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Vulnerability assessment of embankments and bridges exposed to flooding hazards

D2.1 Database of historical flood events in selected areas

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Executive Summary

Floods are a natural phenomenon that can have a significant impact to human-life, ecosystems, cultural heritage and society in general. The three partner countries in the oVERFLOw project, namely Croatia, Netherlands and Slovenia, are particularly vulnerable to cross-border river flooding in their position near the end of major European river systems. The Netherlands is the most flood prone country in the EU. In response the country built strategic large flood defence schemes and developed a sophisticated flood risk management system for levees. Croatia and Slovenia have joint transboundary river basins, a similar infrastructure and risk management approach regarding flood protection measures, while they are both facing increased flood risks caused by climate change impacts.

Two areas have been chosen as pilot site, for deployment and demonstration of the technology developed within the oVERFLOw project. One area is in the Netherlands around the city of Dordrecht (dike rings 16 and 17) and the other area is around the city of Karlovac in Croatia. This deliverable presents a database of previous floods and high-water level events in selected pilot areas, along with information about meteorological conditions in the periods of flood and high water level events. The data includes information on river water level, water flow rate, precipitation intensity and temperature in the selected areas for the periods of approximately 30 years. Based on historical data periods with highest water levels are chosen for a more detailed analysis.

Keywords: Flood events, high water level, hydrological data, meteorological data, case study areas Karlovac and Dordrecht.

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Abbreviations and Acronyms

Abbreviation / Acronym	Description
H2020	Horizon 2020
VNK2	Veiligheid Nederland in Kaart (Safety of the Netherlands on the map)
IMP	Information Management Platform
GIS	Geographic information system
CPA	Civil Protection Agency
IM	Infrastructure Manager

1 Introduction

1.1 Overview of the oVERFLOw Project

Flooding is a significant threat to human-life, ecosystems, cultural heritage and society in general. The three partner countries in the oVERFLOW project are particularly vulnerable to cross-border flooding from major European river systems. The risk based method for assessing flood defences, the so called VNK2 method, developed in the Netherlands is the state of the art, but the determination of the probability of failure is critically dependent on a number of highly uncertain parameters. The probability of failure is a comparison of the resistance (strength of the system) to the load (in this case a flood event). The most significant uncertainties relate to length effects and the location of potential seepage events in the flood defence systems (affecting the dike strength) and the severity of a flood event.

The overall objective of the oVERFLOw project is to strengthen the resilience of dikes to climate change impacts with the specific objective being the development of climate-resilient infrastructure. This will be achieved by:

- Reducing the known uncertainties in the VNK2 approach using techniques and procedures developed by the applicants in recent H2020 projects to provide real-time response of a critical infrastructure object (levee of bridge) during a flood event.
- The technology will be deployed and demonstrated at two pilot sites, at flood prone areas in the Netherlands and Croatia.

1.2 Overview of WP2, Task 2.1 and Deliverable D2.1

Work package 2 Information Management Platform (IMP) awill establish a GIS web based platform, that will implement historical data and climate change and flooding scenarios for selected areas. In this WP downscaled climate change and flooding scenarios, for defining attributes for GIS web-based platform, are developed. An information management platform will be established to store all baseline attributes of embankments and bridges (e.g. age, geometry, materials, maintenance history, flood history related data, etc.), as well as the developed climate change and flooding scenarios. Also, protocols for data collection, storage and provision of information to different parties are being developed.

This deliverable is a result of work within *Task 2.1 Historical data collection and analysis.* It provides information on previous flood events for the selected pilot study areas. The information was collected from sources including; Civil Protection Authorities, CPAs, , Infrastructure Managers (IMs), and from meteorological and hydrological services / agencies. The flood events and climate data are correlated for the periods when the events occurred. The Deliverable provides historical data collection and analyses this data to examine correlation of hydrological and meteorological data in the study areas.

2 Historical events

2.1 Introduction

The Netherlands is the most flood prone country in the EU (Commission Document, 2017). The Great North Sea flood of 1953 caused breaches of the famous levee (embankments and dikes) system causing 1,835 fatalities, the inundation of 200,000 hectares of land and severe damage to cultural heritage (e.g. fortified towns, polder mills and water mills). In response the country built strategic large flood defence schemes and developed a sophisticated flood risk management approach for levees (Rijkswaterstaat VNK Project Office, 2014).

Scour erosion of bridge foundations as a consequence of flooding is the number one cause of failure for bridges located over waterways (Gavin et al., 2018). In addition to other impacts such failures greatly affect emergency response capability during a flood event. In recent years Europe has experienced some of the largest flood events in its history. As an example in May 2014 extensive flooding affected over 1.5 million people across Croatia, Bosnia and Serbia. While the mean daily rainfall in Southern Eastern Europe (SEE) has increased only a little since 1950, the intensity of the extreme rainfall events rose by one third (Stadtherr et al., 2016). In May 2014, daily rainfall amounts were higher than at any time since records exist. The frequency of such potentially devastating extremes in the region has doubled over the past sixty years. According to IPCC projections many countries will be exposed to higher peak river discharges in the near future. The three partner countries in the oVERFLOW project, Croatia, Netherlands and Slovenia, are particularly vulnerable to cross-border river flooding in their position near the end of major European river systems.

2.2 Description of the selected case study areas

2.2.1 Croatia – City of Karlovac

The city of Karlovac is situated in the central continental part of Croatia at the meeting point of the lowland and mountainous regions, between Slovenia on the west and Bosnia and Hercegovina on the east. It is located at the intersection of important road and railway routes from Zagreb to Rijeka and Split and therefore has an important role in transport and economy of the country. Karlovac is also situated at the intersection of four rivers, Kupa, Korana, Dobra and Mrežnica, making it extremely prone to floods. Many settlements, city districts, local roads and the state road D36 are regularly flooded with floods also threatening important international and regional rail lines. In the flood prone area of Karlovac there are a total 375 cultural heritage sites and cultural objects. amongst which is the renaissance fortification system called ‘Karlovac Star’.

Flooding along the Kupa River, See Figure 3.1 is a very common occurrence. It is estimated that over the last several years floods have caused direct and indirect costs are on average 40

million EUR per year. Between October 2012 and April 2013, there were 12 independent high-water level events and in the period from 2014 to 2018, ten major floods were recorded in the wider area of Karlovac, with historical maxima during which extraordinary flood protection measures were implemented. The flood protection system in Karlovac is designed to withstand floods with a 100-year return period, however, it has not yet been completed. An important element of this system (Kupa-Kupa channel) still needs to be optimized and is currently operating at only 20% of maximum capacity (IPA Twinning project, 2010). The flow-rate of 600 m^3/s which is considered as threshold above which serious consequences can be expected has been exceeded several times in recent years. Kupa River is listed as a *preservation areas which are important for species and habitat types* as part of Natura 2000. Currently, there are more than 11 km of flood protection systems in the city of Karlovac which are considered as structures of national importance (Spatial planning Croatia, 1999).

The city of Karlovac has dozens of bridges many of them dating back to 18th century which are affected by flood loads due to the events described above and serve as evacuation routes during flooding events. Because of the lack of a proactive framework, authorities, IMs and CPAs deal with floods in a reactive manner and therefore improving our understanding of flood embankment and bridge vulnerability assessment procedures are critical.

Figure 2 1 Flooded case study area city of Karlovac (left); Kupa river in the city of Karlovac – selected area for analysis (right)

The first flood that is mentioned in the history of Karlovac was in 1579, whilst a larger flood that caused the population to move to higher floors of their houses was occurred in 1613. The largest flood, the so-called "century-long flood", occurred in late May and early June 1939, when the Kupa River reached a record water level of +872 cm and literally flooded the entire city. The second largest flood occurred in December 1966, when the river level in Karlovac was +832 cm. This flood endangered more than 10,000 inhabitants of the town of Karlovac and suburbs, who had to leave their homes. Also, this flood left great material damage to Karlovac industry, especially Banija, which was an industrial zone (Cvitan, 2017).

The construction of a flood defence system began in 1966, the same year when there was a flood, and 17 km of embankments were built along Kupa and Korana rivers. In 1974, the Kupa river was high again, when the water level was +818 cm. Therefore, 10 years later, the Kupa-Kupa channel was dug, which relieved the city centre partially from the impact of flooding (www.kaportal.rtl.hr.).

The city is continuously investing in flood protection measures to reduce both the probability of flood and flood risk but there are still significant flood events occurring every couple of years. These were recorded in Karlovac in 1972, 1974, 1996, 1998, 2001, 2005, 2010, 2012 and 2013, together with already mentioned twelve interdependent high-water levels between October 2012 and April 2013 and ten major floods in the period from 2014 to 2018. Detailed analysis of the flood events in the last 30 years is given in Chapter 3.1.

2.2.2 Netherlands – South Holland region

The South Holland region is situated between the two main rivers in the Netherlands and has an on average very low altitude, see Figure 2-2. Since most parts of the region are below sea level flooding is the most important risk in this region and the neighbouring Schelde mouth region. The area is protected by levees but faces the threats from the sea and from high water levels of the rivers Rhine and Meuse (Maas), see Figure 2-2a. The area is of high economic importance. Flooding of the area would be catastrophic not only for the area itself, but because of its vital infrastructure including; Europe's largest port in Rotterdam, the A15 and A27 highways, and the railway from the port of Rotterdam to Germany called the Betuwelijn. Flooding would also affect the electricity and gas supply in the region (a gas distribution center is located in this area, called the Alblasserwaard Vijfheerenlanden). The interruption of any individual element would cause severe cascading effects including the disruption of energy supplies, food, medicines and impacts to the major financial centres.

a) b)

Figure 2-2 a) South Holland region; b) Flooded area Rhine-Meuse delta region.

Netherlands has one of the best flood protection mechanisms in the world. The on-going "Flood Risk in the Netherlands" (VNK) project has the aim to analyse current flood risks, using flood loading, probabilities and embankment performance probabilities (Rijskwaterstaat, 2014). The VNK Flood Risk in the Netherlands project has mapped the current flood risks in 58 levee systems/dike rings analysing the probability of levee breaches and the possible consequences of a flood. Risk is a combination of probability and consequences (Jongejan et al., 2011). VNK has identified flood risk in each levee system, determining the probability that certain parts of the flood defences (various sections of levee and dune, and hydraulic structures) will fail, and the potential consequences should this occur (economic losses and

fatalities). The selected area for the case study in this project is surrounded by dike rings 16 and 17, as shown in Figure 2-3 and Figure 2-4.

Figure 2-3 Levee systems in the Netherlands (left); Analysed selected area Levee system/Dike ring area 16 Alblasserwaard and Vijfheerenlanden (right) (Vergouwe et al., 2014)

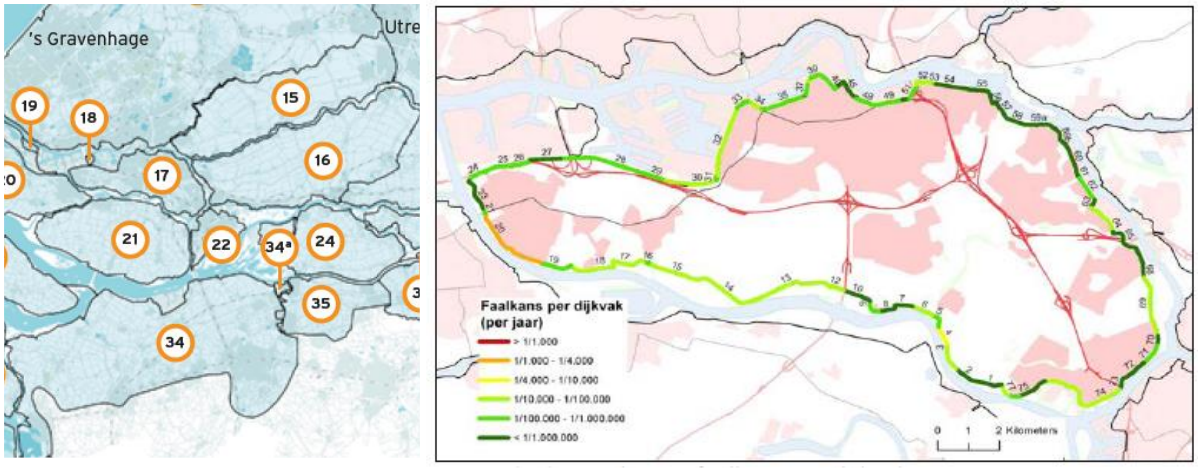


Figure 2-4 Neighbouring dikes 16 and 17 (left); Failure probability for analysed selected area Levee system/Dike ring area 17 IJsselmonde (Horst, 2010)

There are several major flooding events that occurred in the Netherlands that caused significant economic damages and victims (Jak and Kok, 1996).. A major event occurred in winter 1953 in South West Holland. A weather depression – combined with an exceptionally high spring tide – caused a storm surge on the North Sea, pushing water levels to record heights. Some of the dikes collapsed causing 1835 fatalities and enormous economic damage. The event led to construction of an ambitious flood defence system beginning in the 1960s called the Delta Works (Dutch: Deltawerken), designed to protect the estuaries of the rivers Rhine, Meuse and Scheldt.

Two floods occurred recently on the River Meuse, in December 1993 and in January 1995. The flood at the end of 1993 was due to an extreme discharge of the river Meuse larger than

3100 m^3/s. This caused economic damage of about 115 million € and evacuation of 8,000 people. The discharge measured in the Meuse in January 1995 at the border with Belgium was somewhat lower but it lasted longer than the event in 1993. The total damage was lower because people were better prepared regarding the previous experience (Olsthoorn and Tol, 2001).

The river Rhine flood that occurred from November 1994 to February 1995 is one of the worst floods of the 20th century. It effected many regions in Europe caused by the three rivers, the Rhine and its tributaries the Meuse and the Mosel. This event revealed the that the dikes were weak at a number of locations . The dikes in the Netherlands did not actually fail but since safety could not be guaranteed 250,000 people were evacuated. According to the available literature the causes of this event are mainly due to the immediate heavy rainfall and a relatively mild temperatures during the winter period, which has caused massive melting of the snow in the Alps. The discharge along the Rhine river went from 2,200m^3/s (https://water104website.weebly.com/netherlands-flooding-and-impacts.html) to a maximum flow of 12,000 m^3/s (VNK report, 2014) within 18 days. This event led to an ongoing process of dike reinforcement and improvements in the Netherlands, as well the improvements of the disaster and infrastructure management processes at national and EU levels (Olsthoorn and Tol, 2001).

3 Hydrological and meteorological data

3.1 Case study area in Croatia

As presented in chapter 2, the area of city of Karlovac and Kupa river is selected for the case study. Following discussions with local IMs, two bridges in Karlovac were selected as case study locations and therefore data on water levels from two closest measurement stations was collected for analysis. The location of water level measurement stations and location of bridges are presented in Figure 3-1.

Figure 3-1 Case study area of the City of Karlovac with meteorological station and water level measurement stations

3.1.1 Hydrological data

Water levels from two measurement stations for the period from 1990 to 2018 are presented in Figures 3-2 to 3.7. Periods for further analysis were chosen based on the highest water levels, and then correlated with meteorological (temperature and precipitation) and hydrological data (water flows in m^3/s).

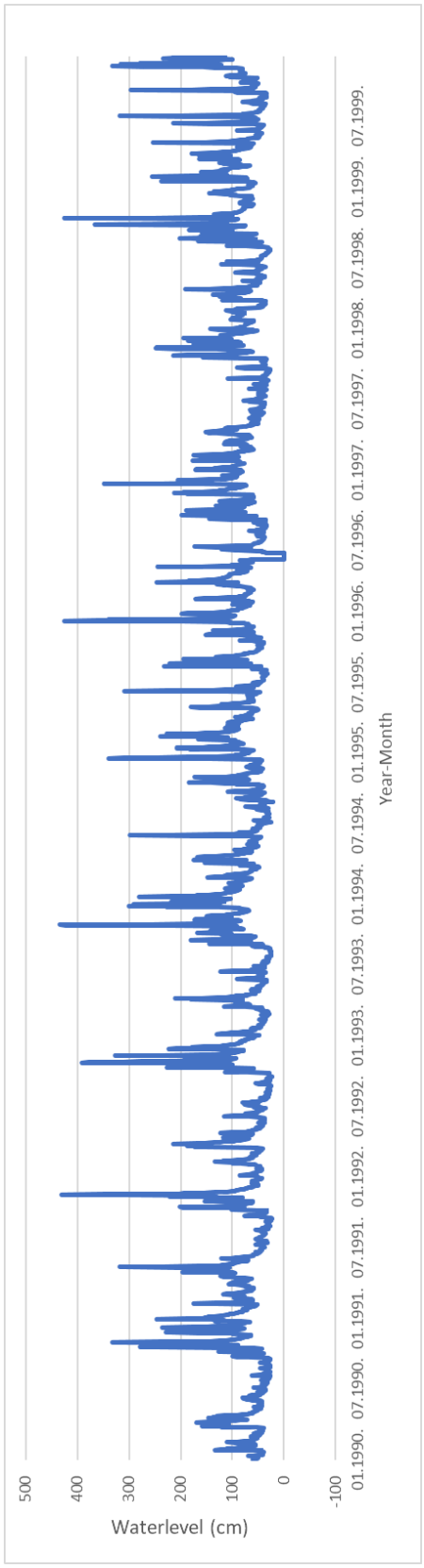


Figure 3-2 Water levels measured on river Kupa, station Kupa-Brodarci for period 1990-2000

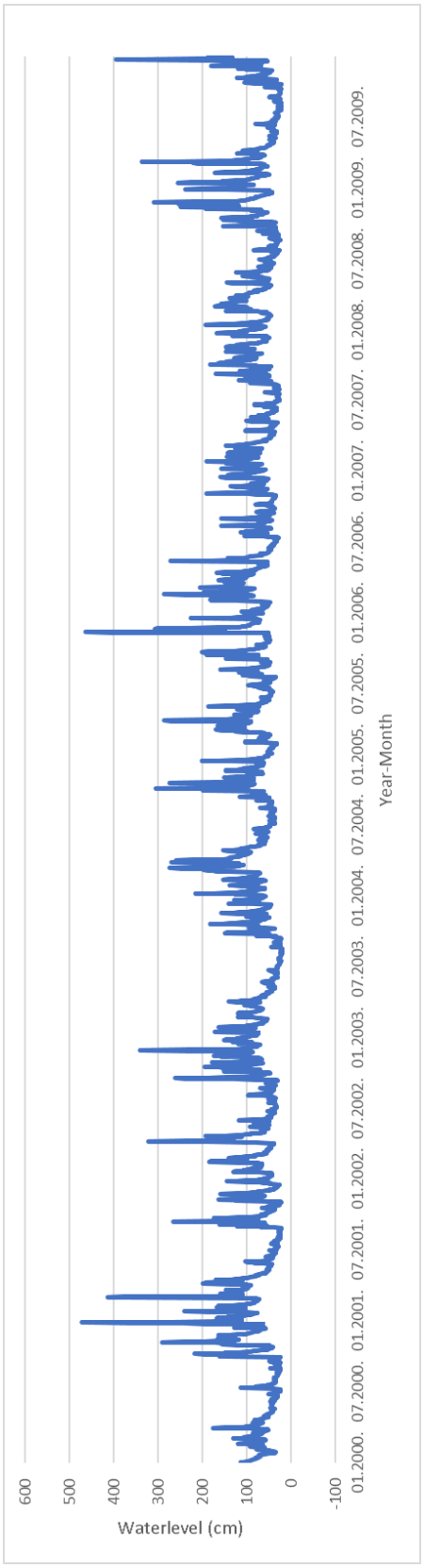


Figure 3-3 Water levels measured on river Kupa, station Kupa-Brodarci for period 2000-2010

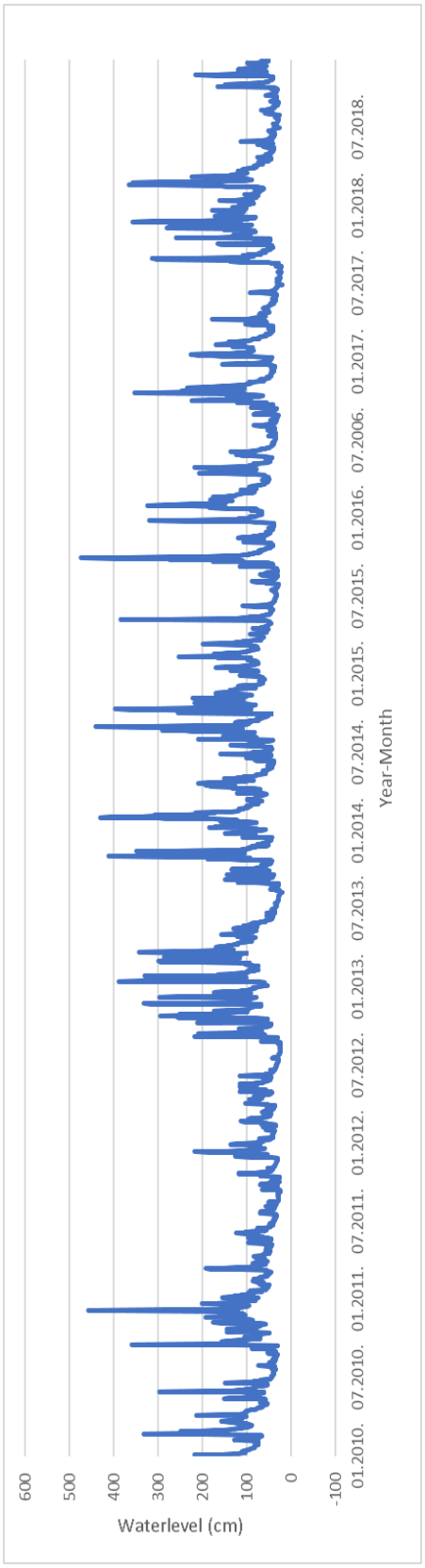


Figure 3-4 Water levels measured on river Kupa, station Kupa-Brodarci for period 2010-2018

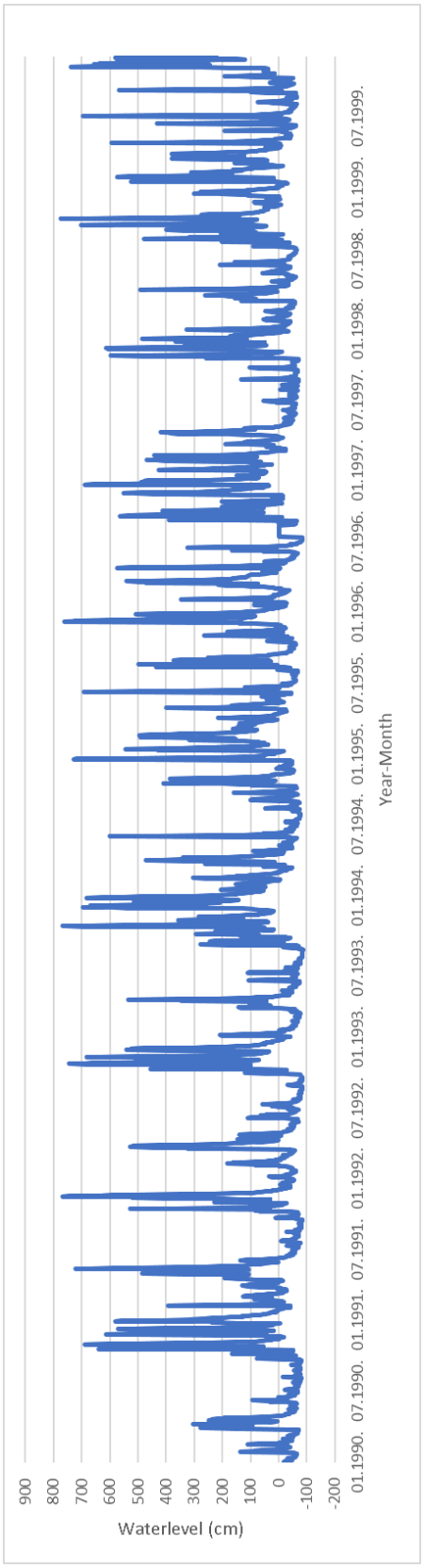


Figure 3-5 Water levels measured on river Kupa, station Kupa-Karlovac for period 1990-2000

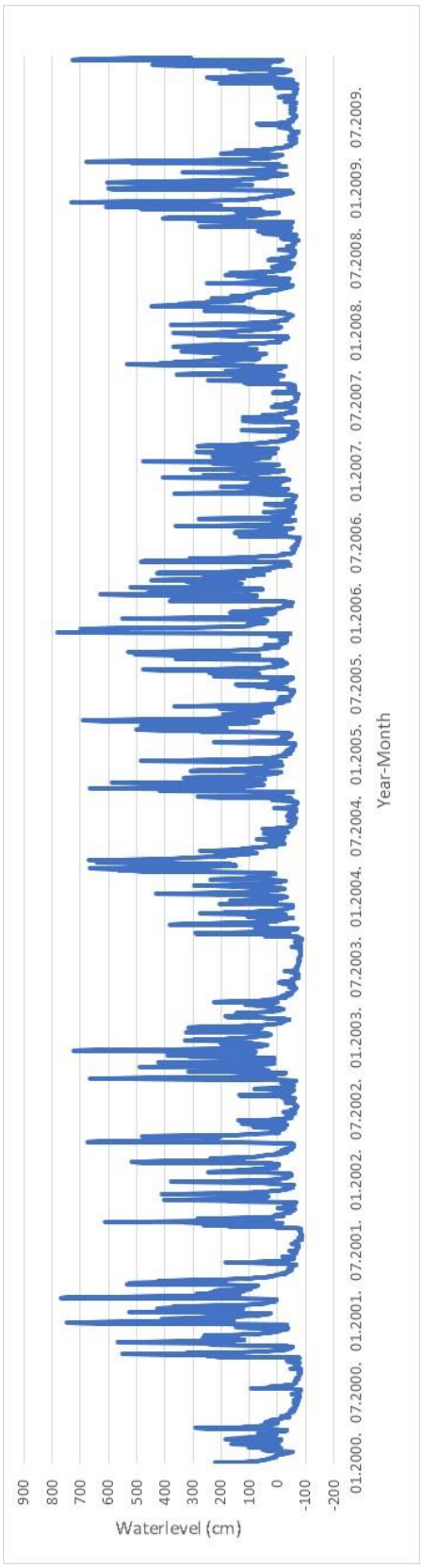


Figure 3-6 Water levels measured on river Kupa, station Kupa-Karlovac for period 2000-2010

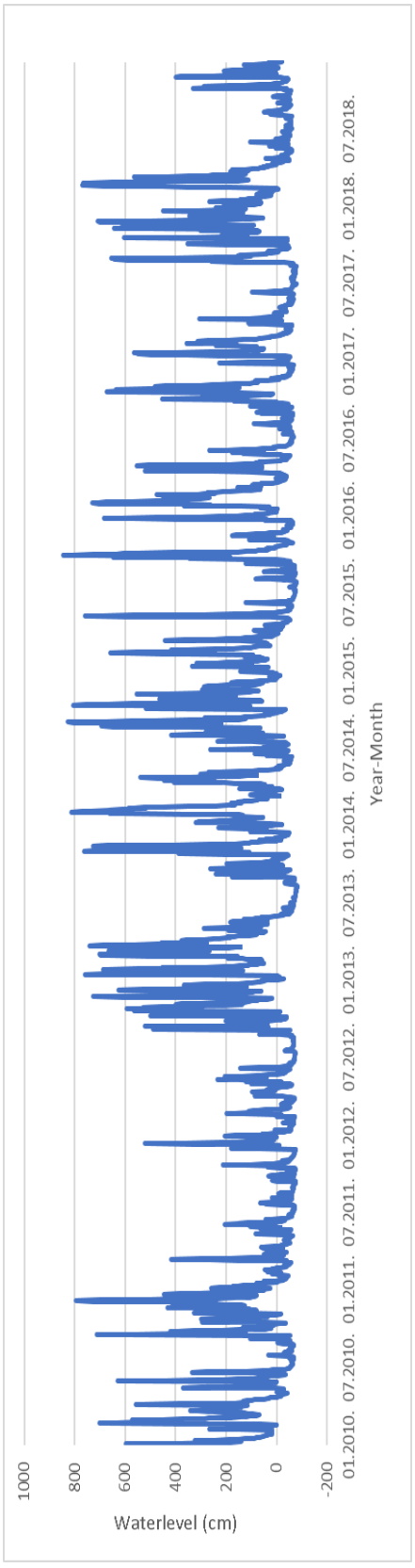


Figure 3-7 Water levels measured on river Kupa, station Kupa-Karlovac for period 2010-2019

.1.2 Analysed periods

Water levels measured in the River Kupa at two stations for the period from 1990 to 2018 have been analysed to detect highest water level events. Based on historical flood events a threshold value was set at 750 cm for the measuring station Kupa-Karlovac. With the aim to further narrow the scope of analysis and based on the publicly available data, a decision was made to analyse the period from 2011 onwards. Detected critical high-water levels and flooding periods based on the chosen threshold values are presented in Table 3 1.

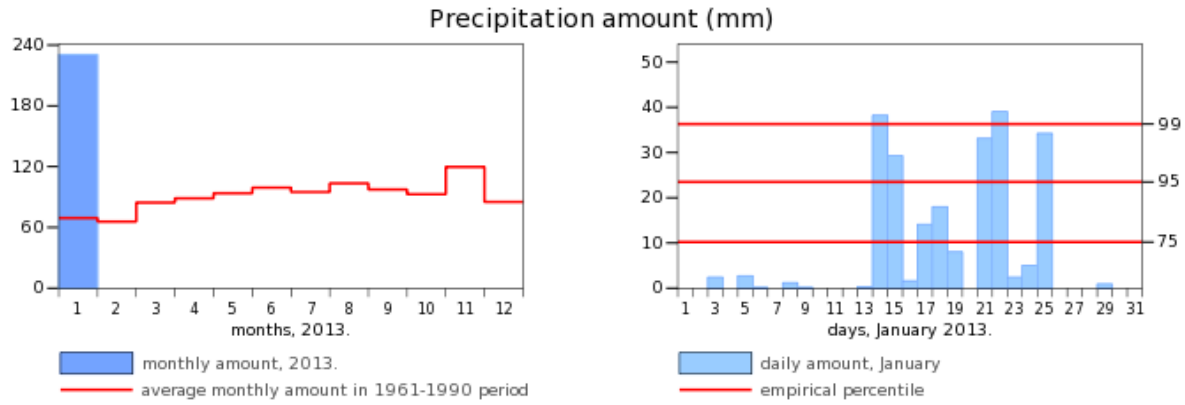
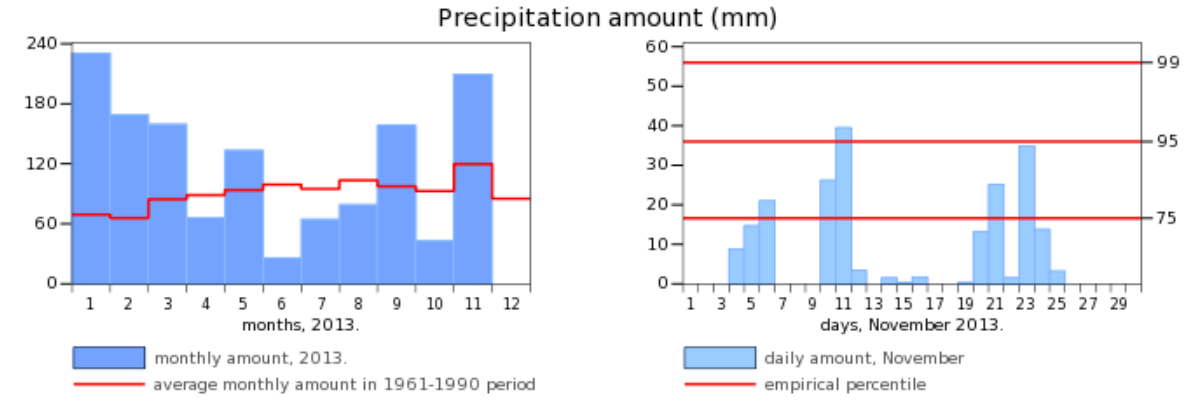
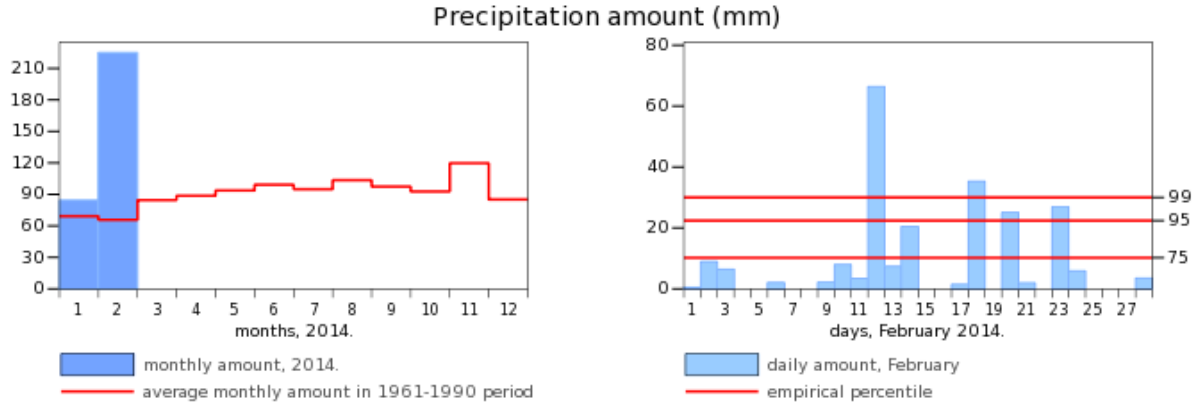
Table 3-1 Dates and related water levels on two measuring stations with the level of water above 750cm on station Kupa-Karlovac

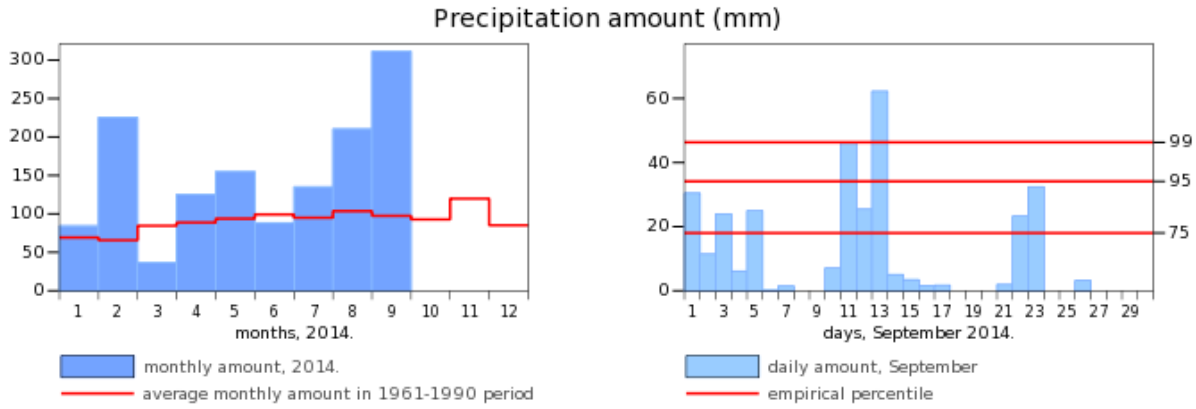
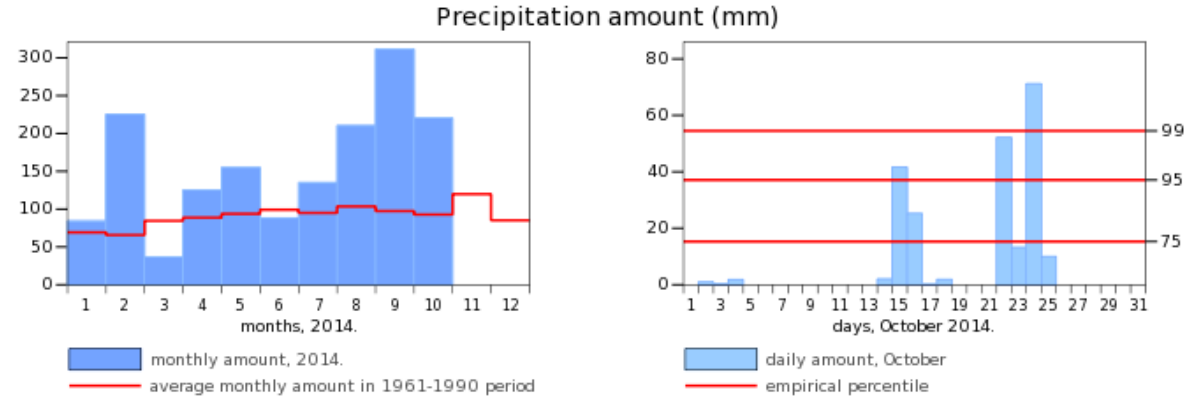
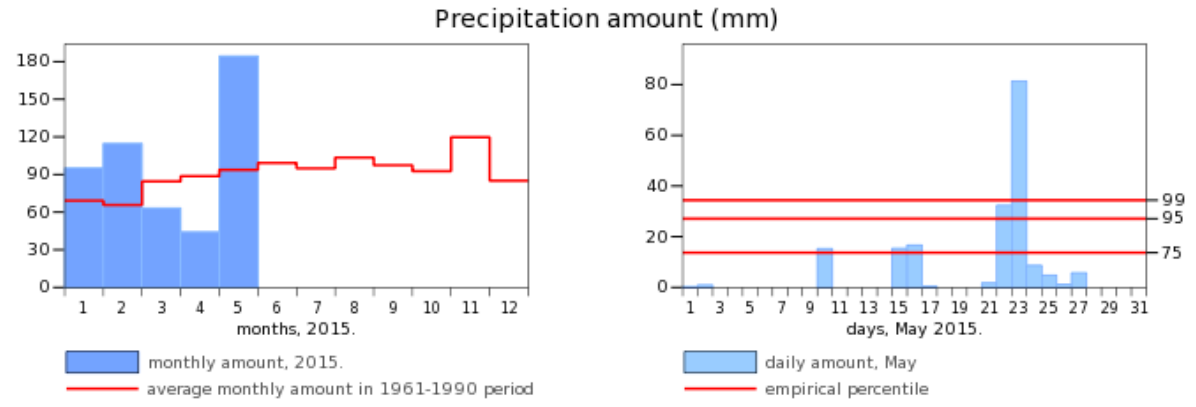
Selected periods		Date of the measured water level (day.month.year)	Water level in cm for station Kupa-Karlovac (cm)	Water level in cm for station Kupa-Brodarci (cm)
I	January 2013	22.1.2013	761	389
		23.1.2013	761	332
II	November 2013	12.11.2013	764	411
III	February 2014	12.2.2014	784	431
		13.2.2014	813	405
		14.2.2014	766	334
IV	September 2014	13.9.2014	805	440
		14.9.2014	828	421
		15.9.2014	761	309
V	October 2014	25.10.2014	805	397
		26.10.2014	753	304
VI	May 2015	24.5.2015	761	385
VII	October 2015	16.10.2015	845	474
		17.10.2015	807	366
VIII	March 2018	13.3.2018	772	366
		18.3.2018	767	357

3.1.3 Meteorological data

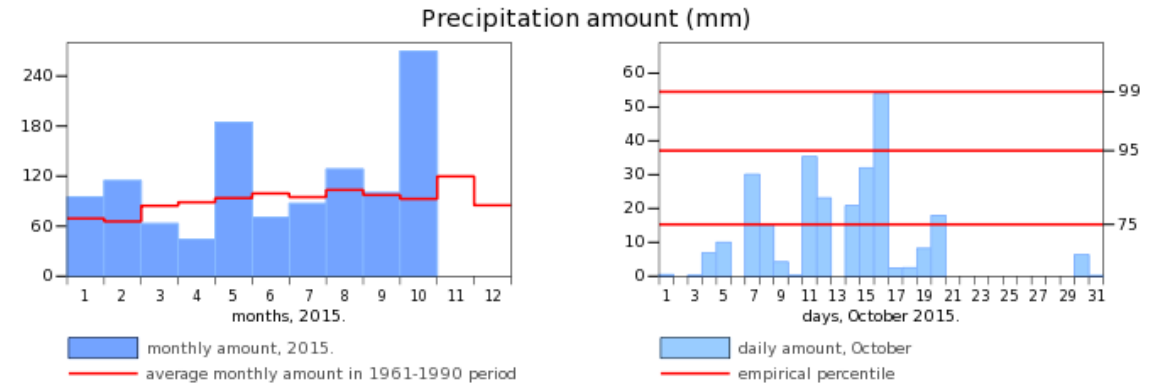
For the selected periods meteorological data has been extracted from the State Hydrometeorological Institute of Croatia (https://meteo.hr/klima.php?section=klima_pracenje&param=klel) for meteorological station Karlovac.

In Figure 3-8 daily and monthly precipitation quantities (mm) are presented for the eight selected periods where the water level exceeded the threshold value (see Table 3-1).

Period I – January 2013

Period II – November 2013

Period III – February 2014


Period IV – September 2014

Period V – October 2014

Period VI – May 2015


Period VII – October 2015



Period VIII – March 2018

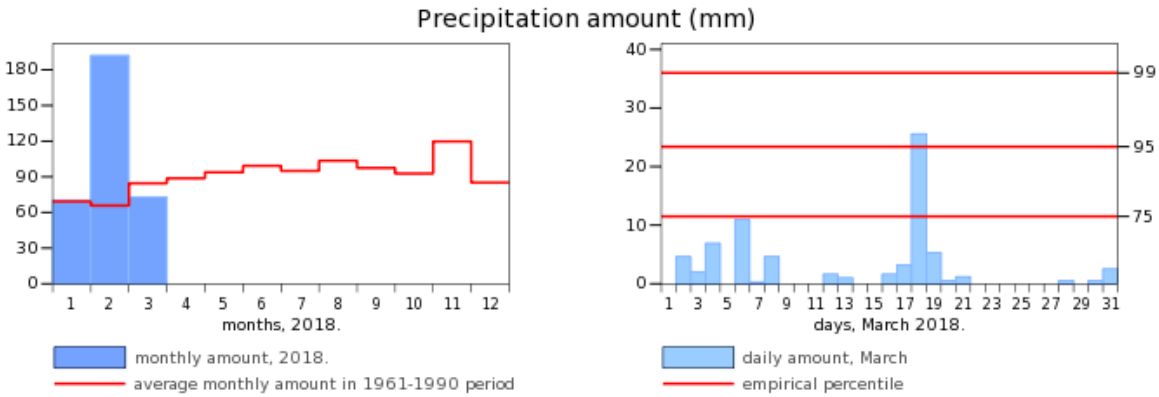


Figure 3-8 Precipitation data for the selected eight periods (months) when high water levels occurred

3.1.4 Correlation between hydrological and meteorological data for the analysed periods

Meteorological and hydrological data for selected eight periods at the case study locations are correlated in the following chapters. Data about water levels, water flows in m^3/s and 24h precipitation data are considered. The duration of the analysed periods is set to one month, three weeks prior to the highest water level and one week after.

3.1.4.1 Period I (January 2013)

In Table 3-2 and Figures 3-8 to 3-10 data meteorological and hydrological data are presented for Period I.

Table 3-2 Period I – water levels stations Karlovac-Kupa and Brodarci-Kupa (cm), water flows station Brodarci-Kupa (m^3/s) and 24 h precipitation (mm) meteorological station Karlovac

Date	Water level Karlovac-Kupa (cm)	Water levels Brodarci-Kupa (cm)	Water flows Brodarci-Kupa (m^3/s)	24h precipitation (mm) Karlovac
1.1.2013	151	97	118	0
2.1.2013	117	95	113	0
3.1.2013	99	90	102	2
4.1.2013	74	85	91.8	0
5.1.2013	76	87	95.9	3
6.1.2013	65	83	87.8	0
7.1.2013	48	78	78	0
8.1.2013	63	87	95.9	1
9.1.2013	34	73	68.8	0
10.1.2013	30	70	63.6	0
11.1.2013	-7	60	47.6	0
12.1.2013	-29	53	37.7	0
13.1.2013	-17	58	44.6	0
14.1.2013	-8	61	49.1	38
15.1.2013	-14	58	44.6	28
16.1.2013	-9	61	49.1	3
17.1.2013	-3	62	50.6	13
18.1.2013	-4	64	53.7	16
19.1.2013	-2	59	46.1	8
20.1.2013	21	73	68.8	0
21.1.2013	290	174	365	32
22.1.2013	761	389	711	40
23.1.2013	761	332	451	3
24.1.2013	672	231	317	5
25.1.2013	567	147	179	34
26.1.2013	467	125	191	0
27.1.2013	327	108	145	0
28.1.2013	226	115	163	0
29.1.2013	162	104	135	2
30.1.2013	141	102	130	0
31.1.2013	135	102	130	0

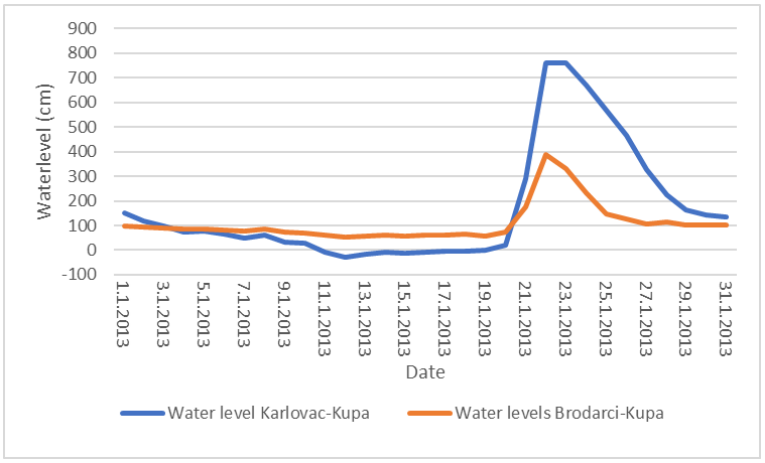


Figure 3-9 Water levels stations Karlovac-Kupa and Brodarci-Kupa January 2013 (mm)

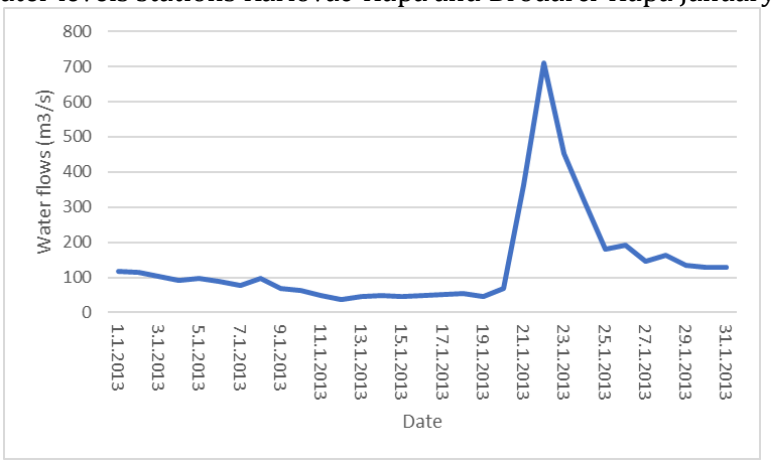


Figure 3-10 Water flows station Brodarci-Kupa January 2013 (m^3/s)

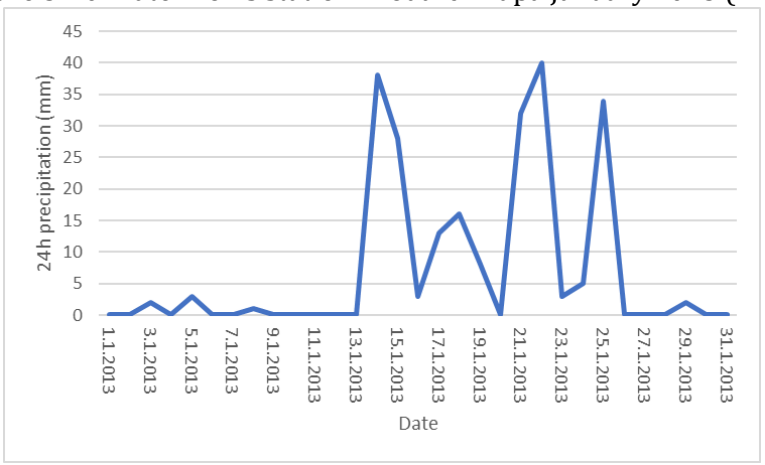


Figure 3-11 24h-precipitation data for January 2013 meteorological station Karlovac

3.1.4.2 Period II (October-November 2013)

In Table 3-3 and Figures 3-11 to 3-13 data meteorological and hydrological data are presented for Period II.

Table 3-3 Period II – water levels stations Karlovac-Kupa and Brodarci-Kupa (cm), water flows station Brodarci-Kupa (m^3/s) and 24 h precipitation (mm) meteorological station Karlovac

Date	Water level Karlovac-Kupa (cm)	Water levels Brodarci-Kupa (cm)	Water flows Brodarci-Kupa (m^3/s)	24h precipitation Karlovac (mm)
22.10.2013	18	68	60.2	0
23.10.2013	18	66	56.9	0
24.10.2013	0	62	50.6	0
25.10.2013	-14	55	40.4	0
26.10.2013	-25	48	31.3	0
27.10.2013	-33	46	28.9	0
28.10.2013	-21	54	39	0
29.10.2013	-41	46	28.9	0
30.10.2013	-24	53	37.7	0
31.10.2013	-18	55	40.4	0
1.11.2013	-35	48	31.3	0
2.11.2013	-48	43	25.5	0
3.11.2013	-44	47	30.1	0
4.11.2013	105	114	160	8
5.11.2013	212	143	246	14
6.11.2013	390	188	426	20
7.11.2013	290	134	218	0
8.11.2013	191	113	158	0
9.11.2013	110	92	107	0
10.11.2013	240	156	293	25
11.11.2013	541	284	804	40
12.11.2013	764	411	804	4
13.11.2013	709	295	468	0
14.11.2013	604	193	323	2
15.11.2013	470	136	224	1
16.11.2013	314	115	163	2
17.11.2013	242	125	191	0
18.11.2013	183	107	142	0
19.11.2013	141	105	137	1
20.11.2013	173	121	179	12
21.11.2013	540	242	656	25

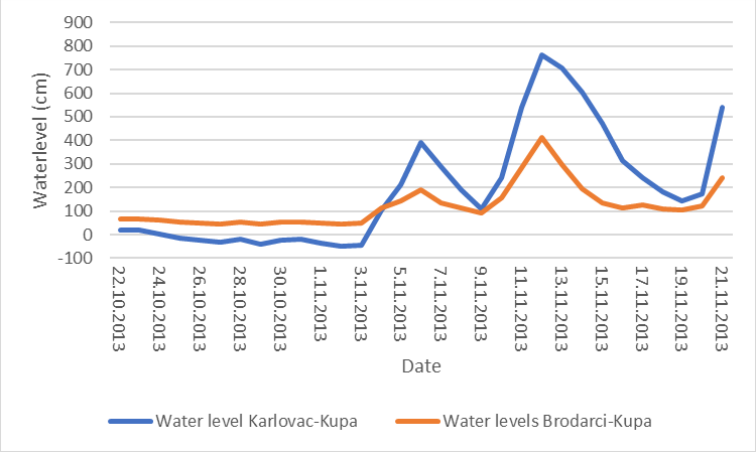


Figure 3-12 Water levels stations Karlovac-Kupa and Brodarci-Kupa October to November 2013

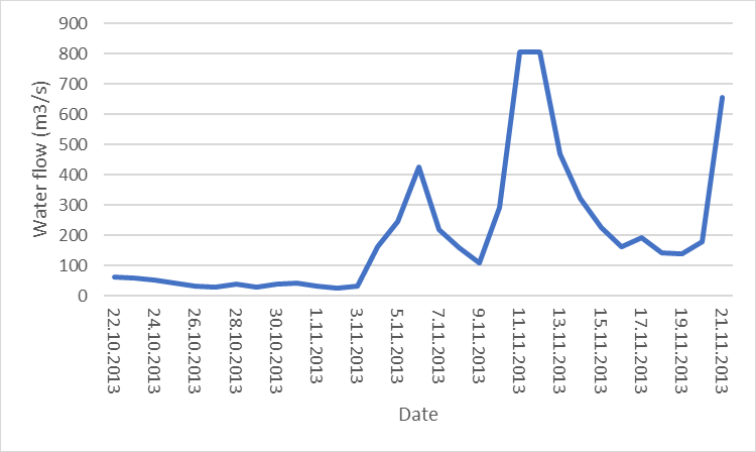


Figure 3-13 Water flows station Brodarci-Kupa October to November 2013

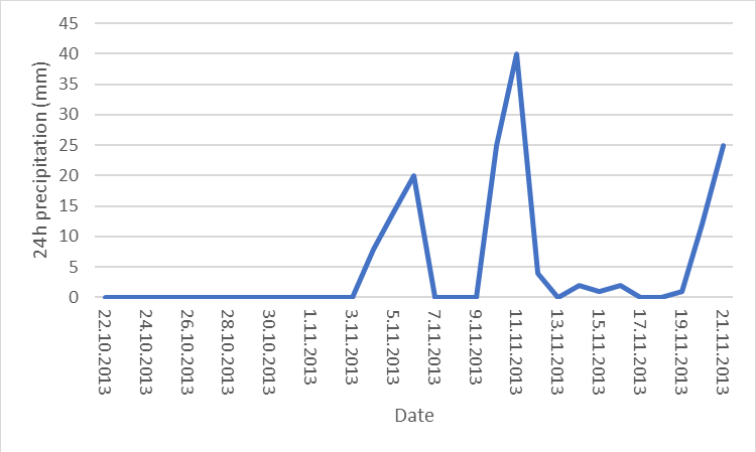


Figure 3-14 24h-precipitation data meteorological station Karlovac October to November 2013

3.1.4.3 Period III (February 2014)

In Table 3-4 and Figures 3-14 to 3-16 data meteorological and hydrological data are presented for Period III.

Table 3-4 Period III – water levels stations Karlovac-Kupa and Brodarci-Kupa (cm), water flows station Brodarci-Kupa (m^3/s) and 24 h precipitation (mm) meteorological station Karlovac

Date	Water level Karlovac-Kupa (cm)	Water levels Brodarci-Kupa (cm)	Water flows Brodarci-Kupa (m^3/s)	24h precipitation Karlovac (mm)
22.1.2014	264	157	297	4
23.1.2014	224	138	230	0
24.1.2014	188	130	206	7
25.1.2014	170	118	171	45
26.1.2014	140	106	140	0
27.1.2014	140	108	145	0
28.1.2014	119	101	127	1
29.1.2014	113	99	123	9
30.1.2014	65	83	87.8	0
31.1.2014	55	78	78	3
1.2.2014	82	99	123	0
2.2.2014	150	159	304	9
3.2.2014	138	140	237	7
4.2.2014	146	140	237	0
5.2.2014	133	121	179	0
6.2.2014	150	124	188	2
7.2.2014	251	141	240	0
8.2.2014	382	177	377	0
9.2.2014	628	282	630	3
10.2.2014	663	302	618	8
11.2.2014	618	258	568	4
12.2.2014	784	431	842	64
13.2.2014	813	405	614	8
14.2.2014	766	334	442	20
15.2.2014	731	308	451	0
16.2.2014	652	219	323	0
17.2.2014	597	191	328	2
18.2.2014	663	307	636	38
19.2.2014	607	231	484	0
20.2.2014	568	208	459	25
21.2.2014	587	217	464	3
22.2.2014	519	172	356	0

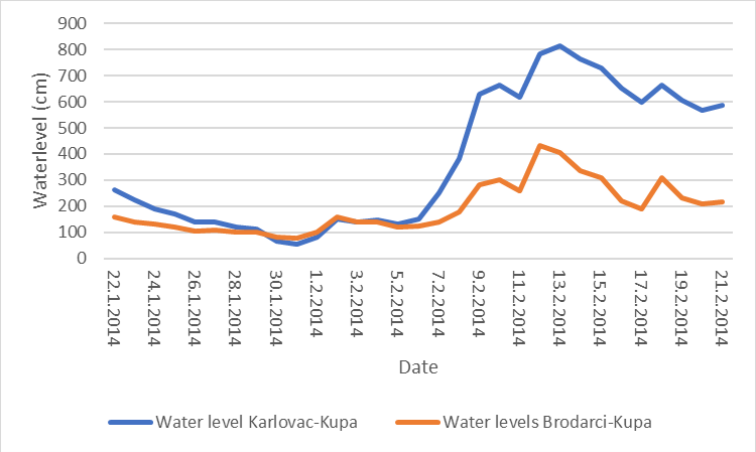


Figure 3-15 Water levels stations Karlovac-Kupa and Brodarci-Kupa (cm)

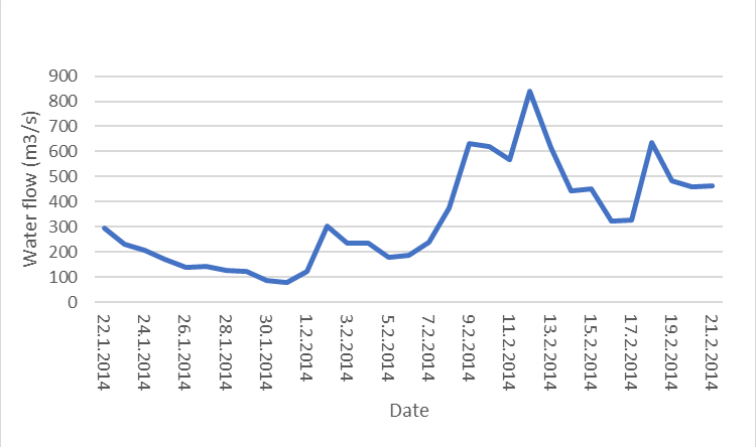


Figure 3-16 Water flows station Brodarci-Kupa (m3/s)

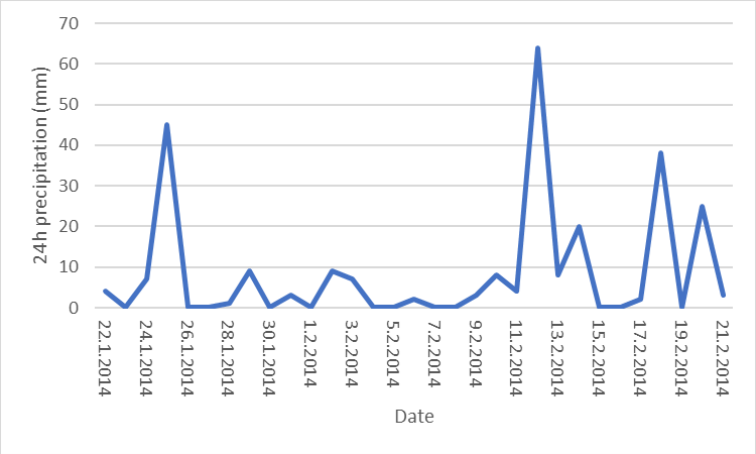


Figure 3-17 24h precipitation data (mm) meteorological station Karlovac

3.1.4.4 Period IV (September 2014)

In Table 3-5 and Figures 3-17 to 3-19 data meteorological and hydrological data are presented for Period IV.

Table 3-5 Period IV – water levels stations Karlovac-Kupa and Brodarci-Kupa (cm), water flows station Brodarci-Kupa (m^3/s) and 24 h precipitation (mm) meteorological station Karlovac

Date	Water level Karlovac-Kupa (cm)	Water levels Brodarci-Kupa (cm)	Water flows Brodarci-Kupa (m^3/s)	24h precipitation Karlovac (mm)
23.8.2014	205	120	177	0
24.8.2014	146	93	109	17
25.8.2014	161	102	130	10
26.8.2014	142	97	118	0
27.8.2014	121	97	118	5
28.8.2014	163	119	174	8
29.8.2014	132	101	127	0
30.8.2014	86	89	100	0
31.8.2014	65	82	85.8	0
1.9.2014	109	103	132	30
2.9.2014	369	170	348	11
3.9.2014	573	226	530	22
4.9.2014	651	240	417	7
5.9.2014	694	290	493	23
6.9.2014	684	265	427	1
7.9.2014	586	175	275	2
8.9.2014	467	130	206	0
9.9.2014	319	112	155	0
10.9.2014	222	109	147	8
11.9.2014	415	190	435	47
12.9.2014	701	341	672	27
13.9.2014	805	440	821	60
14.9.2014	828	421	640	5
15.9.2014	761	309	340	4
16.9.2014	669	213	242	2
17.9.2014	570	134	120	2
18.9.2014	473	110	150	0
19.9.2014	335	101	127	0
20.9.2014	193	94	111	0
21.9.2014	147	101	127	3
22.9.2014	124	95	113	21
23.9.2014	230	115	163	30

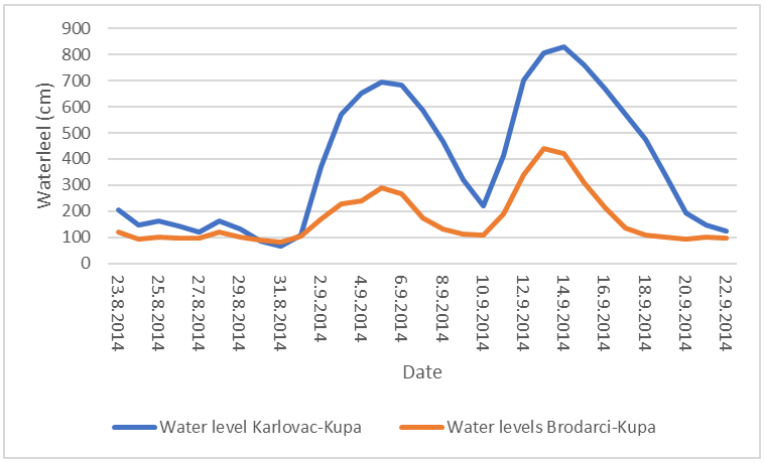


Figure 3-18 Water levels stations Karlovac-Kupa and Brodarci-Kupa period?

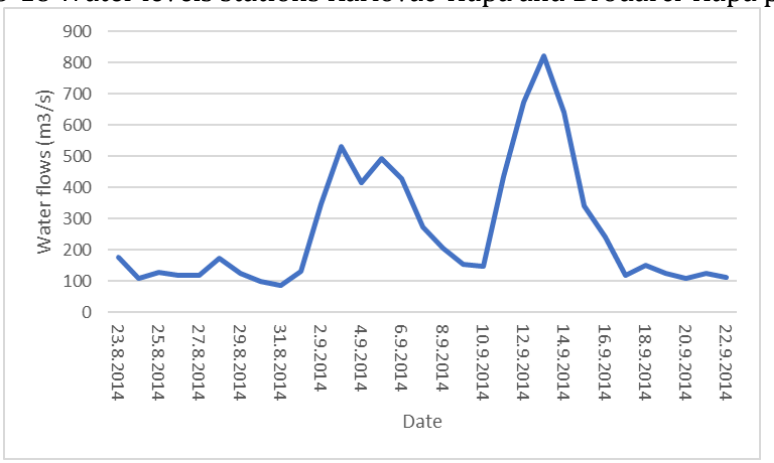


Figure 3-19 Water flows station Brodarci-Kupa period

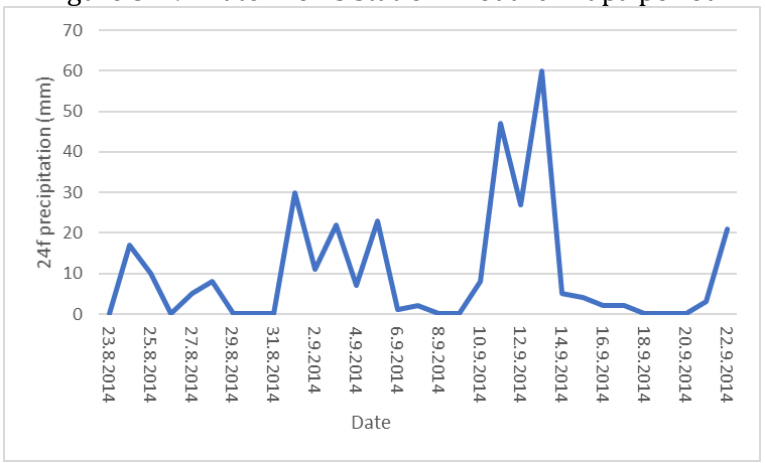


Figure 3-20 24h precipitation data meteorological station Karlovac period

3.1.4.5 Period V (October 2014)

In Table 3-6 and Figures 3-20 to 3-22 data meteorological and hydrological data are presented for Period V.

Table 3-6 Period V – water levels stations Karlovac-Kupa and Brodarci-Kupa (cm), water flows station Brodarci-Kupa (m^3/s) and 24 h precipitation (mm) meteorological station Karlovac

Date	Water level Karlovac-Kupa (cm)	Water levels Brodarci-Kupa (cm)	Water flows Brodarci-Kupa (m^3/s)	24h precipitation Karlovac (mm)
4.10.2014	22	64	53.7	2
5.10.2014	16	63	52.1	0
6.10.2014	-3	56	41.8	0
7.10.2014	-4	56	41.8	0
8.10.2014	-4	57	43.2	0
9.10.2014	-14	53	37.7	0
10.10.2014	-22	51	35.1	0
11.10.2014	-26	51	35.1	0
12.10.2014	-24	52	36.4	0
13.10.2014	-30	49	32.5	0
14.10.2014	-34	48	31.3	3
15.10.2014	91	116	166	40
16.10.2014	518	256	791	25
17.10.2014	415	175	369	0
18.10.2014	287	141	240	2
19.10.2014	173	116	166	0
20.10.2014	133	107	142	0
21.10.2014	105	92	107	0
22.10.2014	217	181	395	52
23.10.2014	615	294	697	70
24.10.2014	722	363	707	10
25.10.2014	805	397	603	0
26.10.2014	753	304	350	0
27.10.2014	664	215	268	0
28.10.2014	564	137	139	0
29.10.2014	453	111	152	0
30.10.2014	294	100	125	0
31.10.2014	160	94	111	0
1.11.2014	114	93	109	0
2.11.2014	91	87	95.9	0
3.11.2014	78	85	91.8	0
4.11.2014	59	81	83.8	0

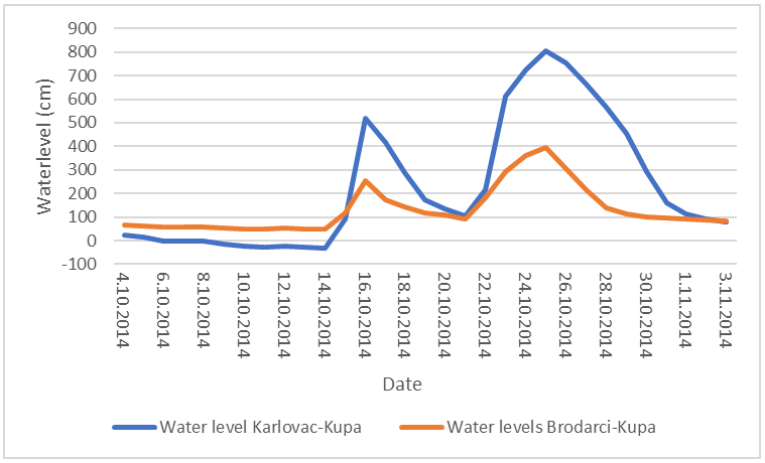


Figure 3-21 Water levels stations Karlovac-Kupa and Brodarci-Kupa Period

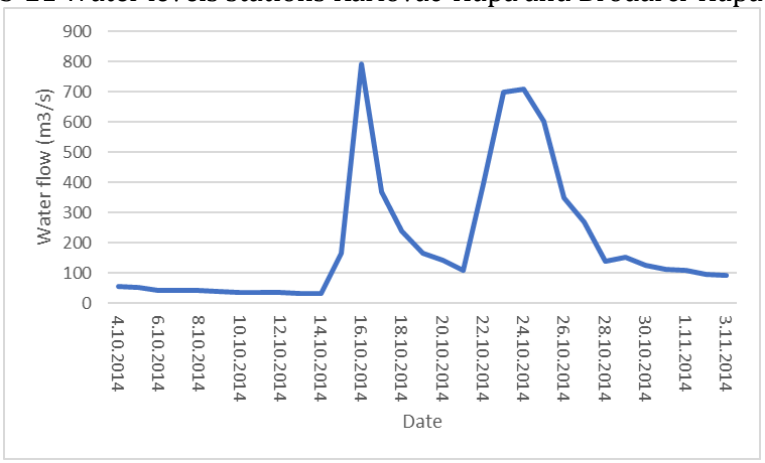


Figure 3-22 Water flows station Brodarci-Kupa Period

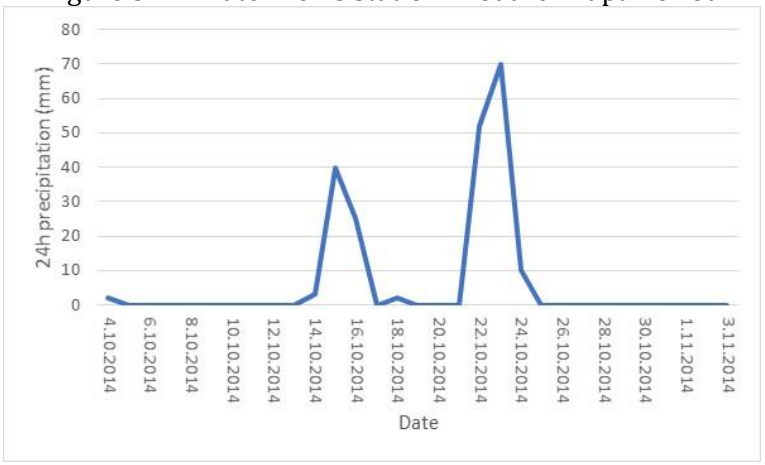


Figure 3-23 24h precipitation data meteorological station Karlovac Period

3.1.4.6 Period VI (May 2015)

In Table 3-7 and Figures 3-23 to 3-25 data meteorological and hydrological data are presented for Period VI.

Table 3-7 Period VI – water levels stations Karlovac-Kupa and Brodarci-Kupa (cm), water flows station Brodarci-Kupa (m^3/s) and 24 h precipitation (mm) meteorological station Karlovac

Date	Water level Karlovac-Kupa (cm)	Water levels Brodarci-Kupa (cm)	Water flows Brodarci-Kupa (m^3/s)	24h precipitation Karlovac (mm)
3.5.2015	48	87	95.9	0
4.5.2015	4	66	56.9	0
5.5.2015	0	68	60.2	0
6.5.2015	-19	58	44.6	0
7.5.2015	-20	59	46.1	0
8.5.2015	-31	55	40.4	0
9.5.2015	-38	52	36.4	0
10.5.2015	-42	51	35.1	16
11.5.2015	-35	54	39	0
12.5.2015	-40	51	35.1	0
13.5.2015	-43	50	33.8	0
14.5.2015	-43	50	33.8	0
15.5.2015	-52	46	28.9	16
16.5.2015	-49	47	30.1	17
17.5.2015	-49	47	30.1	1
18.5.2015	-50	47	30.1	0
19.5.2015	-43	50	33.8	0
20.5.2015	-41	51	35.1	0
21.5.2015	-34	55	40.4	2
22.5.2015	26	80	81.9	35
23.5.2015	587	294	752	80
24.5.2015	761	385	692	8
25.5.2015	685	264	420	5
26.5.2015	558	158	240	1
27.5.2015	424	120	177	7
28.5.2015	282	108	145	0
29.5.2015	160	99	123	0
30.5.2015	102	93	109	0
31.5.2015	67	82	85.8	0
1.6.2015	23	70	63.6	0
2.6.2015	7	66	56.9	0
3.6.2015	-11	59	46.1	0

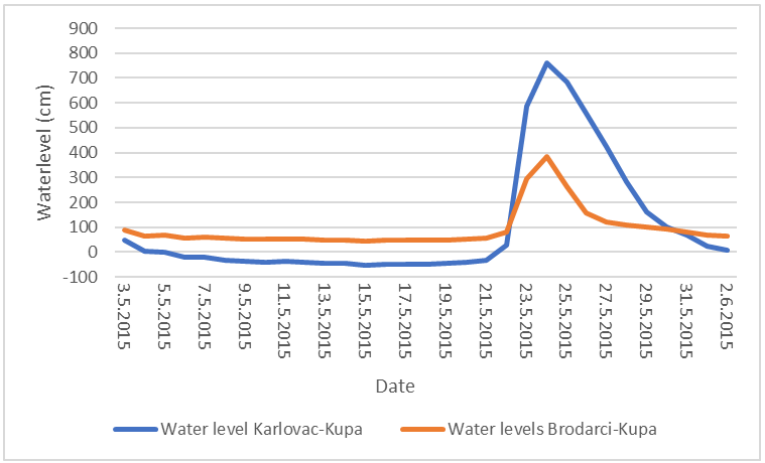


Figure 3-24 Water levels stations Karlovac-Kupa and Brodarci-Kupa May 2015

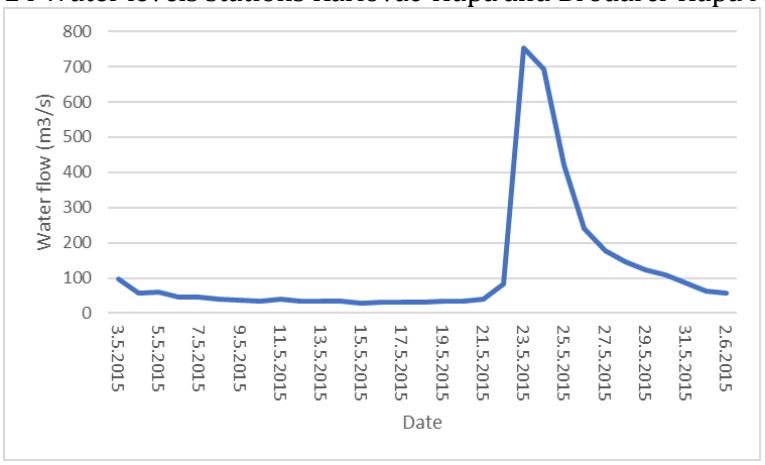


Figure 3-25 Water flows station Brodarci-Kupa May 2015

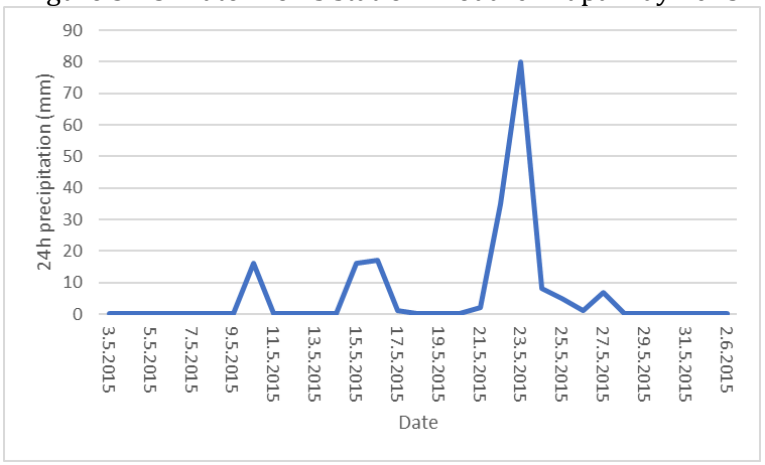


Figure 3-26 24h precipitation data meteorological station Karlovac

3.1.4.7 Period VII (October 2015)

In Table 3-8 and Figures 3-26 to 3-28 data meteorological and hydrological data are presented for Period VII.

Table 3-8 Period VII – water levels stations Karlovac-Kupa and Brodarci-Kupa (cm), water flows station Brodarci-Kupa (m^3/s) and 24 h precipitation (mm) meteorological station Karlovac

Date	Water level Karlovac-Kupa (cm)	Water levels Brodarci-Kupa (cm)	Water flows Brodarci-Kupa (m^3/s)	24h precipitation Karlovac (mm)
25.9.2015	-27	57	43.2	28
26.9.2015	122	115	163	21
27.9.2015	120	97	118	0
28.9.2015	38	67	58.6	0
29.9.2015	17	64	53.7	0
30.9.2015	-19	50	33.8	1
1.10.2015	-50	41	23.3	1
2.10.2015	-54	43	25.5	0
3.10.2015	-24	49	32.5	0
4.10.2015	-31	51	35.1	7
5.10.2015	5	71	65.3	9
6.10.2015	110	101	127	0
7.10.2015	135	118	171	29
8.10.2015	345	176	373	15
9.10.2015	278	139	233	5
10.10.2015	184	109	147	1
11.10.2015	344	172	356	35
12.10.2015	649	275	558	21
13.10.2015	578	187	344	0
14.10.2015	497	183	403	20
15.10.2015	739	403	838	30
16.10.2015	845	474	865	54
17.10.2015	807	366	435	3
18.10.2015	720	263	290	3
19.10.2015	633	185	221	7
20.10.2015	606	187	292	19
21.10.2015	539	150	226	0
22.10.2015	400	116	166	0
23.10.2015	258	107	142	0
24.10.2015	150	96	116	0
25.10.2015	120	94	111	0
26.10.2015	83	85	91.8	0

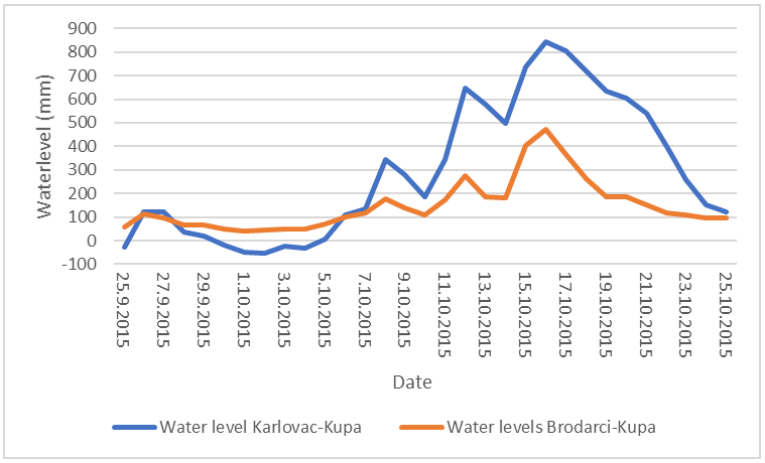


Figure 3-27 Water levels Karlovac-Kupa and Brodarci-Kupa September to October 2015

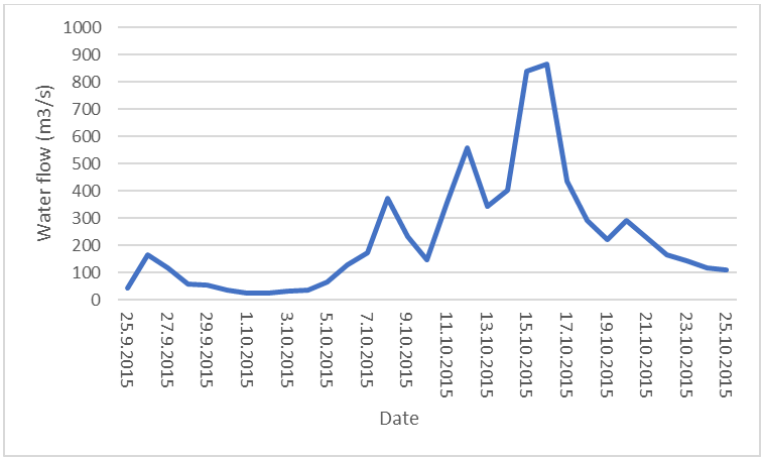


Figure 3-28 Water flows station Brodarci-Kupa September to October 2015

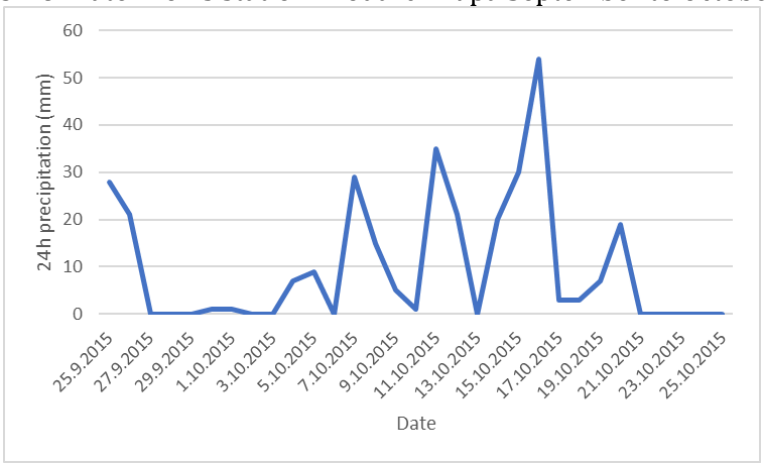


Figure 3-29 24h precipitation data meteorological station Karlovac September to October 2015

3.1.4.8 Period VIII (March 2018)

In Table 3-9 and Figures 3-29 to 3-31 data meteorological and hydrological data are presented for Period VIII.

Table 3-9 Period VIII – water levels stations Karlovac-Kupa and Brodarci-Kupa (cm), water flows station Brodarci-Kupa (m^3/s) and 24 h precipitation (mm) meteorological station Karlovac

Date	Water level Karlovac-Kupa (cm)	Water levels Brodarci-Kupa (cm)	Water flows Brodarci-Kupa (m^3/s)	24h precipitation Karlovac (mm)
20.2.2018	77	83	99.2	3
21.2.2018	72	82	96.6	5
22.2.2018	67	81	94.1	17
23.2.2018	46	74	77.3	17
24.2.2018	30	70	68.9	8
25.2.2018	19	70	68.9	1
26.2.2018	42	79	88.9	2
27.2.2018	62	81	94.1	10
28.2.2018	44	77	84.1	0
1.3.2018	49	83	99.2	0
2.3.2018	12	64	57.5	4
3.3.2018	1	63	55.7	2
4.3.2018	-7	61	52.3	6
5.3.2018	0	64	57.5	0
6.3.2018	22	71	71	11
7.3.2018	33	76	81.8	0
8.3.2018	197	127	225	5
9.3.2018	360	147	288	0
10.3.2018	461	159	328	0
11.3.2018	547	196	463	0
12.3.2018	691	303	618	3
13.3.2018	772	366	624	2
14.3.2018	748	322	509	0
15.3.2018	717	285	442	0
16.3.2018	677	252	417	3
17.3.2018	704	301	568	4
18.3.2018	767	357	602	25
19.3.2018	738	294	404	6
20.3.2018	646	202	276	1
21.3.2018	545	137	188	2
22.3.2018	425	118	198	0
23.3.2018	270	106	162	0

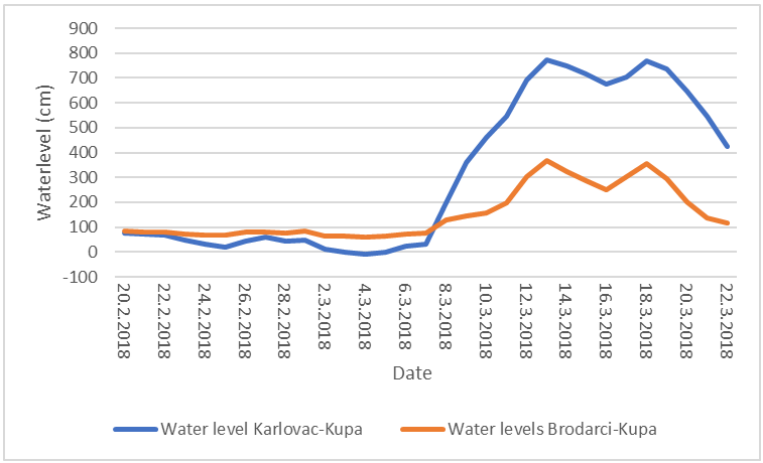


Figure 3-30 Water levels Karlovac-Kupa and Brodarci-Kupa February to March 2018

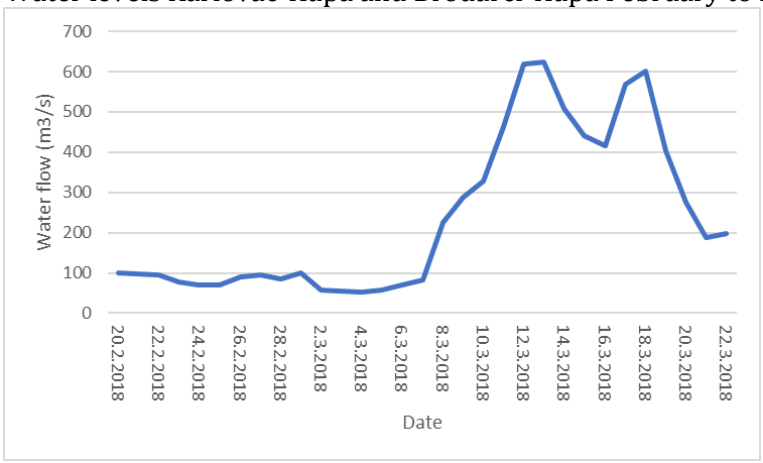


Figure 3-31 Water flows station Brodarci-Kupa February to March 2018

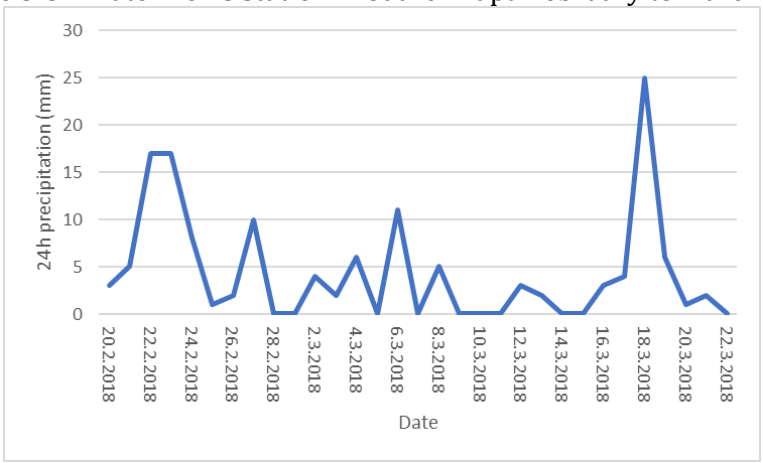


Figure 3-32 24h precipitation data meteorological station Karlovac February to March 2018

3.2 Case study area in the Netherlands

As presented in the chapter 2, the area surrounded by dikes 16 and 17 has been chosen for the case study. The data on water levels was retrieved for periods from 1990 until 2017 i.e. 2020 for two closest measuring stations, Dordrecht (1990-2017) and Vuren (1990-2020), see Figure 3-33 (https://waterinfo.rws.nl/#!/nav/bulkdownload/alle-groepen/).

Meteorological data about temperatures (min, max), precipitation quantities (duration of precipitation, 24-hour precipitation, highest hourly sum of precipitation) for the meteorological station Rotterdam was used for the analysis, as the nearest main meteorological station. The data was retrieved from the Dutch national weather service, The Royal Netherlands Meteorological Institute (KNMI), for the period from 1990 until 2020.

Figure 3-33 Map of the analysed two dike rings area in Netherlands and location of water level measuring stations and meteorological station

3.2.1 Hydrological data

Water levels from two measurement stations, Dordrecht and Vuren, for the period from 1990 to 2017 are presented in Figures 3-33 to 3.38.

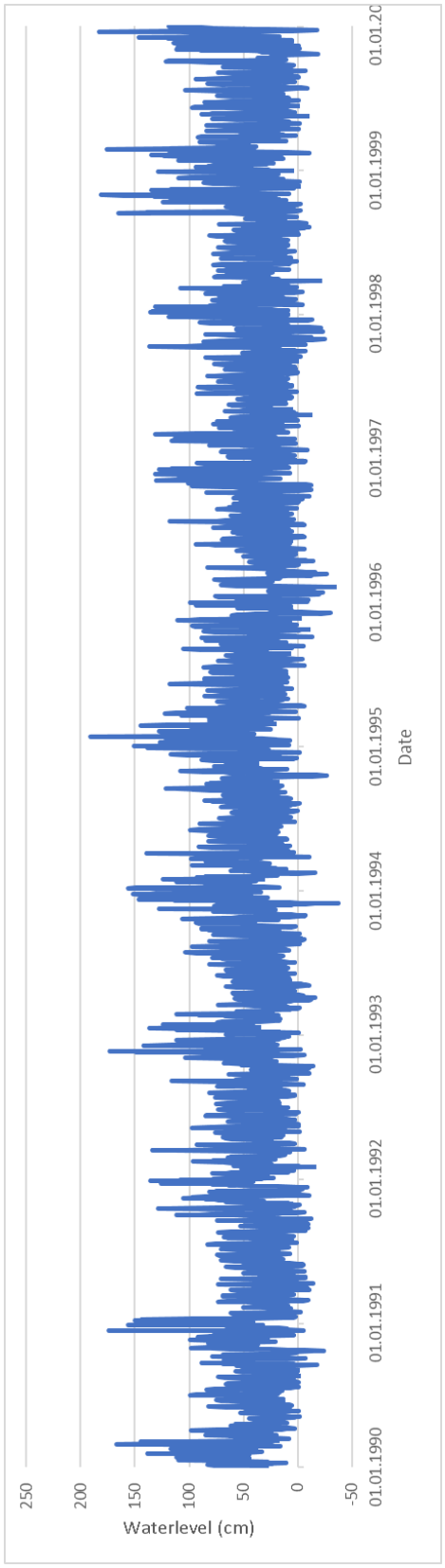


Figure 3-34 Water levels measured on measuring station Dordrecht for period 1990-2000

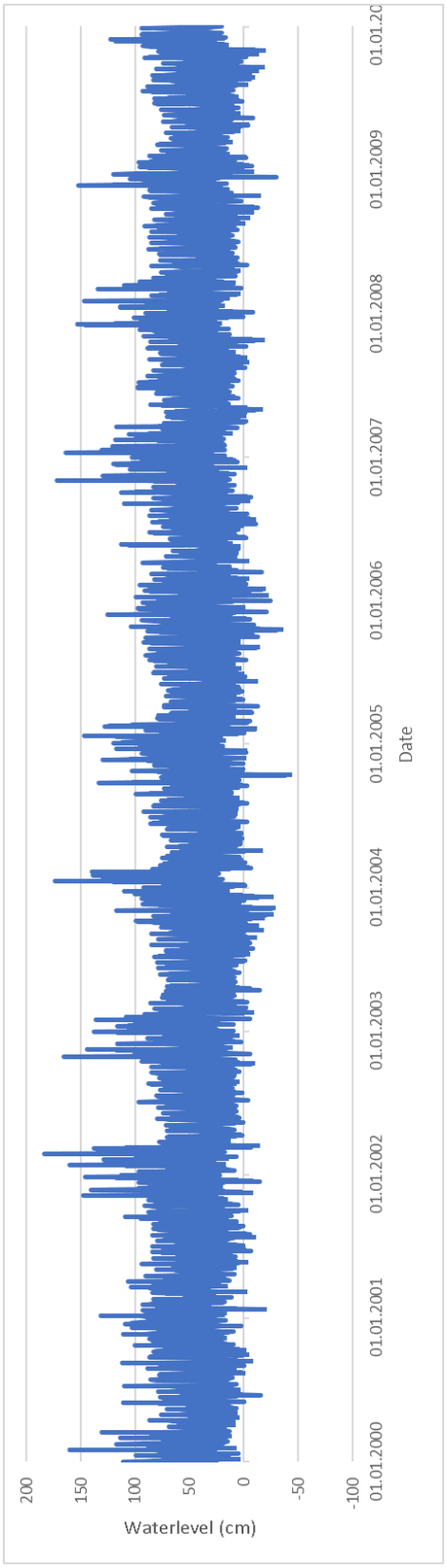


Figure 3-35 Water levels measured on measuring station Dordrecht for period 2000-2010

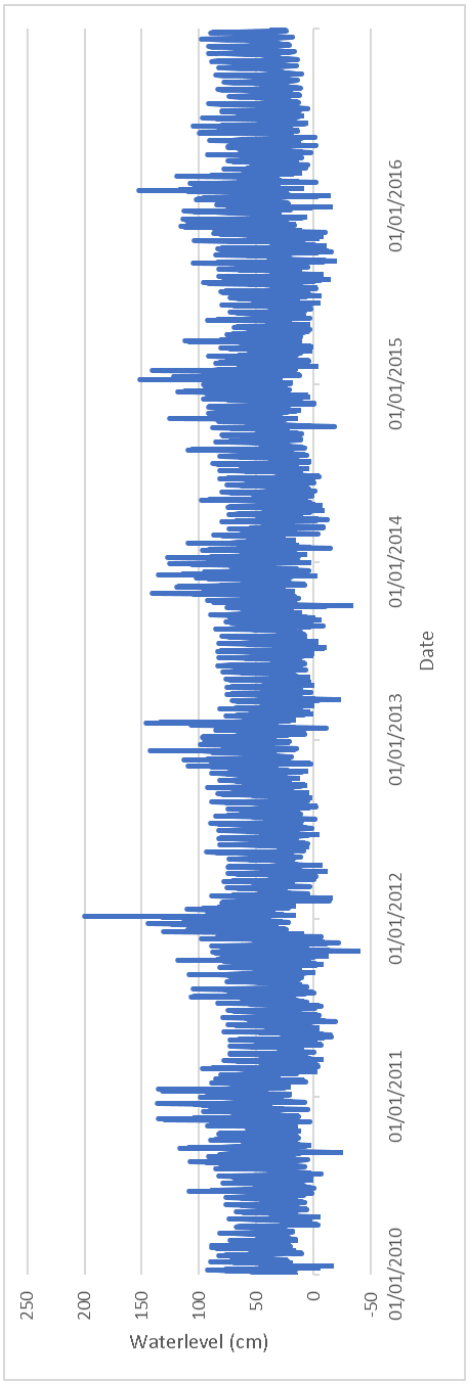


Figure 3-36 Water levels measured on measuring station Dordrecht for period 2010-2017

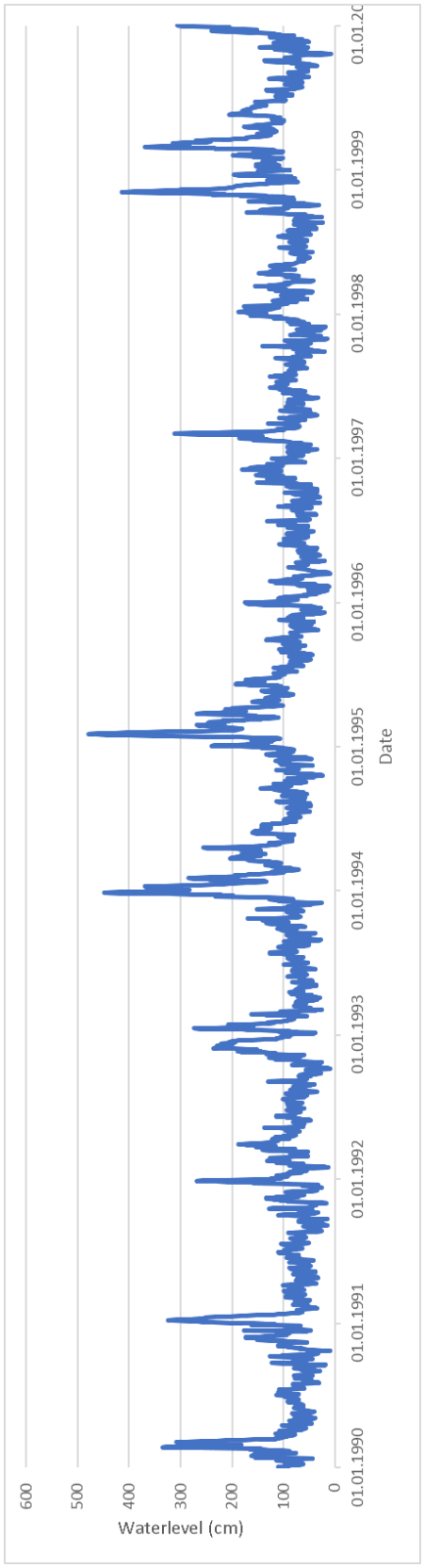


Figure 3-37 Water levels measured on measuring station Vuren for period 1990-2000

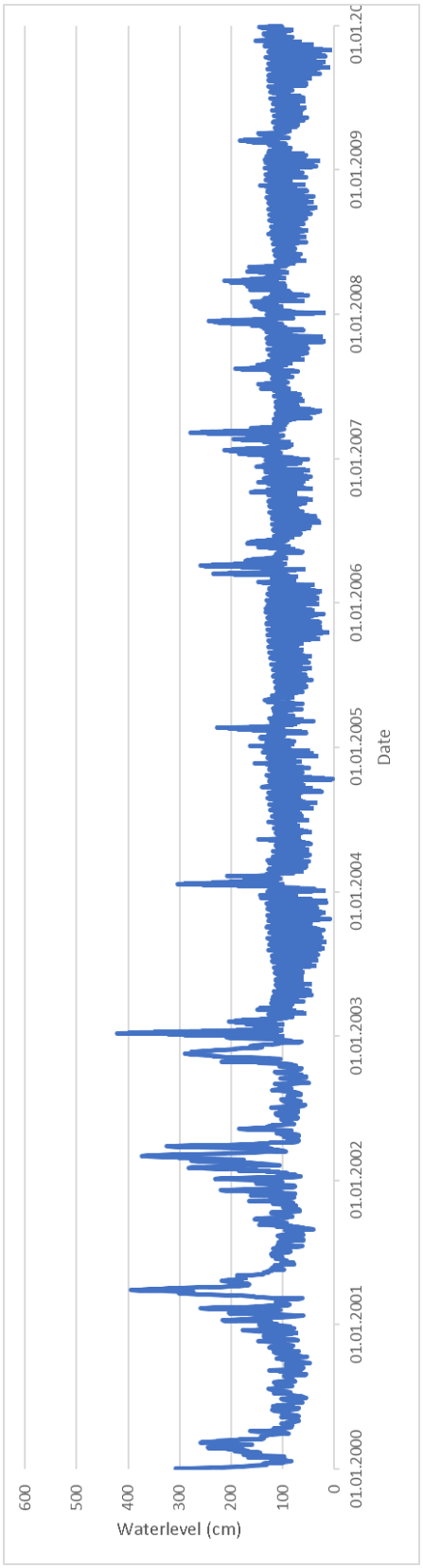


Figure 3-38 Water levels measured on measuring station Vuren for period 2000-2010

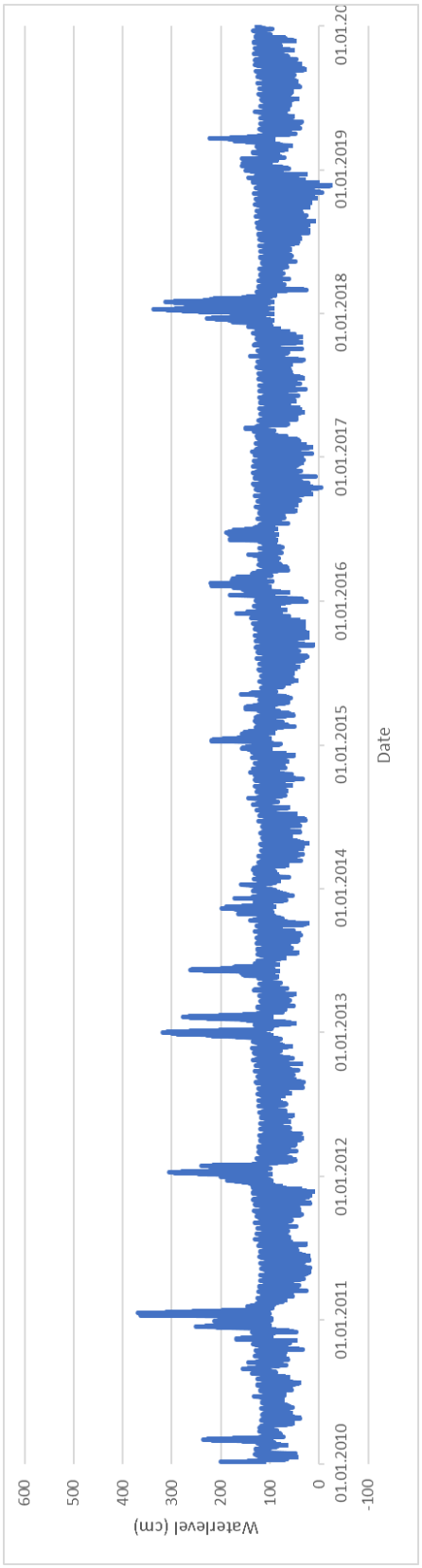


Figure 3-39 Water levels measured on measuring station Vuren for period 2010-2020

3.2.2 Analysed periods

The period that is selected for a more detailed analysis in the Netherlands is the River Rhine Floods (1994 November - 1995 February), Figure 3-39. The available data on water quantities will serve as a basis for development of loading/hazard scenarios and numerical modelling of the probability of failure of the dikes.

Figure 3-40 River Rhine floods 1995 – evacuated and flooded areas (https://geographyfieldwork.com/RhineEffects.htm)

Numerous research on this flood event revealed that it was predetermined by the following conditions. First, the soil was highly saturated with water because of extreme precipitation in the wider area. Second, snow melt from the mountains in the catchment area of the Rhine River sent extreme amounts of water into the Rhine and its tributaries (Chbab 1995; Engel 1997.; Ulbrich and Fink A., 1995; Glaser and Stangl H, 2003). This had caused extreme rise of water levels in a short period of time in France, Belgium, Germany and the Netherlands.

The largest impact in the Netherlands were around the River Waal, where on 2 February 1995 signs of dikes crumbling appeared. The Waal, one of the two Dutch arms of the Rhine, was several miles wide. The potential for greatest damage to the environment and properties was south of the Waal, to the east of Nijmegen, see Figure 3-40 (https://geographyfieldwork.com/RhineEffects.htm).

3.2.3 Meteorological data

As already described in the previous paragraph, snowmelt in the Rhine river catchment area caused water surges into the Rhine and its tributaries at the beginning of 1995. Figure 3-41 shows snow depths at the time of the event in Germany's low mountain ranges and the northern slope of the Alps where the waters are collected into the Rhine. (Nienhuis, P. 2002; Ulbrich, 1996)

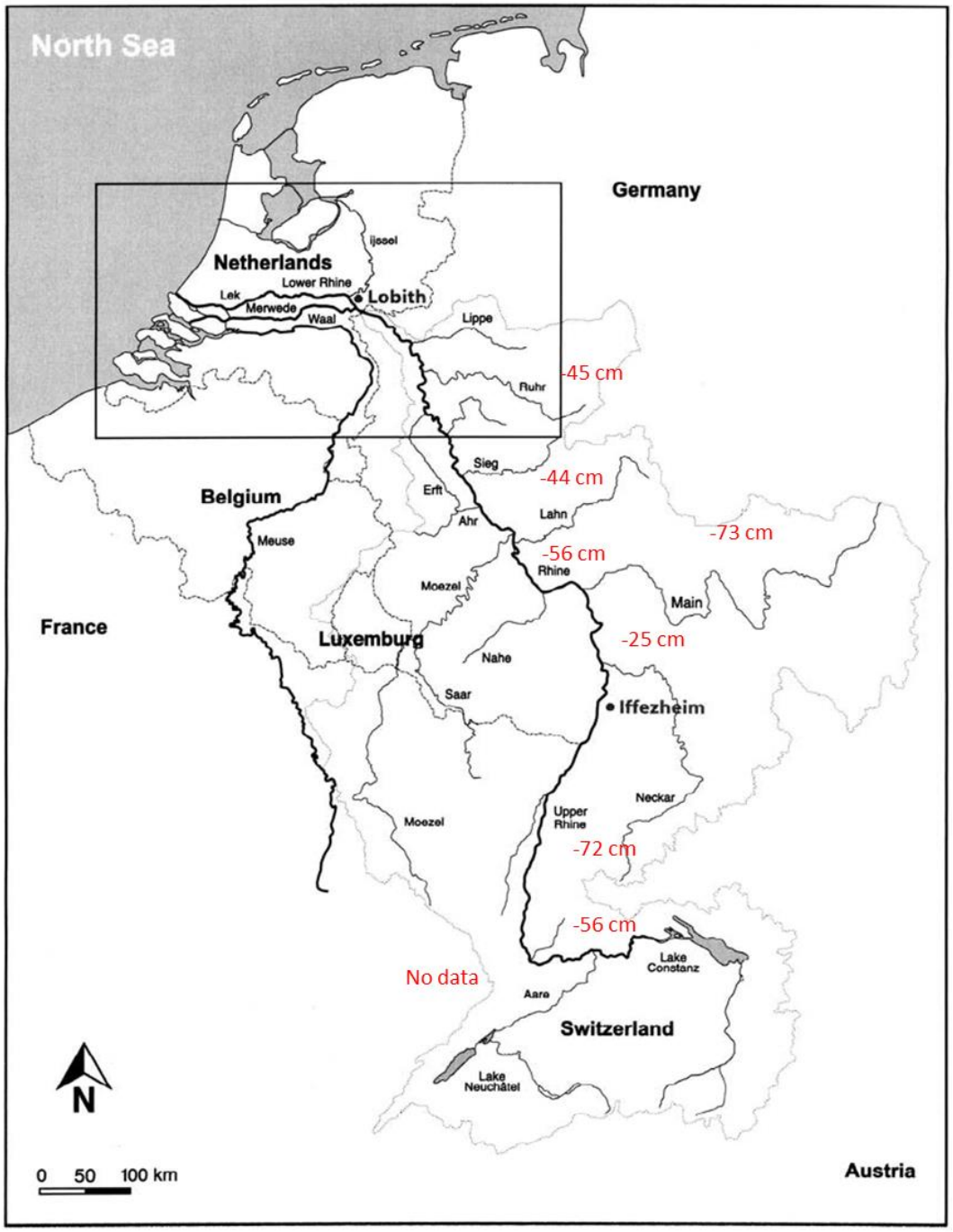


Figure 3-41 River Rhine catchment area - accumulated snowmelt between 19.01.1995 and 31.01.1995 for several stations with elevations between 500 m and 1500 m a.s.l. (Nienhuis, P. 2002; Ulbrich, 1996)

Together with the snowmelt three rainfall peaks occurred at the end of January 1995 (22nd, 25th, 28th and 29th of January) as it can be seen in Figure 3-42. Figure 3-43 and Figure 3-44 show the duration of the precipitation and highest hourly sum of the precipitation (Ulbrich, 1996).

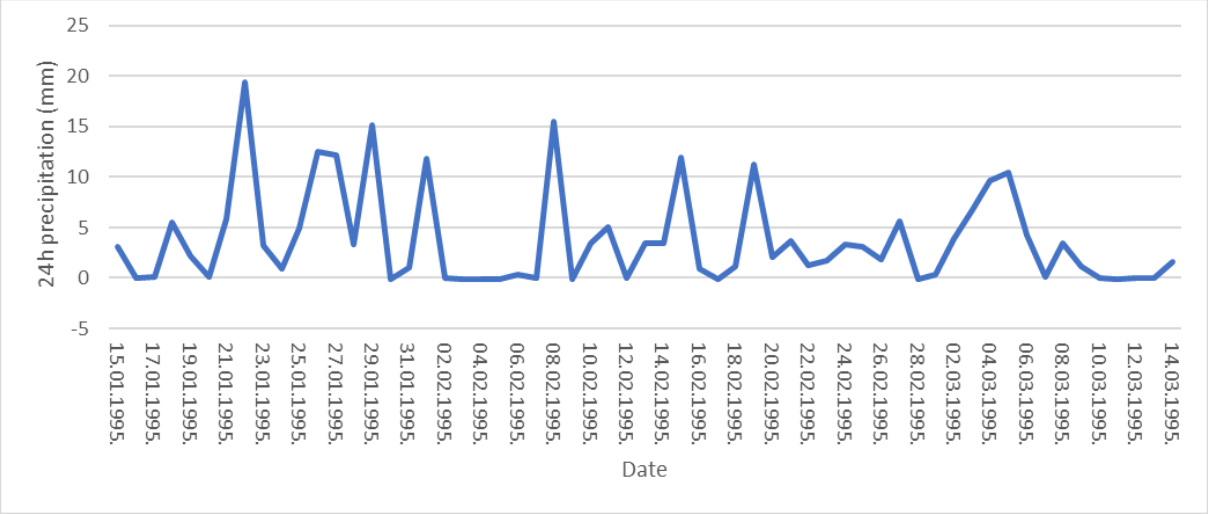


Figure 3-42 24h-precipitation for analysed period from 15.01.1995-15.03.1995 for weather station Rotterdam

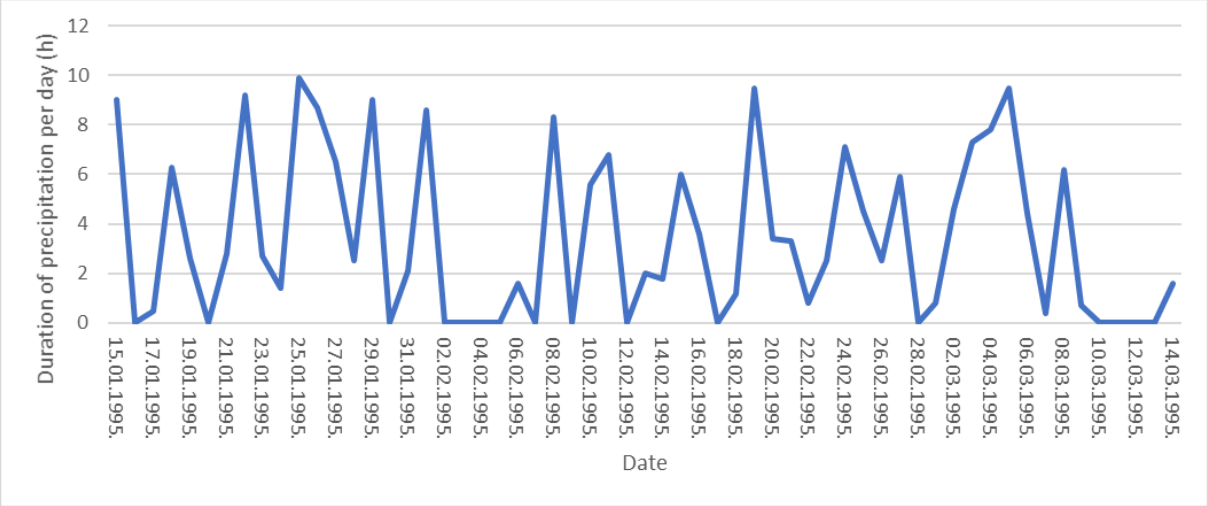


Figure 3-43 Duration of precipitation for analysed period from 15.01.1995-15.03.1995. for weather station Rotterdam

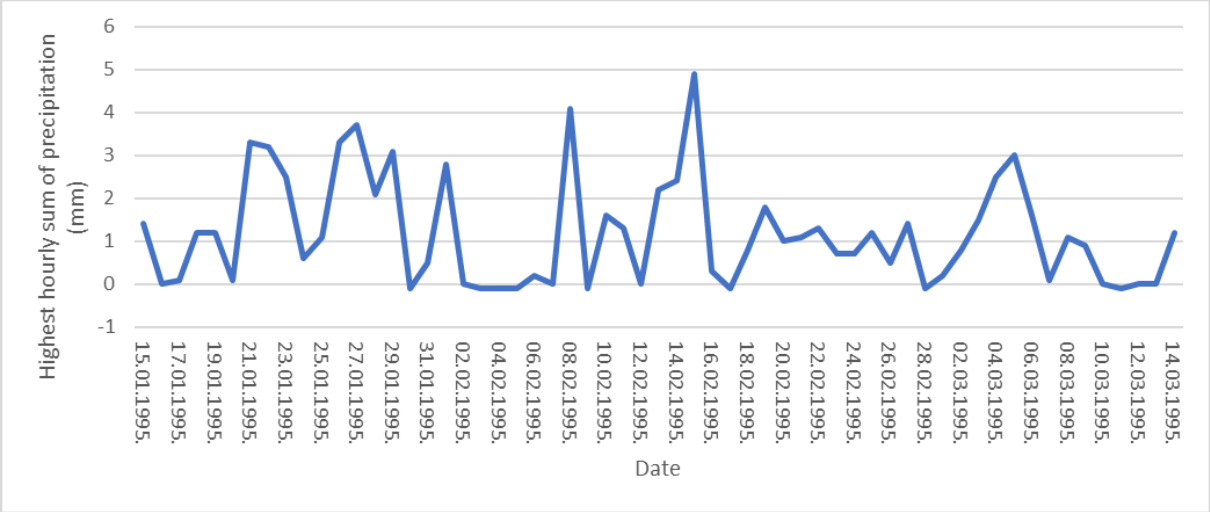


Figure 3-44 Highest hourly sum of precipitation for analysed period from 15.01.1995-15.03.1995. for weather station Rotterdam

Complex climate conditions with shifting anticyclonic and cyclonic circulations between Eastern and Western Europe and from the Atlantic Ocean led to the snowmelt, three extreme precipitation events in a short period of time intersected with intrusions of cold air (Ulbrich and Fink, 1996), see Figure 3-45.

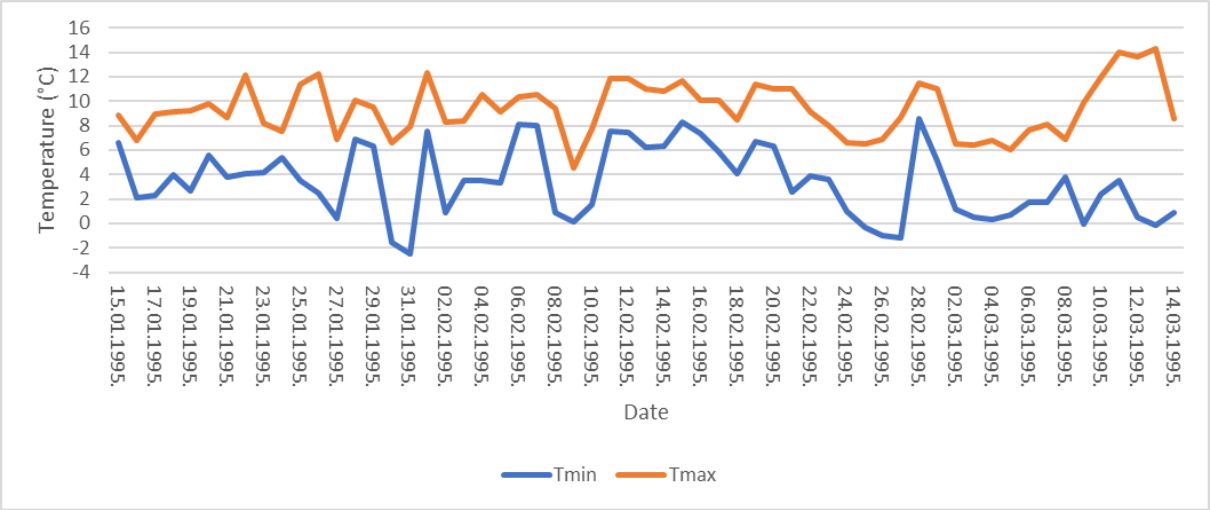


Figure 3-45 Minimum and maximum temperature for analysed period from 15.01.1995-15.03.1995. for weather station Rotterdam

3.2.4 Correlation between hydrological and meteorological data for the analysed periods

Meteorological data presented in the previous paragraph led to the rise of water levels in the whole Rhine Delta in the Netherlands. Figure 3-46 and Figure 3-47 show the water levels for the analysed periods at two measuring stations (Dordrecht and Vuren). At the same time peak discharges at Lobith (i.e. water level NAP+ 16.68 m), where the Rhine enters the Netherlands, were registered at 12,060 m^3/s (Chbab, 1996). Figure 3-48 shows rise in discharges at several stations, Rheinfelden, Worms, Mainz, Andernach, Köln, Rees, front to back, in the period from January to February (Ulbrich and Fink, 1996).

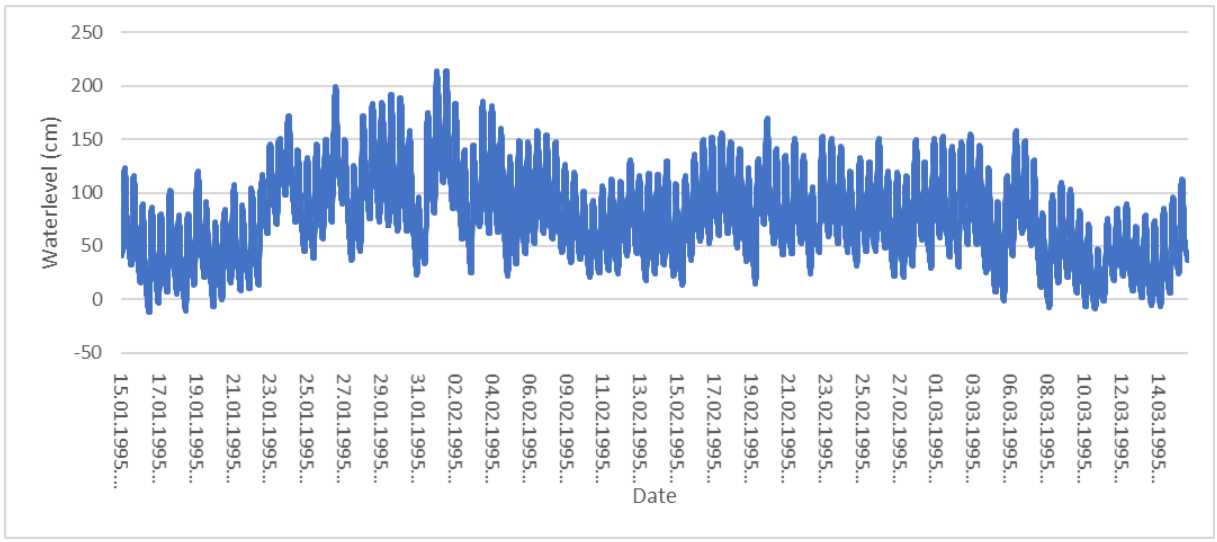


Figure 3-46 Water levels for the analysed period from 15.01.1995.-15.03.1995. for measuring station Dordrecht

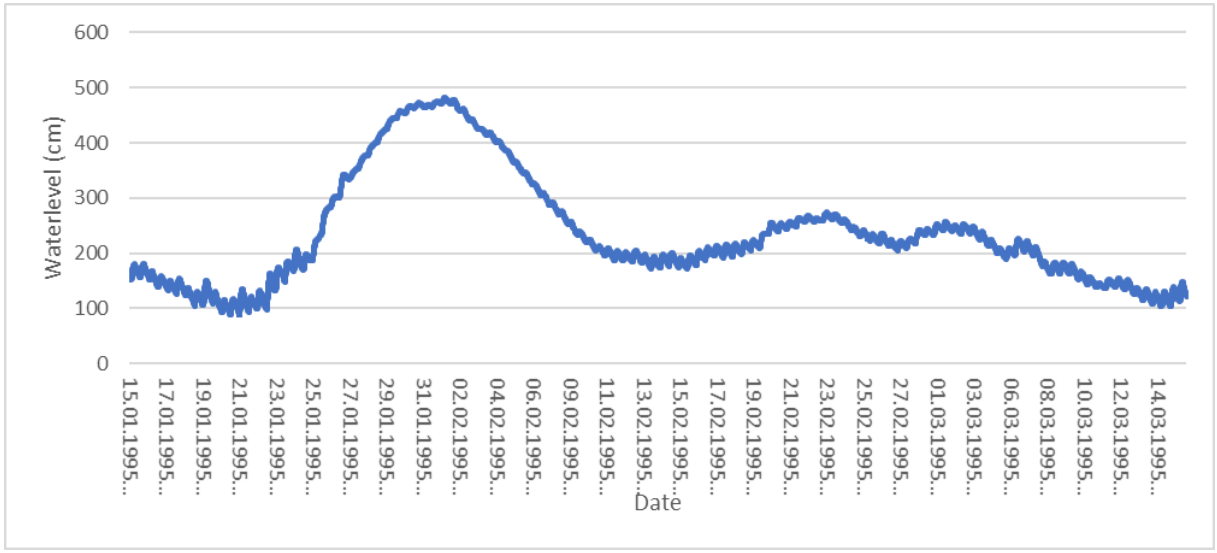


Figure 3-47 Water levels for the analysed period from 15.01.1995.-15.03.1995. for measuring station Vuren

There were three rainfall events at the end of January which caused peak discharges shown in Figure 3-48. High discharge volumes can be correlated to the rainfall events. The first event first major rainfall event started on January 22nd and lasted for about 30 hours. The second major rainfall happened on the 25th of January and the last final moderate rainfall event from January 28th to 29th resulting in the peak discharge volume of 12,060 m3/s at Lobith in the Netherlands (Chbab, 1996; Engel 1997; Ulbrich and Fink, 1996).

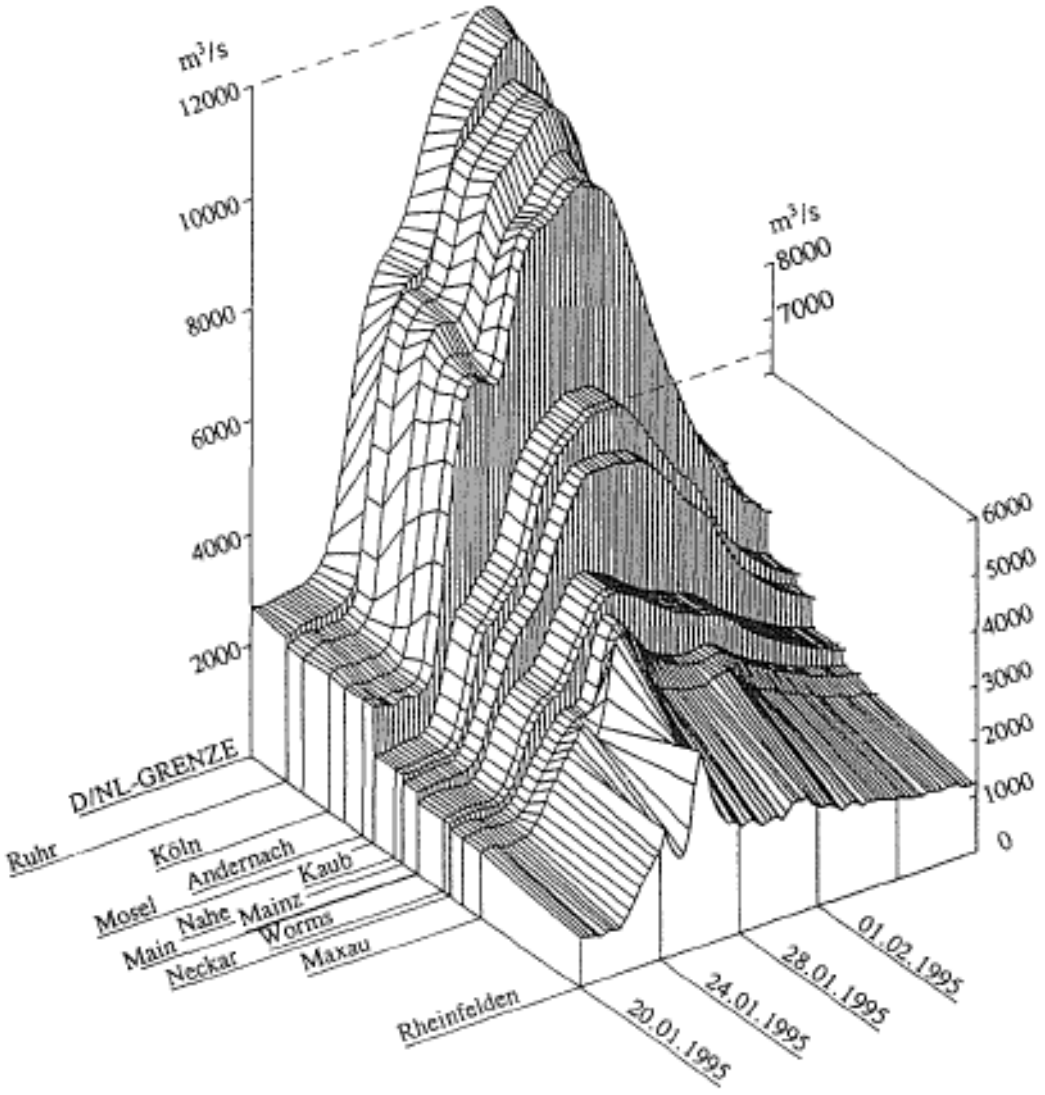


Figure 3-48 Development in time and space of the surge of the river Rhine of discharge rates at several stations for January-February 1995 (Engel, 1996)

4 Conclusion

This report analysed periods from 1990 to 2020 for the selected case study areas in the Netherlands and in Croatia. The aim was to extract the high water level and flood events, together with the weather conditions around those events. The purpose of this analysis is to identify events which led to actual or near failures in the flood protection system, and to use these in the numerical models for the prediction of the future events and dikes' performance.

In order to increase the safety of the inhabitants, the aim is to improve the methods for the condition assessment of the existing flood defence system, such as dikes and embankments, and critical infrastructure, such as bridges. Later work packages will develop methods to provide better input parameters about the existing materials, structure properties etc, that resist the loading described in this report..As a result we will be able to improve the reliability of the numerical models for probabilistic failure assessment.

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