availability of the selected monitoring stations in the Danube and inside the tributaries near to the inflow to the Danube.