Analysis of short-term rainfall characteristics related to the pluvial floods in the city of Zagreb

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ANALYSIS OF SHORT-TERM RAINFALL CHARACTERISTICS RELATED TO THE PLUVIAL FLOODS IN THE CITY OF ZAGREB

MASTER THESIS

Tena Kovačić

Zagreb, September, 2020.

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Summary

Of the master's thesis - student **Tena Kovačić,** entitled

ANALYSIS OF SHORT-TERM RAINFALL CHARACTERISTICS RELATED TO THE PLUVIAL FLOODS IN THE CITY OF ZAGREB

In this Master thesis, reports from civil protection and from public fire brigades of the City of Zagreb were analyzed. Technical interventions of pumping water from facilities and open urban spaces in the period 2009-2018 during extreme hydrometeorological conditions were taken into account and used as impact parameter of pluvial floods. Spatial analysis was performed and a link was made between urban land use in relation to the number of interventions as indicators of flood occurrence. For a given period, total amounts of rainfall measured at the meteorological station Maksimir were analyzed and maximums of daily precipitation for 1, 2, 3, 6, 12 and 24 hours were determined and used as flood hazard parameter for the period 2007-2017. Updated and joined database was made for rainfall and intervention data for the period 2007-2017. The aim of the thesis was to determine what intensities and duration of precipitation could be related the occurrence of flooding. Based on identified precipitation events, thresholds of the intensity and duration of critical precipitation have been determined, related to the flood indicators.

Keywords: urban floods, interventions, precipitation, limit value

1. Introduction

Pluvial urban floods are becoming more frequent and more intense in cities around the world, including Croatia (Novosel, 2020). Among other things climate change is reflected in changes of precipitation, mostly in intensity. The occurrence of floods is becoming more frequent, which causes great material damage with possible loss of human lives. Suddenness and unexpectedness, accompanied by catastrophic consequences, are the main features of all flash floods. Precipitation characterized by short durations and high intensities are main driver of urban flash floods (Bonacci and Roje-Bonacci, 2020). Flash floods can happen anywhere, although low-lying areas with poor drainage are particularly vulnerable, and that is characteristic of many urban areas. Main characteristics of flash floods hydrographs are described by Bonacci and Roje-Bonacci (2020) where the shape of the ascending and descending branches of the flood hydrograph is steep and of short duration. Therefore, flash floods occur with slight indications or without warning, and they reach critical discharges in a very short period of time. Urban floods cannot be prevented, but by taking effective preventive and operative measures, their harmful consequences can be significantly mitigated (HHD and HDON, 2012). Development and improvement of forecasting and early-warning systems is seen as one of the most effective way to mitigate the effects of urban flash floods. Information about rainfall intensities of different duration that could be linked to urban flood impacts is main input for their forecasting and development of early-warning systems. This is especially important since urban floods are usually caused by heavy short-time rainfalls (up to 6 hours) (Bonacci and Roje-Bonacci, 2020).

Research on the spatial characteristics of short-term heavy rainfall in Croatia has not yet been systematically conducted (Jurković, Nimac and Kalin, 2019). There have been certain attempts in determining thresholds for critical precipitation in relation to urban flood incidence in the city of Zagreb done by Hrastovski (2016). Study included analysis of rainfall duration that was more than 24 hours, so shorter rainfall durations that are triggering urban floods should be examined. Project RAINMAN is focusing on development of practice-oriented new tools and innovative methods to reduce the losses in the natural and built environment caused by heavy rain (*RAINMAN - Interreg,* no date). Early warning system is part of risk management of natural hazards and the most common approach consists in comparing the latest rainfall forecasts, from numerical weather predictions, with reference thresholds often derived by statistical analysis on long term records of point measurements (Alfieri *et al.*, 2012). In the absence of a flood damage database, some other indicators such as interventions are used. Cannon *et al.* (2008), and Guzzetti *et al.* (2008), developed rainfall intensity–duration thresholds for the occurrence of debris flows, landslides and floods. This methodology was later adapted by Diakakis (2012) to examine the role of storm totals, peak and average rainfall intensity, and moisture conditions in flood triggering in Greece. Papagiannaki *et al.* (2015) used similar methodology incorporating rainfall records and information on the spatial distribution of the flash flood events in order to define rainfall intensity thresholds for flood triggering. Similar methodology was used and tested in this Master thesis.

The main aim of the thesis was to determine rainfall thresholds based on the intensity which could result in flood events in urban area of Zagreb, specifically the sub-area of Maksimir at the foot of the Medvednica massif. Analysis was made by comparison and conjunction of flood impact indicators with flood hazard parameters. Data about flood impact indicators are reports about interventions related to pumping water during urban flash floods collected by public fire stations and civil protection services. In analyzed period from 2007 to 2017, 989 interventions were recorded throughout the whole city of Zagreb. In the specific analyzed research area that was selected as a smaller part of watershed, 331 interventions were documented. Flood impact parameters are made by analysis of precipitation data. Precipitation data from the meteorological station Maksimir was obtained from the Croatian Meteorological and Hydrological Service. Out of 764 rainfall evets, hourly precipitation data was analyzed and maximum of accumulated rain was calculated for durations of 1, 2, 3, 6, 12 and 24 hours. Rainfall events were separated in groups of related and non-related with flood indicators. Rainfall intensity-duration thresholds for occurrence of pluvial floods were determined by plotting peak rainfall intensities of various time intervals vs. their respective durations for two groups of rainfall events.

The research area was the area of the City of Zagreb, the capital of Croatia, and a detailed analysis was conducted for the Maksimir area within a radius of 4,2 km around meteorological station. This radius was taken to fit in the scale of denoted watershed. Land use analysis for mentioned area was performed to establish the link between urbanization and permeability of surfaces with surface runoff and flooding. On basis of obtained reports from fire brigades about interventions, dates and addresses of water pumping interventions from facilities and open spaces, a cartographic database of interventions together with spatial analyzes, was made.

In following chapters an overview of the main concepts related to the urban floods will be presented with main definitions and factors impacting urban floods. Climate change and rainfall patterns will be mentioned together with proposition on mitigating flood impact. Data collection and study area will be given as well as historical background of floods in Zagreb. Methodology and analysis will be described following with discussion and presentation of results. A review of the problems that could possibly be a cause of flash floods was given accompanied by potential solutions and their application. In discussion the problems during the preparation of the thesis are mentioned as well as possible application of the results and suggestions for further research.

2. Overview of the main concepts related to the urban floods

2.1. Flood

A flood is the accumulation of water over normally dry land. It is caused by the overflow of inland waters (like rivers and streams) or tidal waters, or by an unusual accumulation of water from sources such as heavy rains or dam or levee breaches. Floods are among most common natural disasters (*Flooding and Climate Change: Everything You Need to Know | NRDC*, no date).

2.2. Urban flooding

Flash floods can occur in urban areas, but the term “urban flooding” refers specifically to flooding that occurs when rainfall, not an overflowing body of water, overwhelms the local stormwater drainage capacity of a densely populated area. This happens when rainfall runoff is channeled from roads, parking lots, buildings, and other impervious surfaces to storm drains and sewers that cannot handle the volume (*Flooding and Climate Change: Everything You Need to Know | NRDC*, no date).

There is a general consensus that growth in impervious cover reduces infiltration and increases runoff and flood magnitudes (Blum *et al.*, 2020). With growing population and rapid urbanization impervious area will only increase and residential area will be more susceptible to flood damages.

Due to inadequate spatial planning and uncontrolled urbanization which involves over-concreting and paving large sections of space, the share of impermeable surfaces is extremely increased, which leads to an increase of runoff coefficient and results in several times higher rainfall water that concentrates on urban surfaces (Novosel, 2020).

Water infiltration below the surface of the terrain in urban areas is reduced or disabled, figure 1. Drainage sewerage is dimensioned for low return periods, usually 2 to 3 to a maximum of 10 years. Urbanization on identical surfaces and for identical precipitation cause a significant reduction in concentration time and a large increase in the movement of water velocity on the surface. The relationship between the time of basin concentration and the duration of intense precipitation plays a key role in the formation of the maximum value of flood hydrographs. The basin concentration time is the time required for a drop of effective precipitation to come from the furthest point of the basin to the analyzed profile. Effective precipitation is precipitation which participates in the formation of the direct runoff hydrograph (Bonacci and Roje-Bonacci, 2020).

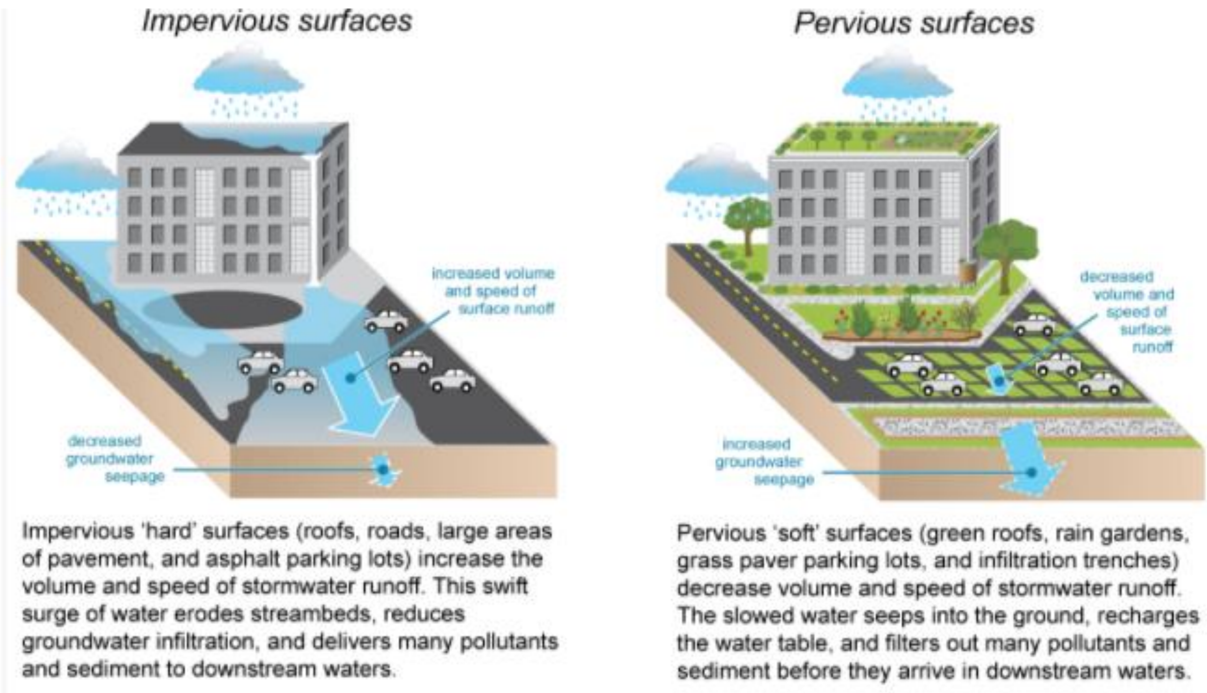

Figure 1. Conceptual diagram illustrating impervious and pervious surfaces

Source: http://managingstormwater.blogspot.com/

In urban areas, the characteristics and areas of catchments often change rapidly, and thus the time of concentration. This makes it significantly more difficult to create reliable abrupt models of urban floods and thus their control. The rising time of flash floods hydrographs is considerably shorter than it was before urbanization, figure 2. The values of maximum flows can be multiple times larger. As a result, certain parts of cities are flooded more often and torrents are formed on the steep city streets (Bonacci and Roje-Bonacci, 2020).

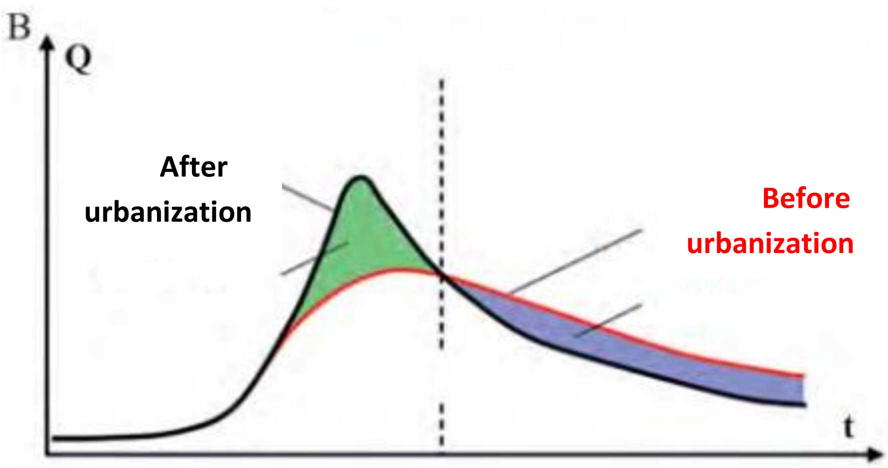

Figure 2. Influence of urbanization on flood hydrograph

Source: adjusted from Bonacci, O. and Roje-Bonacci, T. (2020) 'INŽENJERSKO HIDROLOŠKI VIDOVI POPLAVE ZAGREBA', *Hrvatska vodoprivreda*, (232), pp. 57–61.

Factors that influence shape and formation, maximum flows and flood hydrogram volume are (Bonacci and Roje-Bonacci, 2020):

(1) Precipitation intensity and duration;

(2) Topographic characteristics of the basin (steep slopes, plain terrains, natural or artificial depressions, etc.);

(3) Basin shape (elongated, concentrated, stretched);

(4) The direction of the storm;

(5) Previous ground humidity;

(6) Geological properties and conditions of the terrain surface (karst, vegetation, groundwater level, etc.)

These factors that affect the formation of flash floods, especially urban ones, are the reason why the return periods of intense precipitation does not coincide with the return the periods of floodings that were caused by them (Bonacci and Roje-Bonacci, 2020).

2.3. Climate change and rainfall patterns

Meteorological and climate factors that influence on rainfall patterns are also connected to the urban floods. Climatic changes are responsible for these varying and undetermined rainfall patters. Generally, the atmosphere absorbs the water and moisture from the earth's surface and the rainfall occurs. But, nowadays, the pattern of absorbing moisture has changed. Sometimes, the water is absorbed in higher amounts and sometimes in very little amounts (*Varying Rainfall Patterns and its Impact – iCrowdNewswire*, no date).

Rainfall patterns can be represented spatially as isohyetal maps prepared by interpolating rainfall data at gaged points or temporally by rainfall hyetograph which is plot of rainfall depth or intensity as a function of time; cumulative rainfall hyetograph or rainfall mass curve (Figure 3) that is a plot of summation of rainfall increments as a function of time and a rainfall intensity which is depth of rainfall per unit time (Potočki,K. 2018).

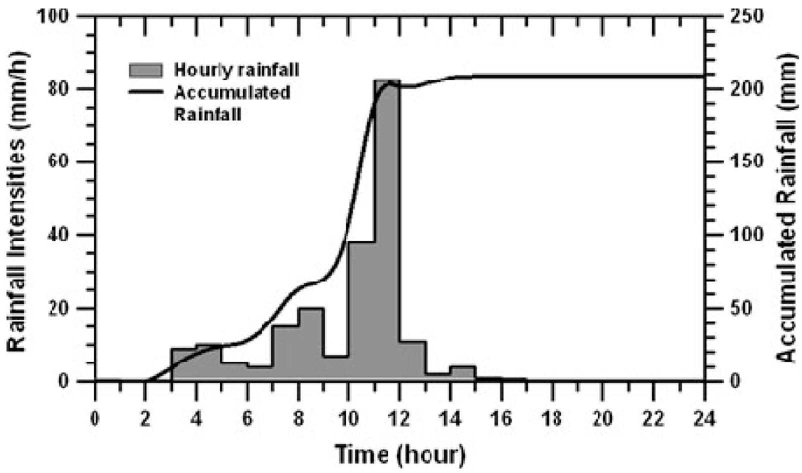

Figure 3. Representation of rainfall pattern by rainfall hyetograph for intensities (bars) and cumulative hyetograph for accumulated rainfall (line)

Source: Muntohar, A. S., & Liao, H. J. (2010). Rainfall infiltration: infinite slope model for landslides triggering by rainstorm. Natural hazards, 54(3), 967-984.

Intensity-Duration-Frequency (IDF) curves describe the relationship between rainfall intensity, rainfall duration, and return period (or its inverse, probability of exceedance). IDF curves are obtained through frequency analysis of rainfall observations (Colorado State University, 2015) and give an information on flood probability.

2.4. Urban drainage systems and urban floods

The causes of flooding are varied, from above mentioned urban watershed characteristics and meteorological factors to the urban infrastructure. Effects of most causes can be managed if not prevented. Some of the factors related to the urban floods are related to the urban drainage systems and are mentioned below.

2.4.1. Combined drainage system

Sewage collection system of pipes and tunnels designed to simultaneously collect surface runoff, sewage water and streams flow from the nearby hills which are collected in a shared system (*Combined sewer - Wikipedia*, no date). When the capacity of the interceptors is reached, overflows occur to the receiving waters (Tchobanoglous, Burton and Stensel, 1991). Many cities like Zagreb continue to operate on previously constructed combined sewer systems which is outdated in modern terms.

2.4.2. Lack of maintenance of drainage systems

Dimensions of underground pipes, but also open regulated channels can evacuate limited amounts of water defined by projects done several decades ago. Even in cases where they are regulary maintained, water inflows after flash floods can significantly exceed their projected capacity. Due to age and insufficient maintenance, but also due to clogging of the inlet openings through which water from the surface enters the underground, various alluvium during floods, their capacity becomes significantly lower than designed which causes flooding and damage to the upstream parts of urban stream basins. In parts where open regulated channels of urban streams function, natural flooded areas are mostly excluded. This fact affects reshaping of the flood hydrogram and a significant increase in its maximum flow, which can be seen in the figure 2 (Bonacci and Roje-Bonacci, 2020).

Current state of drainage and sewage system in Zagreb is described in Andročec et. al. (2016). Major problem is an outdated infrastructure. Zagreb has about 30,000 kilometers of water pipes. Most of them are made of asbestos, concrete or PVC. These pipes rupture due to wear and tear, water leaks out and applies sand to other pipes that burst under weight, ultimately leading to flooding during heavy rains or pavements collapse (*Jutarnji list - Zašto se toliko vode izlilo u centru Zagreba: Ovo su četiri ključna uzroka velike poplave*, no date). Some additional factors that caused urban flood are detected: parts of system cannot withstand high water pressure in a short time. The water flows into the main system until it is overloaded, then the water begins to return. One of solutions is the installation of pumping stations in problematic areas. Roots of trees penetrate into sewer and water pipes and thus damage the pipes. To inspect the pipes, cameras and robots are used to cut such roots and thus clean the pipes. Maintenance and upgrading of infrastructure are the key to managing a large amount of precipitation in a short time (Jutarnji list - Zašto se toliko vode izlilo u centru Zagreba: Ovo su četiri ključna uzroka velike poplave, no date; Andročec, Kuspilić and Nakić, 2016)

2.5. Flood risk and legal framework

Flood risk is the combination of the probability of a flood event and of the potential adverse consequences to human health, the environment, cultural heritage and economic activity associated with a flood event (van Alphen *et al.*, 2009). Return periods are often used to describe how often a flooding event will occur. Return periods are an average of how often a flood event of that magnitude will occur, and so the probability or chance of flooding should be used instead (*Flood risk and flood risk management | Local Government Association*, no date). Main results of flood risk analysis are flood risk maps which are demanded by the EU Flood Risk Directive 2007/60/EC for events with low, medium and high frequency. The Directive is carried out in coordination with the Water Framework Directive. Responsibility of implementation of the Floods directive lays on authorities at national, regional, local and at catchment level. They are involved in designing the optimal measures needed to reduce flood risk in the area with preparedness and response in time. Decision makers are responsible for deciding which measures should be implemented and when ('Towards Better Environmental Options for Flood risk management Why this initiative ?')

There are many drivers that offset floods including financial and social risk. Flood risk is based based on historical data as well as on a number of factors such as rainfall, river-flow and tidal-surge data, topography, flood-control measures, and changes due to building and development (*Flood Insurance: Flood - 'The Legal Definition' - FloodSmart Insurance*, no date). The best way to mitigate floods depends on how well changes in flood risk can be predicted at short and long timescales (Merz *et al.*, 2014).

Flood risk maps are main results of flood risk analysis and should show potential adverse consequences associated with the flood scenarios presented in the flood hazard maps, expressed in the indicative numbers of inhabitants potentially affected, the type of economic activity, installations that may cause accidental pollution in case of flooding and potentially affected protected areas, like nature reserves (van Alphen *et al.*, 2009). Mapping heavy rain hazards and risks helps to communicate the topic e.g. to citizens or emergency management units in the municipality (Interreg Central Europe-Rainman, 2020).

According to the Water Act, Croatian Waters are obliged to prepare flood risk maps for Croatian territory. Pluvial urban floods are still not included in the flood risk maps but results obtained and showed in this work could be incorporated and partly used in pluvial flood risk scenarios in the city of Zagreb.

2.6. Heavy Rain Risk Management and Spatial Planning with outlook on Croatia

Legal basis for spatial planning in the Republic of Croatia is the Physical Planning Act passed by the Croatian Parliament on 6 December 2013. The responsibility for the national level lies with the Ministry of Construction and Physical Planning, which recently has started with the preparation of the National Development Strategy of the Republic of Croatia by 2030. Apart from this, yet there are no binding planning instruments for the national level in force. An integral part of the spatial plan of a county or the City of Zagreb may also be the spatial plan of areas with special features for areas with natural values of the county or City level determined by a special law (Scharmann and Cibili, 2020).

The spatial plans and river basin management plans have a significant role in the flood risk limitation and reduction through the reduction of a potential number of people and goods exposed to the risk. Since the biggest problems continue to be the built-up areas and the existing values exposed to heavy rain events, the main challenge is their adaptation (e.g. gradual replacement of a combined sewer system with a separate one), reorganization and change of use. In the un-built parts of the basins it is possible to reserve space for the implementation of flood risk reduction measures (e.g. a retention basin), and construction can be restricted in the critical zones. If that is not possible, for example due to property rights issues, it is recommended to familiarize potential users of space with the hazards or realistic scenarios in the specific area (Scharmann and Cibili, 2020).

In preparation of the National Development Strategy of the Republic of Croatia by 2030 the Ministry of Construction and Physical Planning is being involved in the green infrastructure theme. Following this, the ministry highlights the theme of Green Cities, with two specific sub-themes: Green infrastructure in urban areas and circular management of space and buildings, with both themes having an unquestionable impact on the territory and landscape (Scharmann and Cibili, 2020).

2.7. Methods of mitigating flood impact in urban environment

For flood prevention, protection and mitigation, a good combination of structural measures, preventive measures and operative measures during flood events are necessary: building codes and legislation to keep structures away from flood prone areas, appropriate land use, adequately designed flood plains and flood control structures planning, mitigation, early-warning systems, correct risk communication and preparedness of the populations on how to act during floods. Flood forecasting can be effectively combined with other measures for flood prevention such as retention, land use and structural measures, flood emergency and public awareness. (E. Union, 2003).

2.7.1. Green infrastructure

Use of nature-based solutions and green infrastructure are one of the ways in fighting floods and are becoming more popular as additional solution to the existing technical (engineering based) measures. Similar concept is presented through Natural water retention measures - they cover wide range of actions that are implemented by different sectors or considered in different planning processes dealing with water, flood risk management, biodiversity protection, climate change adaptation or urban planning. Some of these measures aim to directly modify the ecosystem, while others focus on changes of practice of economic factors, figure 4.

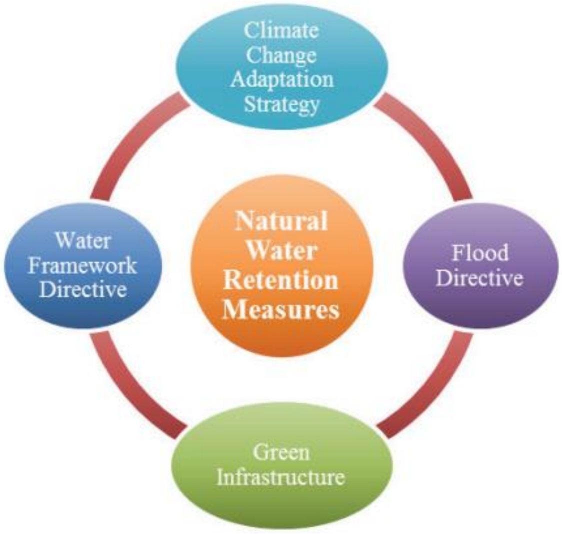

Figure 4. Natural water retention measures and selected EU policy initiatives

Source: Martina Zeleňáková, Daniel Constantin Diaconu, Ketil Haarstad: Urban Water Retention Measures, Procedia Engineering (2017)

Green infrastructure is a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation and climate mitigation and adaptation. This network of green (land) and blue (water) spaces can improve environmental conditions and therefore citizens' health and quality of life. In urban areas green infrastructure includes green roofs, rain water harvesting, permeable surfaces, swales, channels and rills, filter strips, soakaways, infiltration trenches, rain gardens, detention basins, retention ponds and infiltration basins (*Green Infrastructure - Environment - European Commission, no date*).

3. Floods in Zagreb area

The case of urban floods occurring in Zagreb is specific. Urbanization has affected the slopes of Medvednica and flash floods are partly developing in the urbanized area, and partly are caused by water pouring out of about thirty so-called Zagreb streams flowing along the southern and southeastern slopes of Medvednica massif into the city, figure 5. (Bonacci and Roje-Bonacci, 2020). This fact clearly indicates specificity and rapid change of conditions that are responsible for flash floods, and thus the exposure of the city of Zagreb to possible future urban falsh floods.

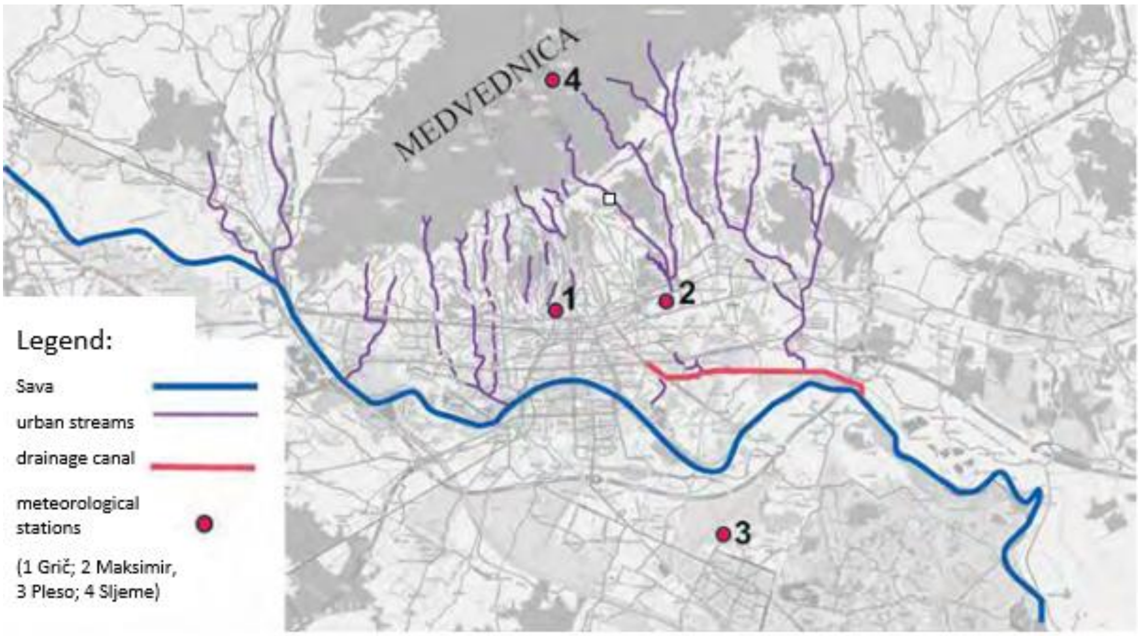

Figure 5. Overview of watercourses, canals and hydrological stations in the city of Zagreb

Source: Bonacci, O. and Roje-Bonacci, T. (2020) 'INŽENJERSKO HIDROLOŠKI VIDOVI POPLAVE ZAGREBA', Hrvatska vodoprivreda, (232), pp. 57–61.

3.1. History of flood events in the City of Zagreb

The city of Zagreb has experienced several flooding events throughout its history due to the high waters of the Sava River, and streams from mountain Medvednica. The first recorded flooding of the area of the city of Zagreb happened due to high waters of Sava river that occurred in 1469, while the first flood caused by streams from Medvednica was recorded in 1645. A few years later, on July 26th 1651, a flood that took 52 lives was recorded in the area of the town, and in 1656 the waters of the stream from Medvednica rushed through the town. The Sava River flooded the city again in 1716. During 1750, 1751, and 1770, floods from Medvešćak stream were recorded, followed by a series of flood years by all streams from Medvednica massif, in 1845, 1850, 1859 and 1864 (Vujasinović, 2015).

Urban development of Zagreb is a typical example of construction of the city in the area along the river endangered by floods. In beginning of the last century, the city located in the higher parts of the lowlands along the Sava River, did not suffer much damage from the river overflow. To eliminate possible damage due to gradual expansion of the city into the lowlands along the river, and more intensive use of land, need for planning and construction of facilities to eliminate the harmful effects of water was required. The process of settlement, construction and use of inundation areas along the Sava River was much faster than the construction of flood protection facilities, which resulted in the catastrophic flood in October 1964 (Vujasinović, 2015). A representation of that flood can be found in figure 6.

The cause of this flood was heavy six-day precipitation in the upstream part of the basin in Slovenia, which fell on saturated soil that could not accept all that amount, and rainwater flowed into the Sava. Only partially built protection system, inadequate, inconsistent and vulnerable, could not withstand the onslaught of high water, and large areas of the city were flooded, mostly on the left bank. This flood has so far been recorded as one of the largest natural disasters of its kind in Zagreb, both in terms of the number of human casualties and the great material damage it caused. 17 lives were lost, 40 000 people were left homeless. 10 000 apartments, 3297 buildings were destroyed and 120 companies were damaged. Around 2 km of motorways, 81 substations were destroyed, and 65% of the city's material from construction land warehouses as well as many other material was lost. 14 km long and 4 km wide, the flooded area covered 6,000 ha. Estimated damage was 160,000 billion dinars at the time, which was about 9.18% of the republic's GDP (Vujasinović, 2015).

Figure 6. Flood in Zagreb in 1964

Source: https://www.voda.hr/sites/default/files/pdf_clanka/hv110_-_strucni_prikaz_-_marusic.pdf

3.2. Urbanization

The main drainage system of the central part of Zagreb was built at the turn of the 18th and 19th centuries. Uncontrolled urbanization leads to excessive pressure and undertaking of the drainage system which is calculated on the basis of the current number of inhabitants and residential buildings. More than a hundred years ago, those numbers were much lower and today they are incomparable to those when the system was being built, figure 7 (*Jutarnji list - Zašto se toliko vode izlilo u centru Zagreba: Ovo su četiri ključna uzroka velike poplave*, no date; Andročec et al., 2016)

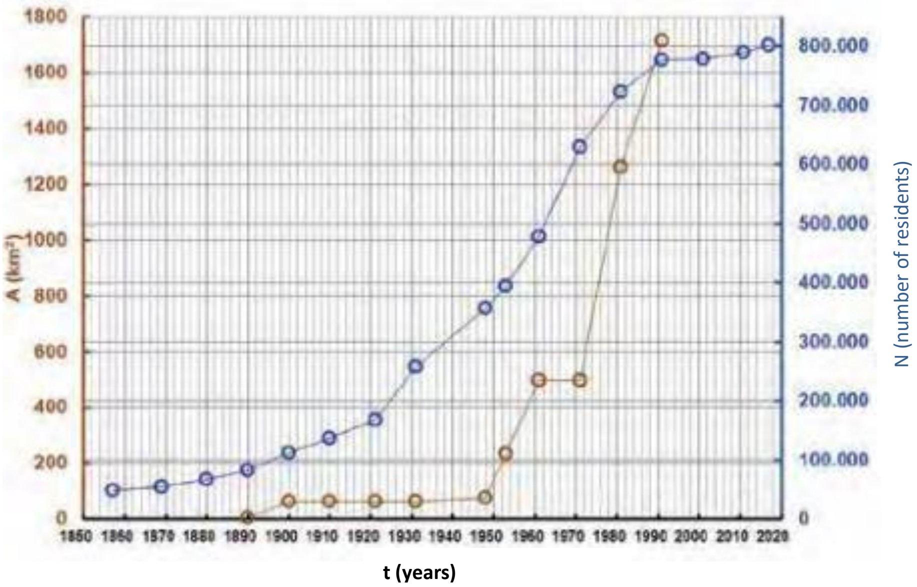

Figure 7. An overview of population growth from 1856 and the expansion of the city of Zagreb from 1890

Source: Bonacci, O. and Roje-Bonacci, T. (2020) 'INŽENJERSKO HIDROLOŠKI VIDOVI POPLAVE ZAGREBA', *Hrvatska vodoprivreda*, (232), pp. 57–61.

3.3. Flood protection in the City of Zagreb

The reason for the concentration of rainwater occurrences in city of Zagreb is due to heavy rainfall inflow to torrential watercourses that stretch from the mountain massif of Medvednica to the city center, as well to the city rainwater drainage system (Rubinić *et al.*, 2019). According to Marin Galijot from Zagreb Water Supply, city's public sewerage system has more than 2,200 kilometers of public canals, and 20 percent forms the backbone of the system. These canals receive all rainwater that comes from Medvednica massif.

A series of measures can reduce the flood damage that is inevitable. The solutions that are proposed and implemented must foresee the consequences for the upstream and downstream part of the flow in relation to the place where the works on the watercourse are performed. Immediate measures for the construction and creation of a system for manipulating large waters consist of several facilities like reservoirs, retentions, open canals, embankments, etc. (Tropan, 1994).

Project solutions made in 1899 and 1905, and from 1990 to 1918, carried out regulatory works on the Sava river, by which most of the current route of the riverbed in the area of Zagreb was formed. With the urban development and expansion of Zagreb followed the necessity to upgrade existing, building of new embankments and other water structures to protect or reduce flood damage. After the flood in 1964 a revision of the study and project documentation followed to upgrade embankment for higher level and safer protection from flood waters of the Sava river, as well as part of the torrential watercourses from Medvednica. Today's flood embankment system was built on the basis of 1000-year flood event together with the function of the Jankomir overflow and the Odra discharge canal, shown on figure 8. (Marušić, 2019).

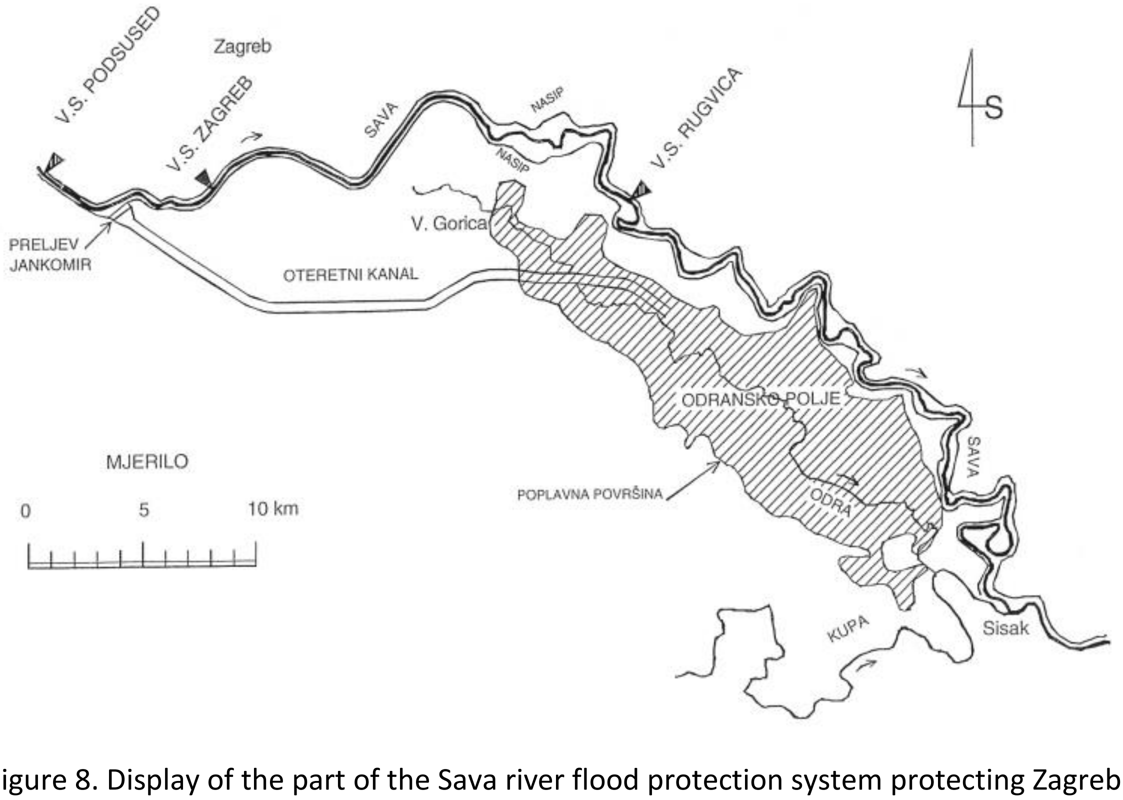

Figure 8. Display of the part of the Sava river flood protection system protecting Zagreb urban area from Podsused to Sisak with the Jankomir spillway

Source:https://www.voda.hr/sites/default/files/pdf_clanka/hv110_-_strucni_prikaz_-_marusic.pdf

4. Data and Methodology

4.1. Data collection

For the purpose of this Master thesis data from multiple sources had to be collected in order to be examined. Below is a list of collected data with sources.

Flood hazard data

- Daily precipitation (mm per day), from 2007 to 2017 for meteorological station Maksimir
- Hourly precipitation (mm per hour), from 2007 to 2017 for meteorological station Maksimir

Source: Croatian Meteorological and Hydrological Service.

Flood impact data

- Intervention logs from 2007 to 2018. Data of intervention location, date, time, cause and type of intervention for the administrative area of the city of Zagreb

Source: Public Fire Department Zagreb and the National Protection and Rescue Directorate.

Source: National Protection and Rescue Directorate

Spatial data

- Land use data – layer database with spatial information of land areas in Zagreb.

Source: Zagreb City Office for Strategic Planning and City Development.

After obtaining relevant input data from The Meteorological and hydrological service of Croatia and Public Fire Department Zagreb it was necessary to check and format data for later use. Intervention data contained all interventions in the period from 2007 to 2017, and many of them weren't related by rainfall events. It was necessary to filter them out so only relevant data remained. For these remaining interventions, the given addresses in text form needed to be transformed to geographical coordinates for later spatial analysis in the Quantum GIS software. This was done by implementing the Google geocoding API together with an Excel script to translate written addresses to latitude and longitude.

Rainfall data needed to be prepared in a similar manner. From the hourly precipitation data given in a txt file. It was necessary to extract precipitation data for each day and hour of the observed timeframe. The precipitation data was a basis for calculating accumulated rainfall in the span of 1 2, 3, 6, 12 and 24 hours. It was necessary to identify rainfall events after that. Various authors have different approaches to defining a rainfall event. As this paper is heavily based on the findings of Papagiannaki *et al.* (2015) their definition of a rainfall event was taken as relevant. By this definition a rainfall event is defined as precipitation which was proceeded by 24h without rain. For each such rainfall event the respective maximal accumulated rainfall was determined for the given timeframes of 1h to 24h. For each of the 764 rainfall events it was investigated whether they resulted in interventions, by cross-referencing rainfall events with intervention data.

The peak storm intensity plot was created based on max accumulated rainfall data for each rainfall event by dividing the max accumulated rainfall with the respective duration to obtain the intensity. The data was divided in two groups, one with rainfall events which caused floods and the second which didn't. Next it was necessary to determine a threshold. An empirical approach was taken based on other authors, but other methods were briefly considered as basis for future research. As a control mechanism the resulting thresholds were analyzed with a rudimentary correctness assessment to draw conclusions.

4.2. Data processing

Flood risk, as combination of flood event probability and of the potential adverse consequences to human health, can be evaluated by analyzing two distinct but connected datasets. The first dataset are flood impact indicators and second are flood hazard parameters. By cross-referencing them one can draw conclusions about possible indicators of flood risk.

Rainfall data for the meteorological station Maksimir has been analyzed as part of this thesis. Data from year 2007 to 2017 was available thanks to The Meteorological and hydrological service of Croatia. This raw data first needed to be formatted and processed to be useful in future calculations. The raw rainfall data was in a txt format containing rainfall quantities and time data in hours. For each day a cluster of data was processed to prepare hourly precipitation values for later analysis. This served as the input for calculating maximum accumulated rainfall over various durations. Improvements could be made in the logging process to make later processing of data easier.

Public Fire Department Zagreb and the National Protection and Rescue Directorate made available data about interventions in that period. Since the data contained interventions with various causes it was necessary to filter out unnecessary data. The remainder of data was processed to draw conclusions about the rainfall intensity thresholds that cause flash floods in Zagreb. Many interventions had inconclusive causes and it would be helpful for future research to determine a basic notation system for intervention causes, duration and location.

Inconclusive, interventions and following causes and consequences were double checked by reviewing newspaper reports.

To distinguish different events rainfall data was grouped in rainfall events based on the works of Papagiannaki *et al.* (2015). For each rainfall event the maximal intensity for the duration of 1, 2, 3, 6, 12 and 24 h were calculated to visualize the threshold for which flood events occur.

Data used for landscape analysis was available thanks to the Zagreb City Office for Strategic Planning and City Development. Layers that contained purpose and land development were provided and analyzed in Quantum GIS platform.

4.3. Spatial analysis of interventions

In the period from 2007 to 2017 the Public fire department of Zagreb recorded 989 interventions in Zagreb relatable to rainfall. Based on the recorded addresses a graphical representation of these interventions has been created, figure 9.

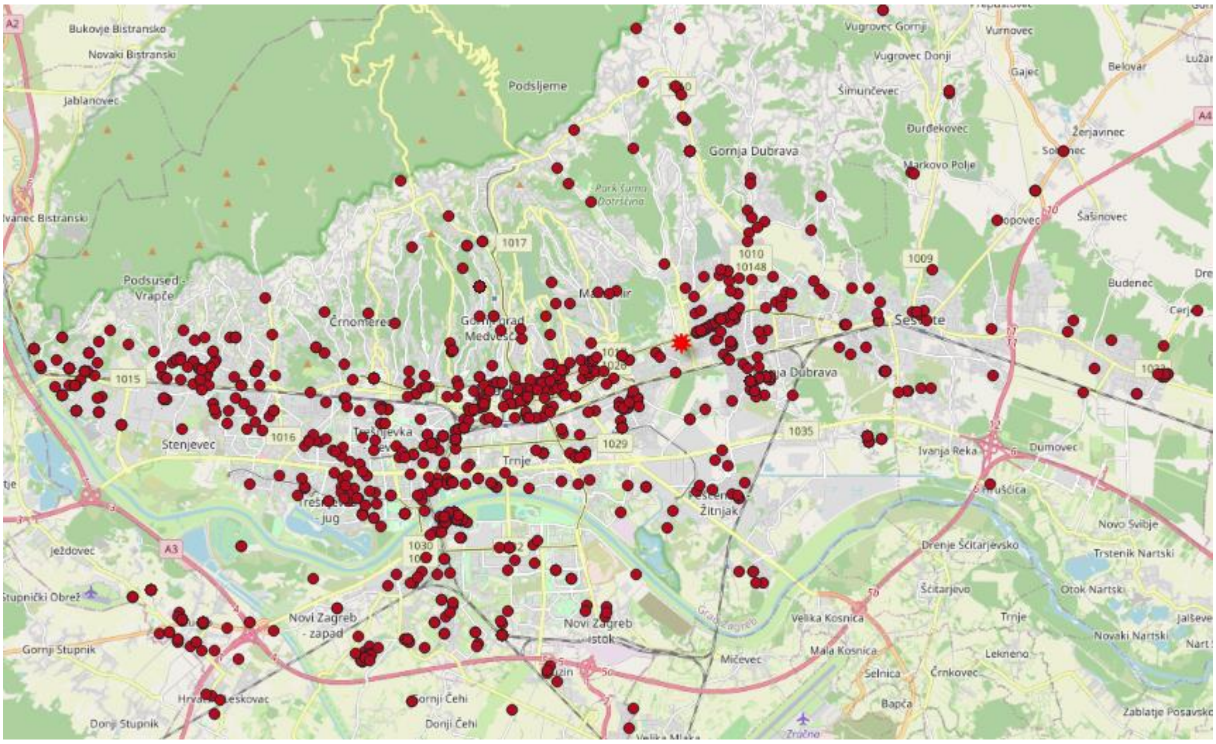

Figure 9. Interventions recorded by the Public fire department of Zagreb (red dots) in the period from 2007 to 2017, related to rainfall events. Location of meteorological station Maksimir is marked as red star.

Since a single measuring station does not adequately represent rainfall data throughout the city of Zagreb, the study has been limited to the watershed with an area of 142,8 km^2, which contains the meteorological station Maksimir (denoted by star in figures).

Most of these interventions however can be observed in a radius of 4,2 km around the meteorological station where high urbanization and population density can be observed. Out of 331 interventions within the watershed, 273 (82%) are in the 8,4 km circle around the meteorological station, figure 10. Work of other authors (Potter and Colman, 2003) indicated that flash floods occur on a local scale from 10 up to 1000 km^2. Since geographical characteristics of the analyzed area have an impact on precipitation events the watershed area has been evaluated with related interventions. Microclimatic phenomena have an increased impact on urban environments. Therefore, a smaller area around the meteorological station has been selected to reliably represent rainfall data and its impact on flash floods. A circle with diameter of 8.4 km (area of 55.4 km^2) has been chosen because it fits well into the watershed to simultaneously consider the effects of runoff on the occurrence of flash floods in urban areas. Furthermore, with the increase in altitude towards Medvednica massif and moving away from the meteorological station, local heavy showers can significantly change their character and duration (Bonacci, 1994).

The National Digital Forecast Database (NDFD) uses 5 km grid to represent weather data (Glahn and Ruth, 2003) including rainfall, which suggest that rainfall data from the meteorological station Maksimir adequately represent rainfall data within the selected circle, area of 55,4 km^2.

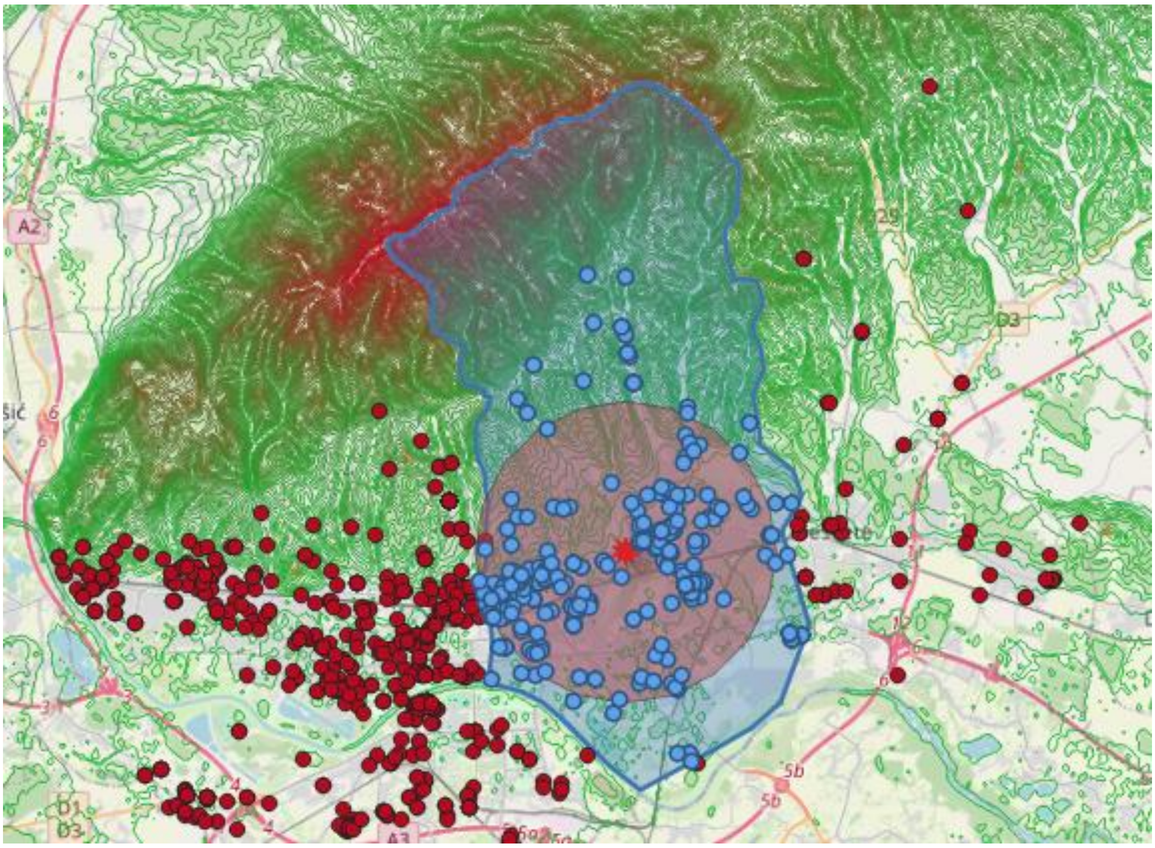

Figure 10. Interventions within watershed boundary

City Office for Strategic Planning and City Development made available data about the level of urbanization and land use of the affected flood areas. By analyzing the purpose of land area within this circle it can be observed that the land is mostly developed with only 37% of 54 km^2 being undeveloped. Most of the undeveloped land is agriculture (21%) and forests (7%). Of the developed areas the largest share are residential areas (34%), commercial (13%) and traffic areas (8%), figures 11, 12, 13 and 14. Figure 12 shows that 96% of interventions occurred at mostly developed urbanized area where majority of surfaces are impermeable. Similar observations can be seen on figure 15 showing that 57% of interventions occurred at residential and miscellaneous area and 28% of interventions were noted at traffic area.

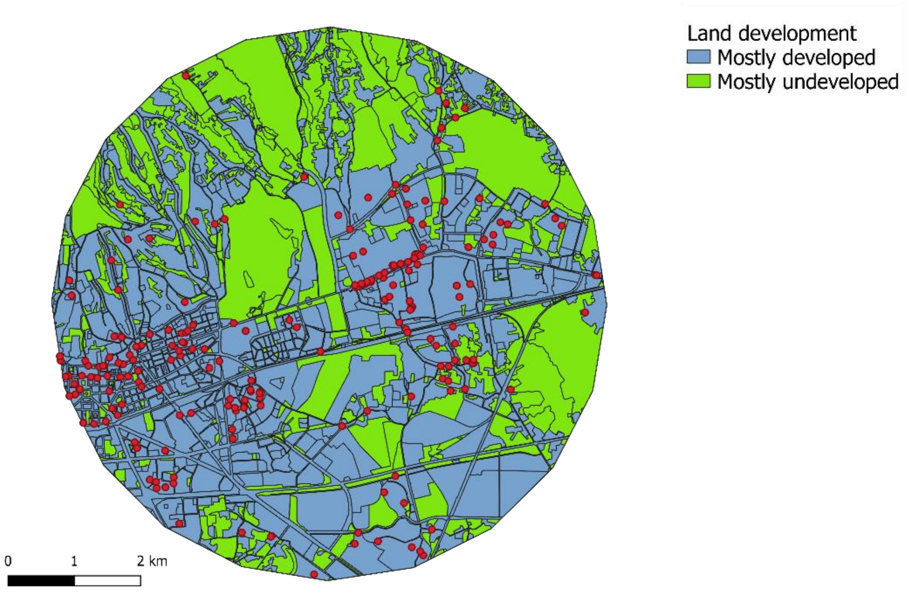

Figure 11. Land area by development

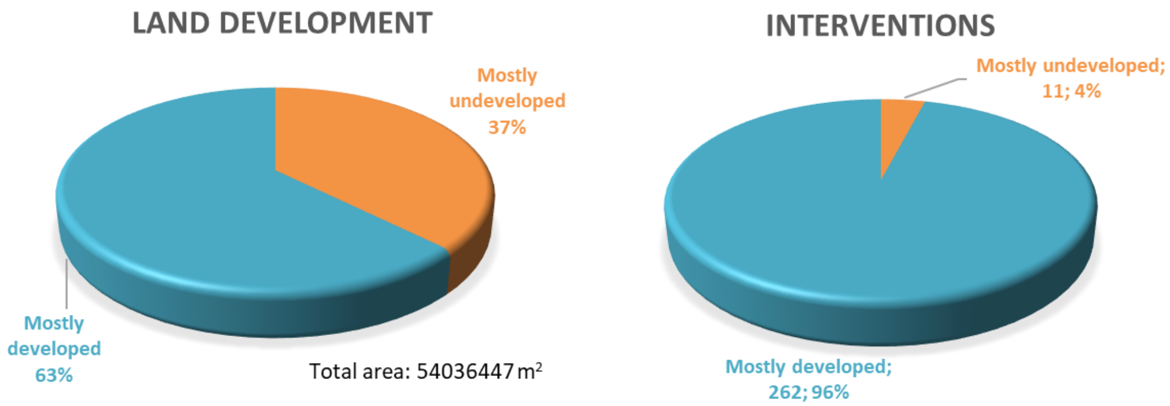

Figure 12. Land development as percentage of total area and number of interventions per development category

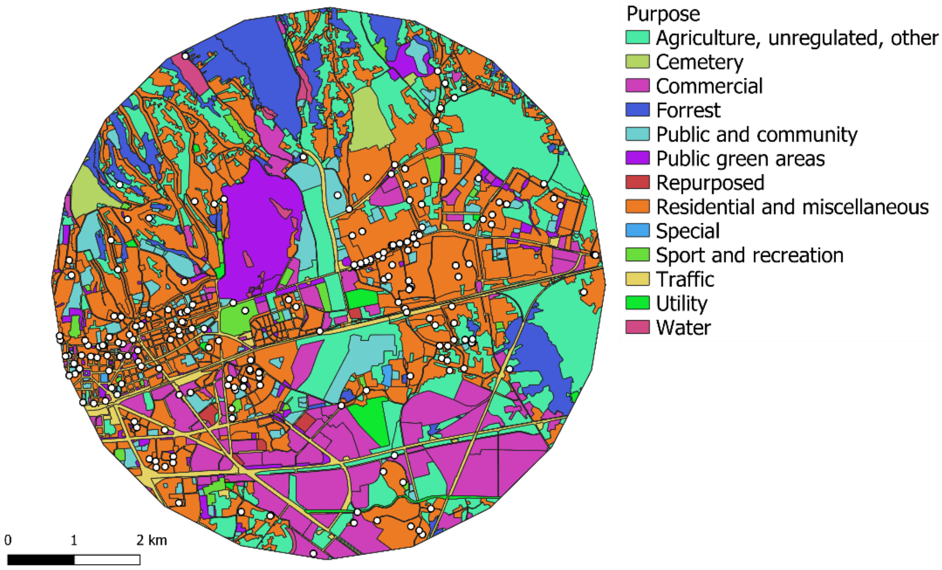

Figure 13. Land area by purpose

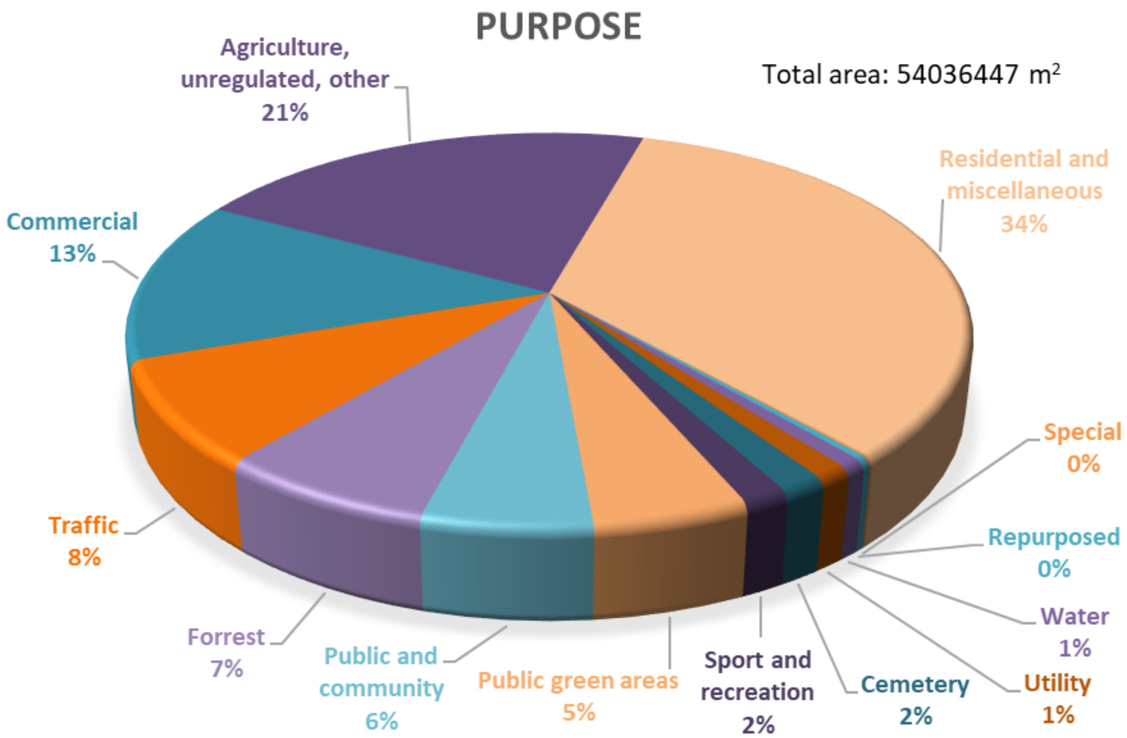

Figure 14. Land area by purpose as percentage of total area

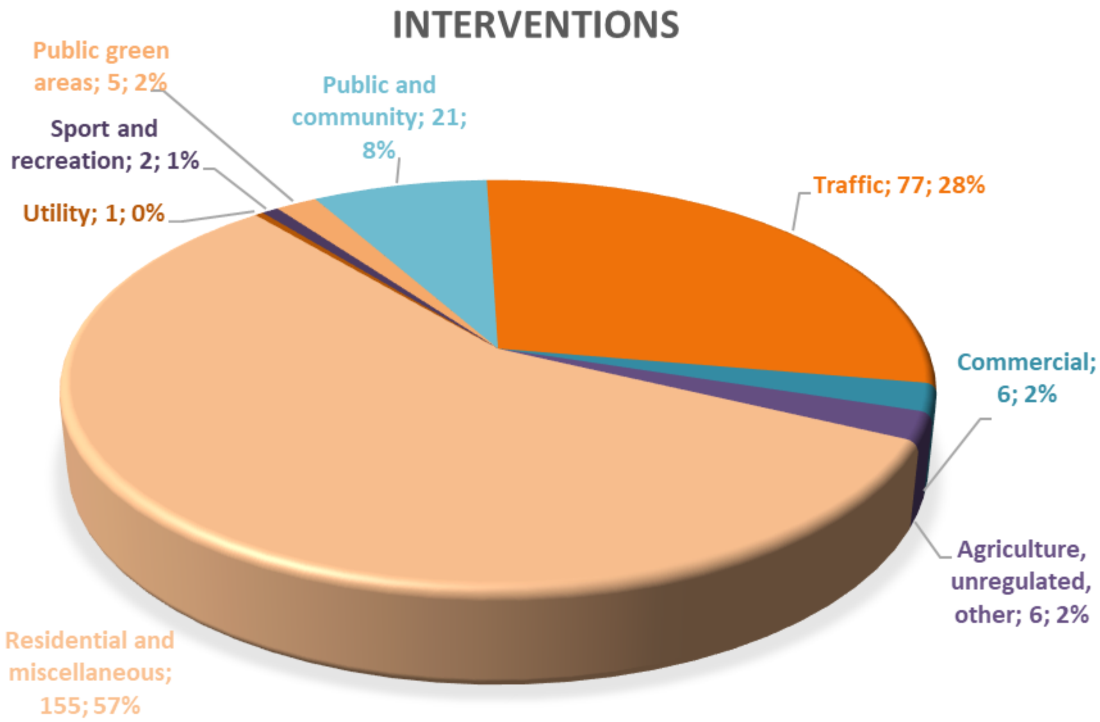

Figure 15. Interventions per purpose category

4.4. Rainfall quantity and intensity

A rainfall event is considered to start if it is preceded by more than 24 h without rain, regardless weather flooding occurred or not. The maximum accumulated rain in 1, 2, 3, 6, 12 and 24 h of each rainfall event is calculated as the moving sum through the respective timesteps.

Considering this definition, 764 rainfall events have been recorded in the period from 2007 to 2017. Of them 88 resulted in 331 interventions within the watershed boundaries. Most those interventions (73%) are in the warm season from April to September. By comparing that number to the percentage of rainfall events that occur in the warm season (53%) a conclusion can be drawn that in warm seasons the rainfall events are more likely to cause flash floods than in cold season, figure 18.

To get a better view of rainfall data in the observed period, a percentile graph has been created of maximal accumulated rainfall over the span of 1, 2, 3, 12 and 24 hours. It can be observed that a lot of rainfall events have low levels of rainfall. Half the rainfall events have 2-5mm of rainfall, while 80 percent have accumulated rainfall between 4 and 15 mm. No rainfall event has accumulated rainfall over 100mm, except the cumulative rainfall over the span of the entire rainfall event.

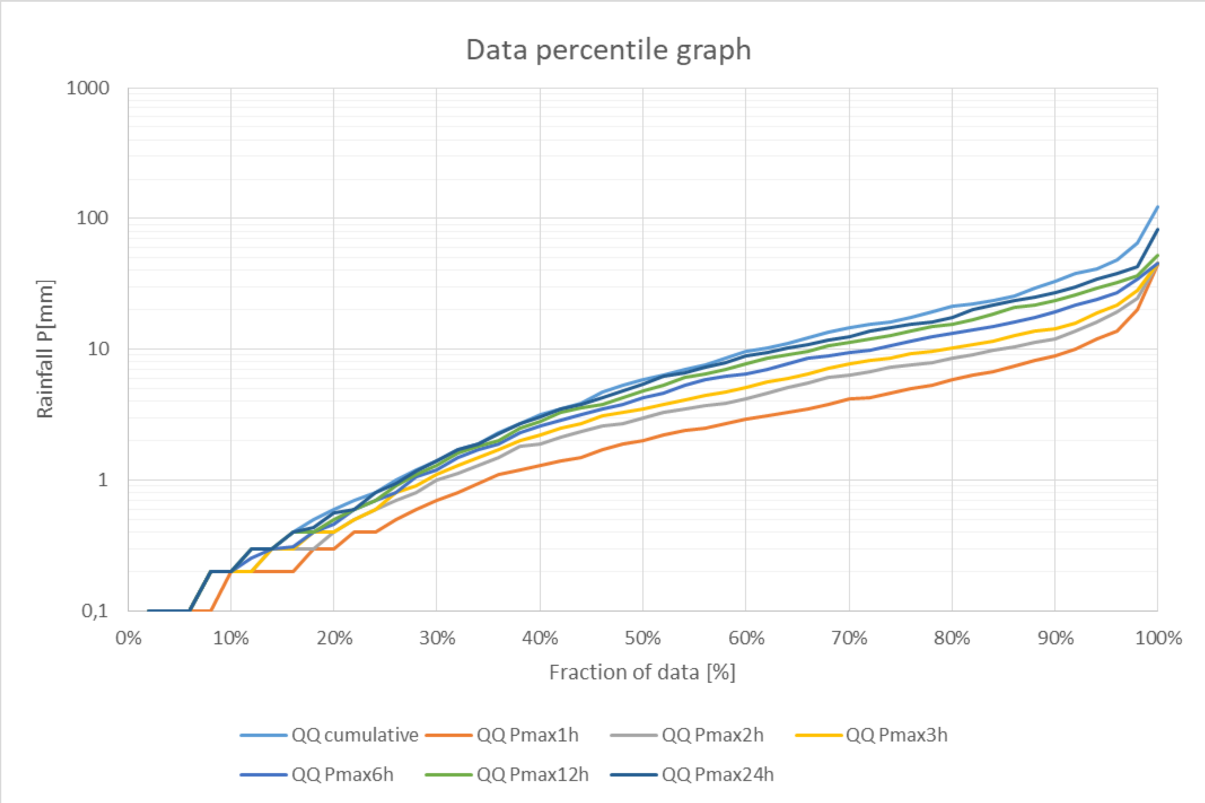

Figure 16. Accumulated rainfall data percentile graph

Table 1. Rainfall data statistics [mm]

		accumulated	Pmax1h	Pmax2h	Pmax3h	Pmax6h	Pmax12h	Pmax24h
	MIN	0,1	0,1	0,1	0,1	0,1	0,1	0,1
	MAX	123,2	44,6	45,9	45,9	45,9	51,9	82,2
	STD	16,59	5,10	6,31	7,06	8,64	10,12	12,01
	MEAN	5,9	2	3	3,5	4,3	4,8	5,45
Percentile	**0,25**	0,9	0,5	0,6	0,7	0,7	0,8	0,875
	0,5	5,9	2	3	3,5	4,3	4,8	5,45
	0,75	16,8	4,8	7,425	8,7	11,4	13,225	15

Table 1 shows an overview of rainfall data gathered by The Meteorological and hydrological service of Croatia in the period from 2007 to 2017. The collected data is represented in a processed form to show accumulated rainfall for each rain event. Therefore min, max and other values represent rainfall events. For example, there was a rainfall event that had max accumulated rainfall over the span of one hour 44,6 mm.

Figure 17 displays the same data in a graphical manner for it to be more intuitive. It can be observed that the standard deviation increases with the observed timespan, indicating a wider spread of acquired data.

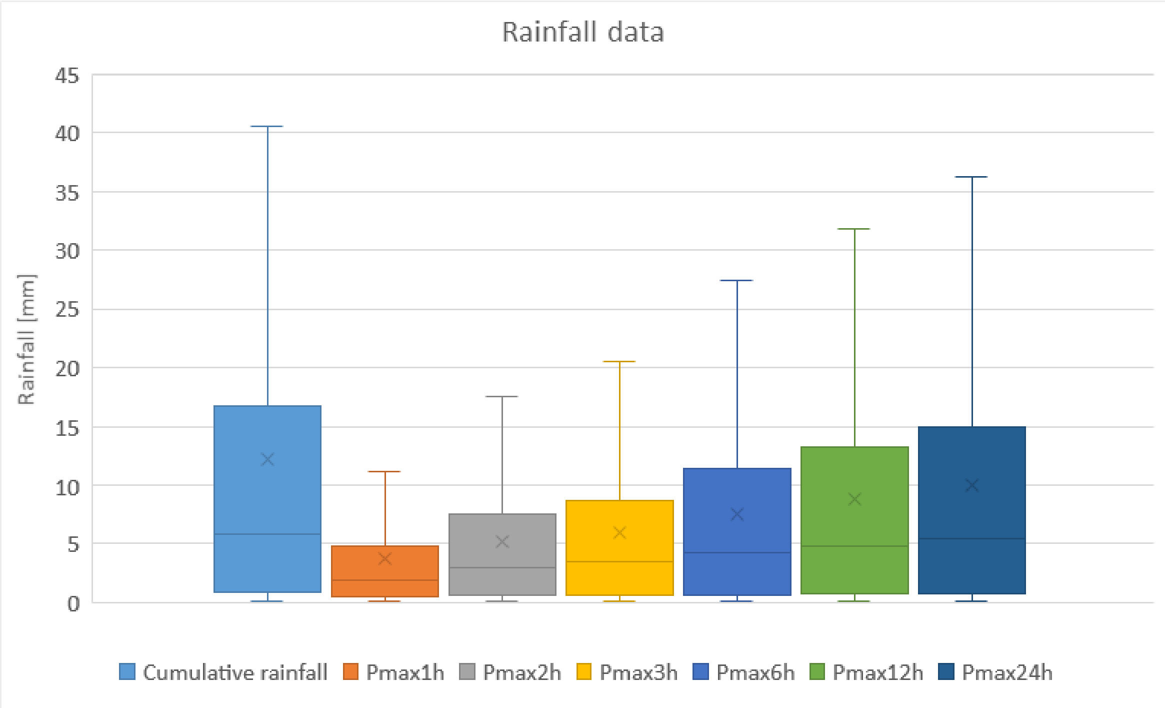

Figure 17. Statistical representation of rainfall data for selected durations.

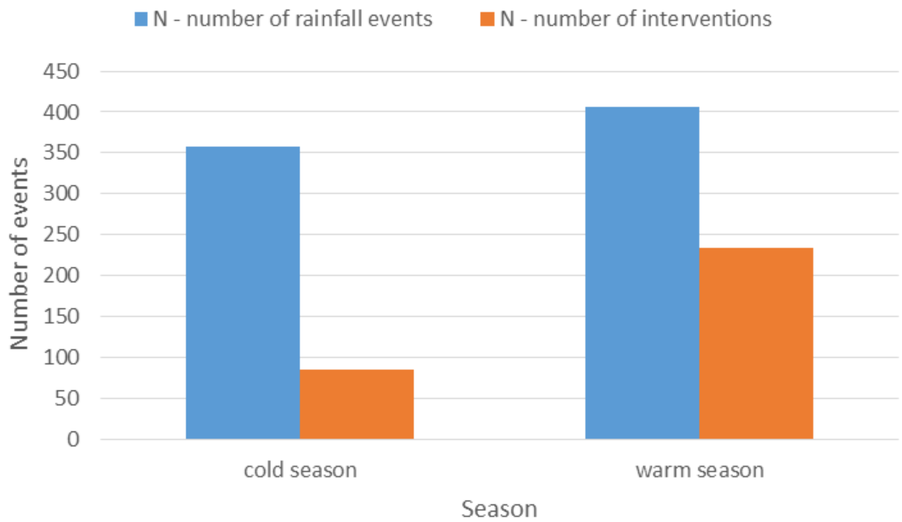

Figure 18. Number of rainfall events and intervention in cold and warm season

Analysis of the rainfall event and intervention data was made for each month respectively. Even though April and May have more rainfall events, the number of interventions is significantly higher in June and August, figure 19. Colder months such as December and January have a similar number of rainfall events but significantly lower number of interventions. The most likely possible cause is the freezing conditions and milder intensity of rainfall events. It is worth noting that the year 2014 had the most interventions and rainfall events out of all analyzed years, table 2.

Table 2. Rainfall and intervention data throughout the years and months

N - number of interventions														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**sum**	**perc.**
2007	0	1	0	0	2	0	1	12	0	0	0	0	16	5,05%
2008	0	0	0	0	0	16	0	0	0	1	1	0	18	5,68%
2009	0	0	0	0	4	18	2	3	0	0	1	0	28	8,83%
2010	0	0	1	0	0	4	0	14	11	0	1	0	31	9,78%
2011	0	0	0	0	4	2	0	0	0	0	0	0	6	1,89%
2012	0	0	0	0	3	1	0	0	0	0	1	0	5	1,58%
2013	0	1	10	1	0	0	3	19	2	0	1	0	37	11,67%
2014	1	18	0	1	14	9	23	20	7	10	0	0	103	32,49%
2015	0	1	0	0	3	1	0	1	0	4	0	0	10	3,15%
2016	1	5	2	0	0	8	0	0	0	0	0	0	16	5,05%
2017	0	0	0	0	2	16	2	0	4	1	8	14	47	14,83%
sum	2	26	13	2	32	75	31	69	24	16	13	14	317	100,00%
perc.	1%	8%	4%	1%	10%	24%	10%	22%	8%	5%	4%	4%		
cold season		84				warm season		233						

Legend:
top 20%
bottom 20%

N - number of rainfall events														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**sum**	**perc.**
2007	4	8	5	5	8	8	6	6	5	9	5	5	74	9,69%
2008	6	4	9	9	6	5	6	5	5	3	7	6	71	9,29%
2009	5	5	8	7	8	10	3	7	5	3	6	8	75	9,82%
2010	2	5	5	4	9	4	7	6	7	3	7	5	64	8,38%
2011	4	1	3	6	8	6	6	3	3	7	1	9	57	7,46%
2012	5	2	3	7	7	5	6	3	5	8	6	8	65	8,51%
2013	5	6	7	6	7	4	5	3	8	5	7	4	67	8,77%
2014	9	9	5	7	9	8	9	8	5	5	7	3	84	10,99%
2015	10	5	5	9	5	4	6	4	6	6	1	4	65	8,51%
2016	4	7	9	5	8	7	6	6	4	7	6	3	72	9,42%
2017	5	3	4	9	8	9	4	5	7	6	6	4	70	9,16%
sum	59	55	63	74	83	70	64	56	60	62	59	59	764	100,00%
perc.	8%	7%	8%	10%	11%	9%	8%	7%	8%	8%	8%	8%		
cold season		357				warm season		407						

It can be observed in table 2 that the number of rainfall events remains constant throughout the years with the year 2014 having the most by a slight margin. The intervention data however shows that most of the interventions happened in recent years with the year 2014 having almost a third of all recorded interventions attributed to flash floods in the observed timespan. Even though 10 years is not enough to predict trends of rainfall intensity, this result indicate the need for exploration of longer periods and other climate indicators.

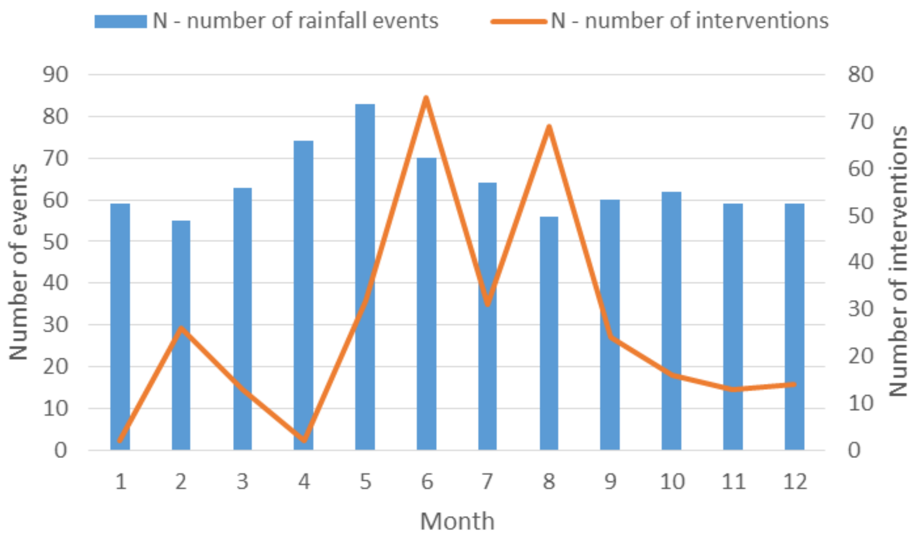

Figure 19. Number of rainfall events and interventions

Figure 20 shows data of rainfall events that resulted in a flood from the viewpoint of duration. It can be observed that most of the rainfall events that can be related to flash floods indicators lasted more than 24 hours (61%). Rainfall events lasting from 6 to 24 hours also related to a large proportion of interventions (24%). This indicates that saturation of ground and drainage systems has significant impact on the occurrence of flash floods.

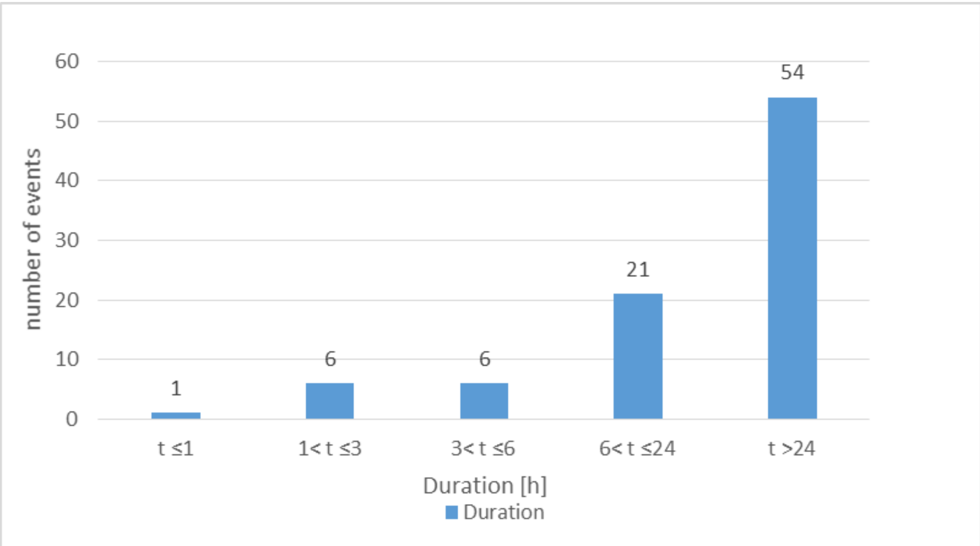

Figure 20. Duration of rainfall events that can be related to urban floods

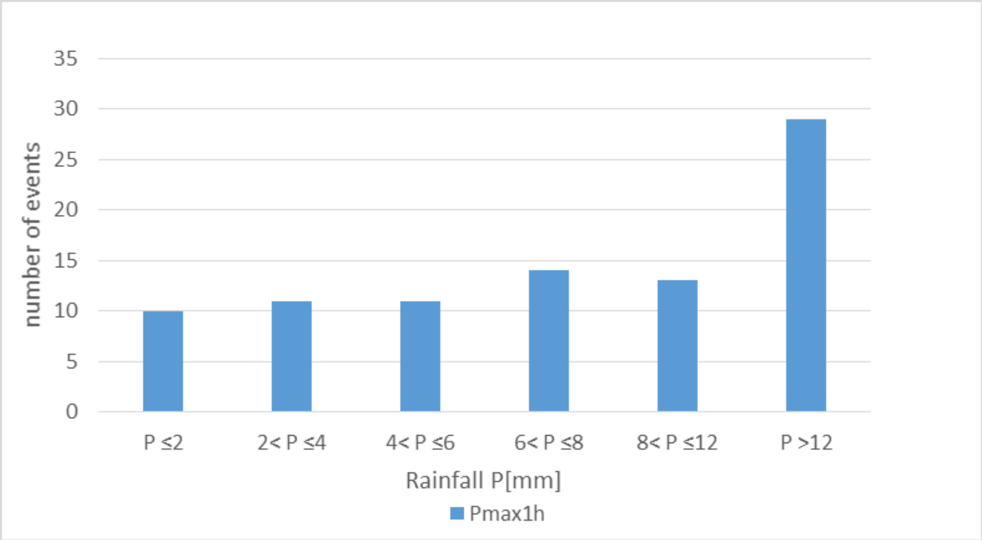

Figure 21. Maximum accumulated rainfall during 1h for events that can be related to floods

Analyzing max accumulated rainfall over the period of 1 hour it can be observed that only rainfall events with P higher than 12mm can be related to an increase in flooding probability, figure 21. In such events, the ability of the drainage systems short term capacity to accept such high quantities of water has a much higher impact than ground saturation.

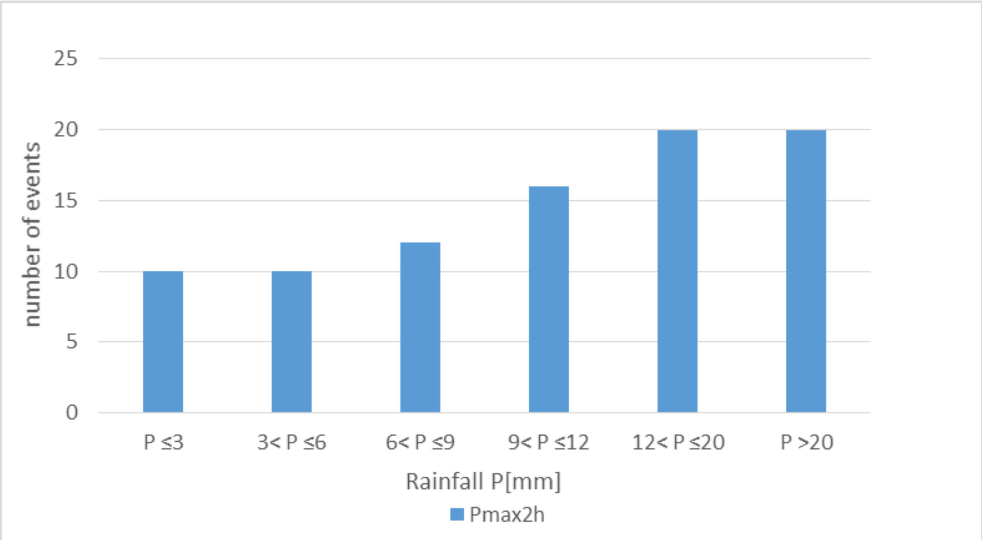

Figure 22. Maximum accumulated rainfall during 2h for events that can be related to floods

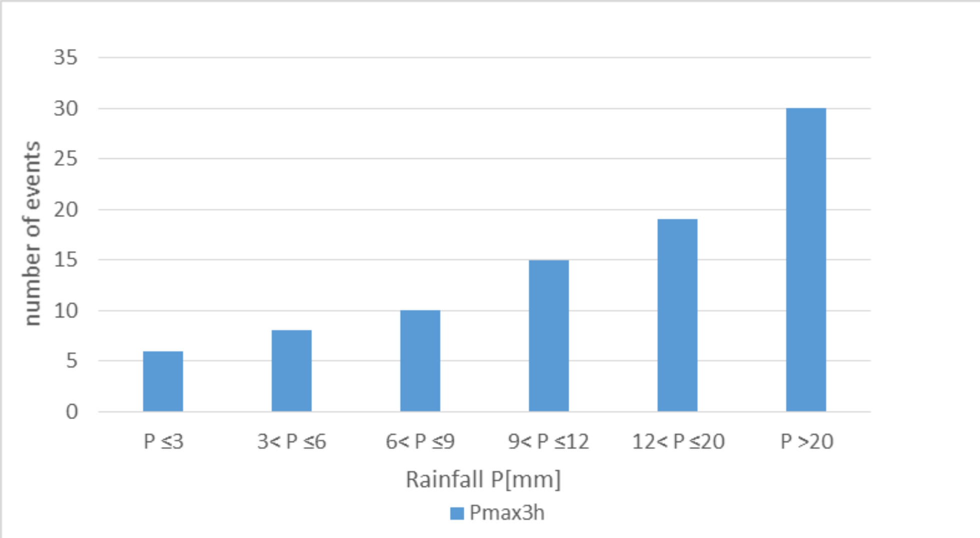

Figure 23. Maximum accumulated rainfall during 3h for events that can be related to floods

Similarly to figure 21, figures 22 and 23 show that max accumulated rainfall over the period of 2 and 3 hours causes significantly more interventions with higher rainfall amount. It can be observed that for Pmax2h an increase in interventions happens at the P=12mm mark, while for Pmax3h a steady increase with rainfall amount can be observed. This indicates that ground and drainage system saturation have a higher impact for max accumulated rainfall data over 3 hours.

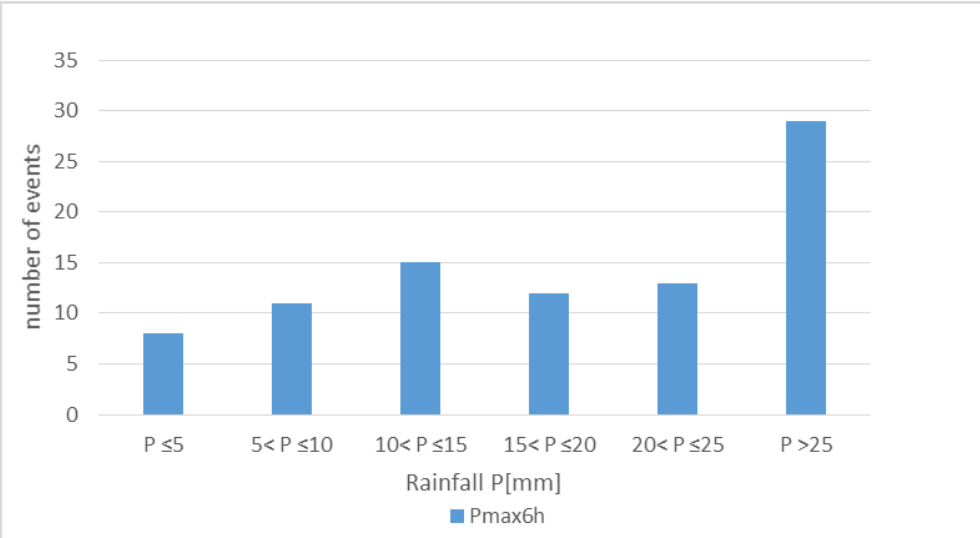

Figure 24. Maximum accumulated rainfall during 6h for events that can be related to floods

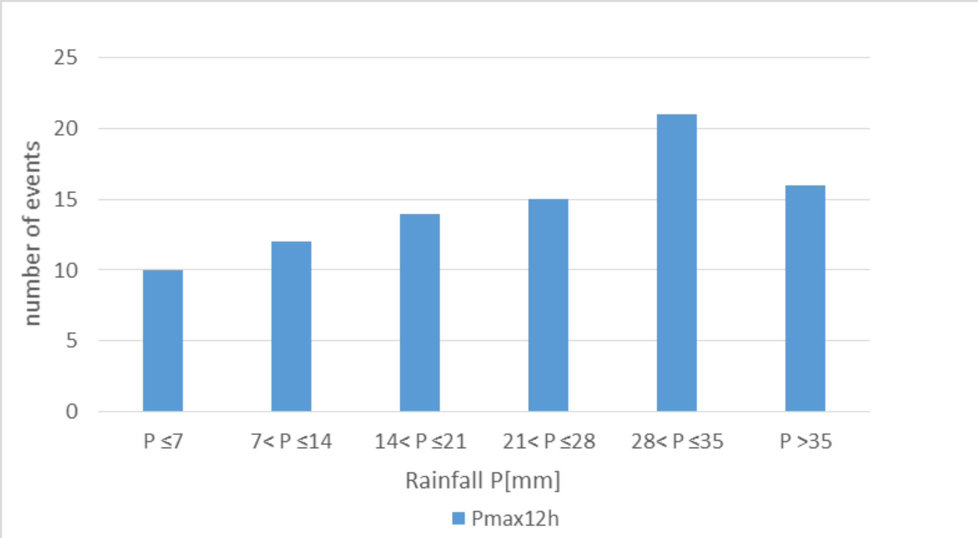

Figure 25. Maximum accumulated rainfall during 12h for events that can be related to floods

Maximum accumulated rainfall over the period of 6 and 12 hours are further investigated to show the impact of long term rainfall on interventions, figures 24 and 25. For rainfall events that last a longer period, the accumulated rainfall increases, thus further separating the flash flood events from rainfall events that have a saturating impact on the ground and drainage system.

Figure 26 shows that accumulated rainfall P>10mm causes almost all flooding events. Most of the rainfall events which resulted in interventions are in the range between 20 and 40mm.

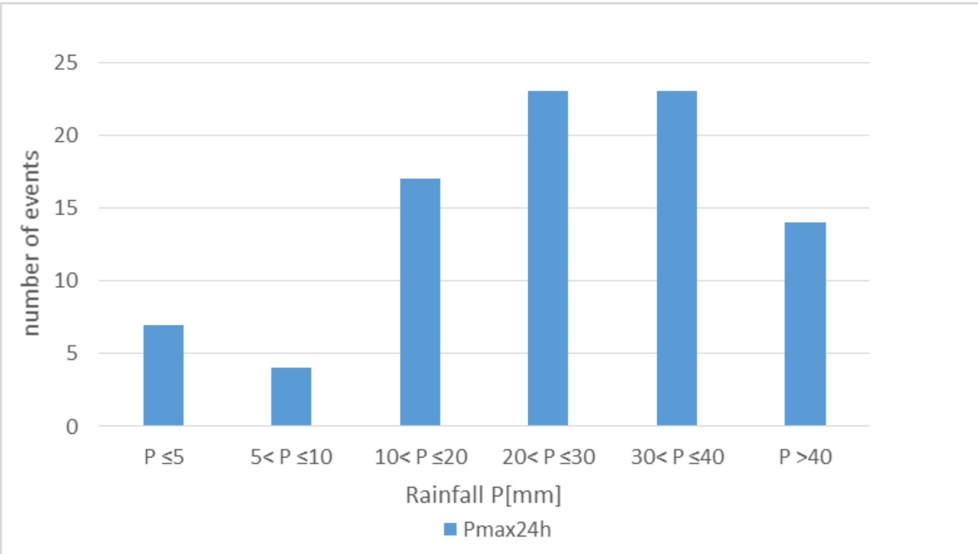

Figure 26. Maximum accumulated rainfall during 24h for events that can be related to floods

5. Results

5.1. Relation between hazard and impact indicators

It can be observed that interventions happen regardless of rainfall quantity. What is however indicative, is that with higher rainfall the number of interventions, and interventions per rainfall event rise significantly.

Figure 27 displays the number of events and operations for various ranges of max accumulated rainfall within 1h. Although highest number of rainfall events (29) occurred between 0-5 mm, number of interventions increased when more precipitation has fallen, in the range from 5-10 mm. However, the impact intensity, measured as the average number of operations per event, is the highest in range of 35-40 mm, with 15,5 interventions per event.

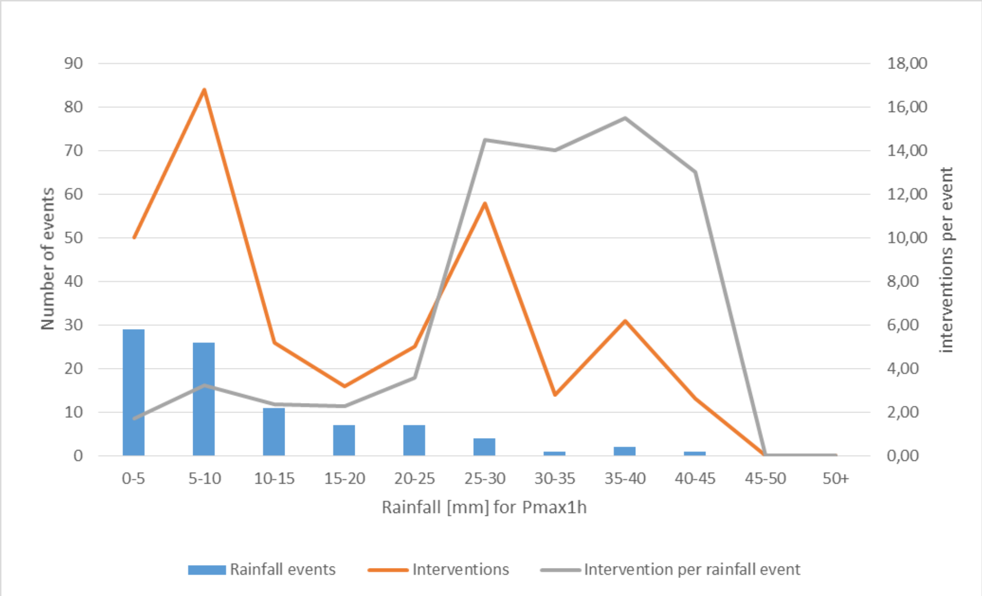

Figure 27. Number of events, interventions and average number of operations per event for various ranges of maximum 1h of accumulated rain in (mm)

With max accumulated rainfall in 2h, figure 28, the highest number of rainfall events occurred in the range from 5-10 mm when the number of recorded interventions was 56 while the highest number of interventions was 63 in the range of 30-35 mm of rainfall. Average per rainfall event in that range is 12,6 while maximum of 13 is denoted from range of 45-50 mm with a sharp rise above 25 mm.

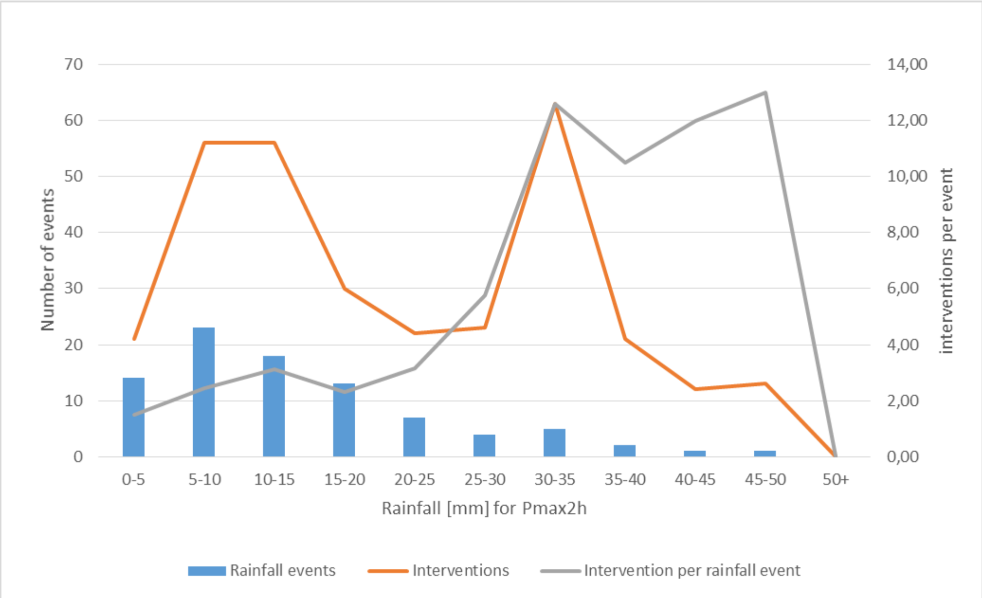

Figure 28. Number of events, interventions and average number of operations per event for various ranges of maximum 2h of accumulated rain in (mm)

On the figure 29 number of events, interventions and average number of operations per event for various ranges of maximum accumulated rainfall in 3h are shown. Highest number of events is registered in the range of 5-15 mm. Maximum number of interventions (80) were in the range of 30-35 mm, while the average for interventions per event is 15,5 in the range of 40-45 mm. Similarly, to the previous graph, a sharp rise in number of interventions per rainfall event can be observed above the 25mm mark.

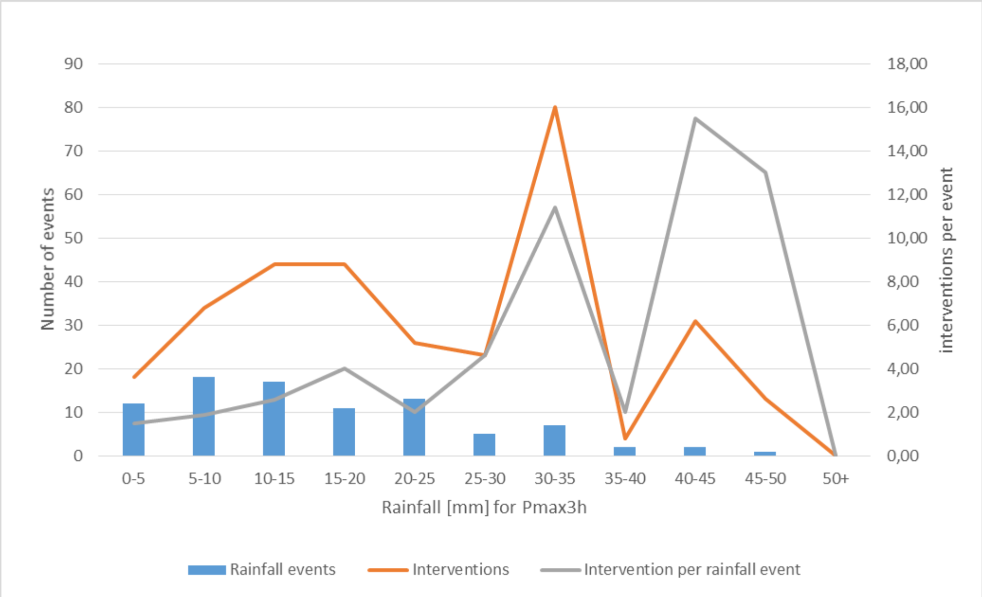

Figure 29. Number of events, interventions and average number of operations per event for various ranges of maximum 3h of accumulated rain in (mm)

Figure 30 represents number of events, interventions and average number of operations per event throughout multiple of maximum accumulated rain within 6h. Highest number of rainfall events (15) is registered in the range of 10-15 mm, maximum number of interventions (77) in the range of 30-35 mm while the most interventions per event ratio (13) are in the range of 45-50 mm.

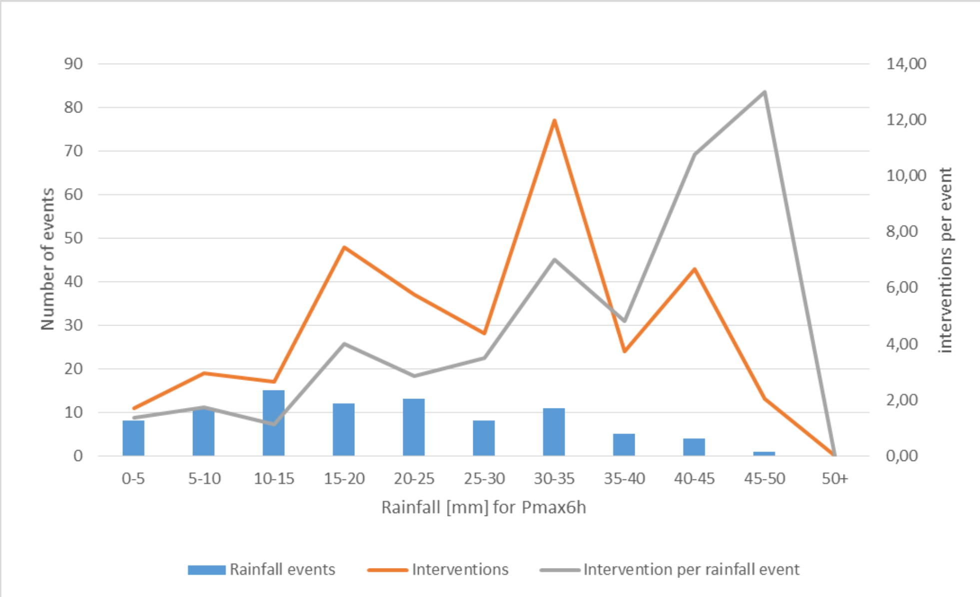

Figure 30. Number of events, interventions and average number of operations per event for various ranges of maximum 6h of accumulated rain in (mm)

Figure 31 represents number of events, interventions and average number of operations per event for various ranges of maximum accumulated rainfall within 12h. In this case, highest number of rainfall events (16) was registered in the range of 25-30 mm, and the highest number of interventions (74) are in the range 30-35 mm and average of interventions per event is 8 in the range of 45-50 mm. The sudden rise of intervention to rainfall ratio happens at lower rainfall quantities than previously observed, at 20mm

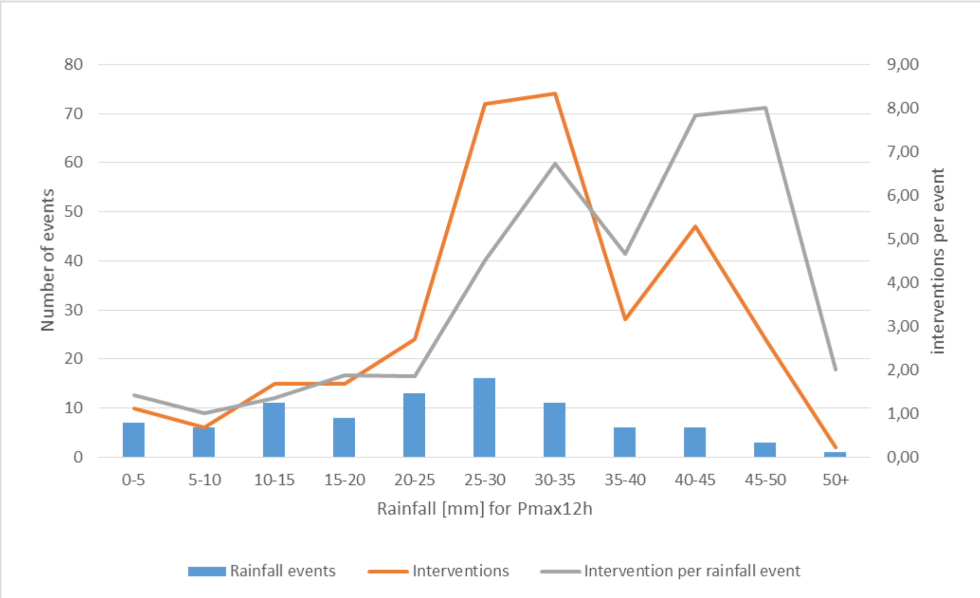

Figure 31. Number of events, interventions and average number of operations per event for various ranges of maximum 12h of accumulated rain in (mm)

Figure 32 shows number of events, interventions and average number of operations per event for various ranges of maximum accumulated rainfall in 24h. Maximum number of rainfall events (14) was recorded in the range of 35-40 mm. Maximum number of interventions (85) is also in the same range and the denoted average of interventions per event (8,5) is in the range with more than 50 mm precipitation. The intervention to rainfall ratio increases seemingly steady. Upon closer inspection it can be observed that the sharpest rise happens also at 25 mm.

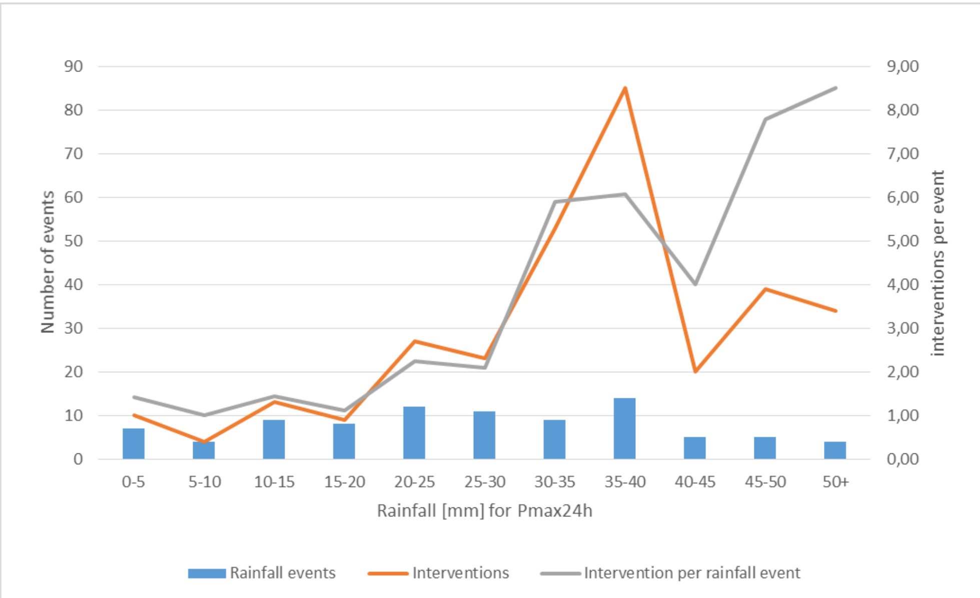

Figure 32. Number of events, interventions and average number of operations per event for various ranges of maximum 24h of accumulated rain in (mm)

Overall it can be concluded that when we observe maximum precipitation of 1, 2, 3 and 6h, highest number of rainfall events happen mostly in the area of 10-15 mm. When we observe maximums in longer period of time like 6 and 24 hours, maximum number of rainfall events shift to more accumulated rain, in this case range of 25-30 and 35-40 mm. Maximum number of interventions does not always overlap with highest number of rainfall events but still stays high enough. Disparity can be result of poor infrastructure in certain problematic areas. It is also possible that some areas demonstrate particular vulnerability are prone to flooding more than others.

Table 3 shows calculated correlation factors between max accumulated rainfall data and interventions. ρ value of around 0,6 indicates that there is a fairly good correlation between accumulated rainfall and number of interventions. With increasing the accumulated rainfall period the correlation factor drops. This indicates that flash floods with high rain quantities in short period are the most relevant for predicting flood events in Zagreb (Papagiannaki *et al.*, 2015).

Table 3. Spearman's rank-order correlation

Pmax	**1h**	**2h**	**3h**	**6h**	**12h**	**24h**
ρ	0,6061	0,5709	0,5419	0,5020	0,4726	0,4620

5.2. Peak storm intensity

Peak storm intensity as a tool for flood predictions allows us to mitigate flood damage and prepare a timely response to the events. The goal of this paper was to establish a rainfall intensity threshold that flags potential flooding events. For this purpose, the previous rainfall data of rainfall events were analyzed by an empirical approach. Possible alternatives with a more statistical approach were briefly introduced as a possible extension. These approaches however do not account for the severity of the rainfall but rather the expected outcome of a rainfall event, weather it has potential to cause flood events. As such, they should only be taken as an indicator rather than a fixed threshold.

By dividing the maximal accumulated rainfall intensities with their respective duration an intensity can be calculated for each rainfall event. Figure 33 represents the visualization of that data. Orange marked are rainfall events which caused floods while blue marked events didn't cause floods. As anticipated orange rainfall events are concentrated on top of the graph while blue events are concentrated on the bottom. It is however visible that there is no clear border between these two, meaning that no clear threshold can be evaluated by simply looking at the graph. Other authors, Papagiannaki *et al.*, (2015) suggested to take maximum rainfall intensities which did not relate to interventions as the upper threshold, and the minimum rainfall intensities which did relate to intervention as the lower threshold.

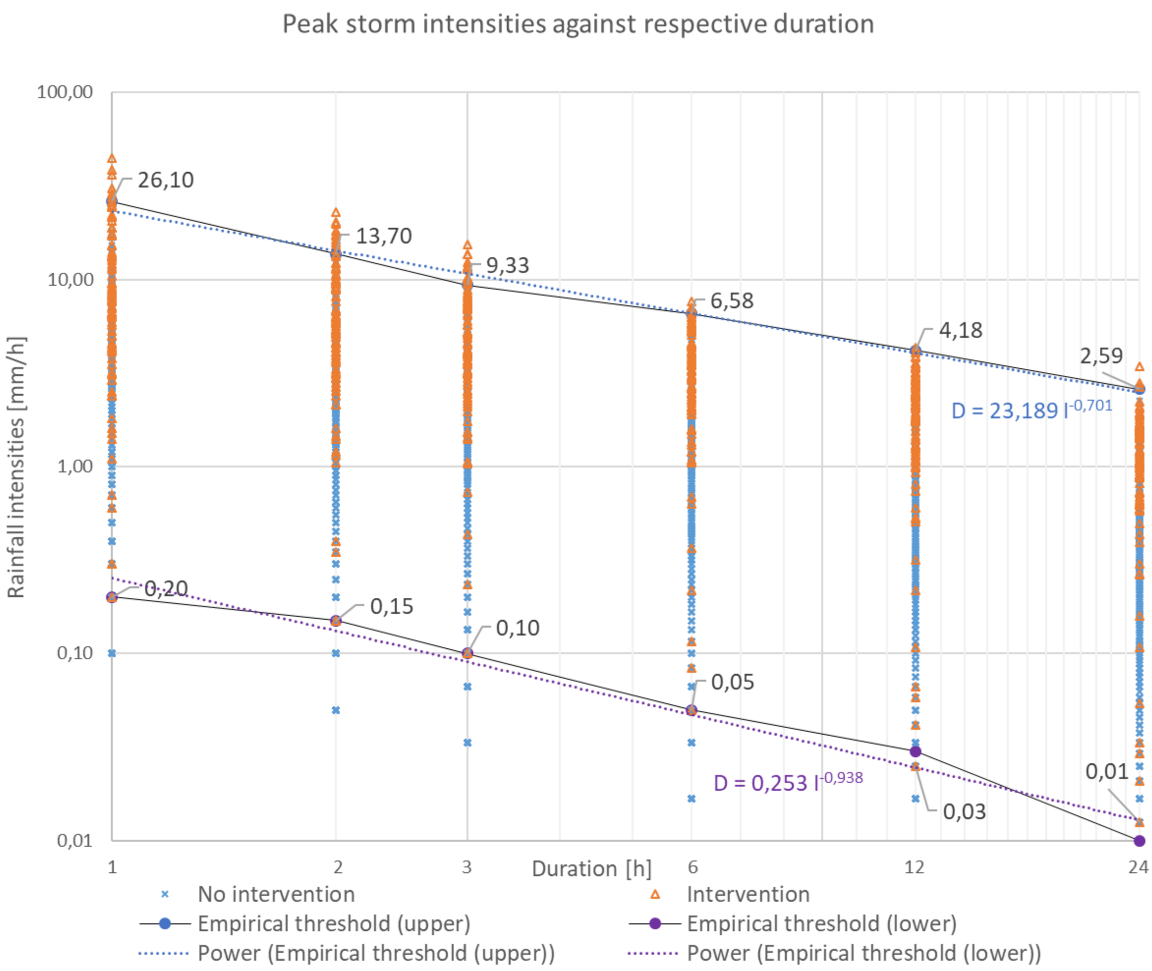

Figure 33. Peak storm intensities against respective duration

By fitting a trendline through the respective datapoints a power function for the threshold intensity can be obtained.

- For upper empirical threshold

$$I = 23{,}189 \cdot D^{-0{,}701} \tag{1}$$

- For lower empirical threshold

$$I = 0{,}253 \cdot D^{-0{,}938} \tag{2}$$

Maximal accumulated rainfall during the period of 1h has been determined as most relevant for the prediction of flood events. By calculating the predicted flood threshold for *D*=1, *I*=23,189 mm. Figure 27 shows a sharp increase in average flood event per rainfall in this class. Hence it can be concluded that the threshold values adequately indicate flood risk.

Work of other authors, Papagiannaki *et al.*(2015) show comparable results for the upper threshold for rainfall intensities. Lower threshold in this paper is off by an order of magnitude, indicating that additional work can be done in analyzing intervention cause to filter out events which don't have their cause in rainfall events. The same empirical approach was also applied by Hrastovski, M. (2016).

Since the lower threshold is related to very small rainfall amounts it could be related to falsely included interventions in the database (e.g. pumping water from broken infrastructure and not from rainfall event) and that are too low for operational purposes. Determined lower threshold gives also smaller amounts when compared to other previously mentioned research. Therefore an additional threshold levels are explored, i.e. alternative approach based on work of other authors Hong, Kim and Jeong (2018) has been introduced. Hongs' approach is based on a statistical analysis of rainfall events with threshold rainfall quantities for fixed probability ranges. Similar methodology to the Hongs' work is introduced where percentile data has been evaluated as a possible threshold indicator.

Table 4. Max accumulated rainfall [mm] for given percentile of rainfall data

Percentile	Pmax1h	Pmax2h	Pmax3h	Pmax6h	Pmax12h	Pmax24h
0,25	0,9	0,5	0,6	0,7	0,7	0,8
0,5	5,9	2	3	3,5	4,3	4,8
0,75	16,8	4,8	7,425	8,7	11,4	13,225

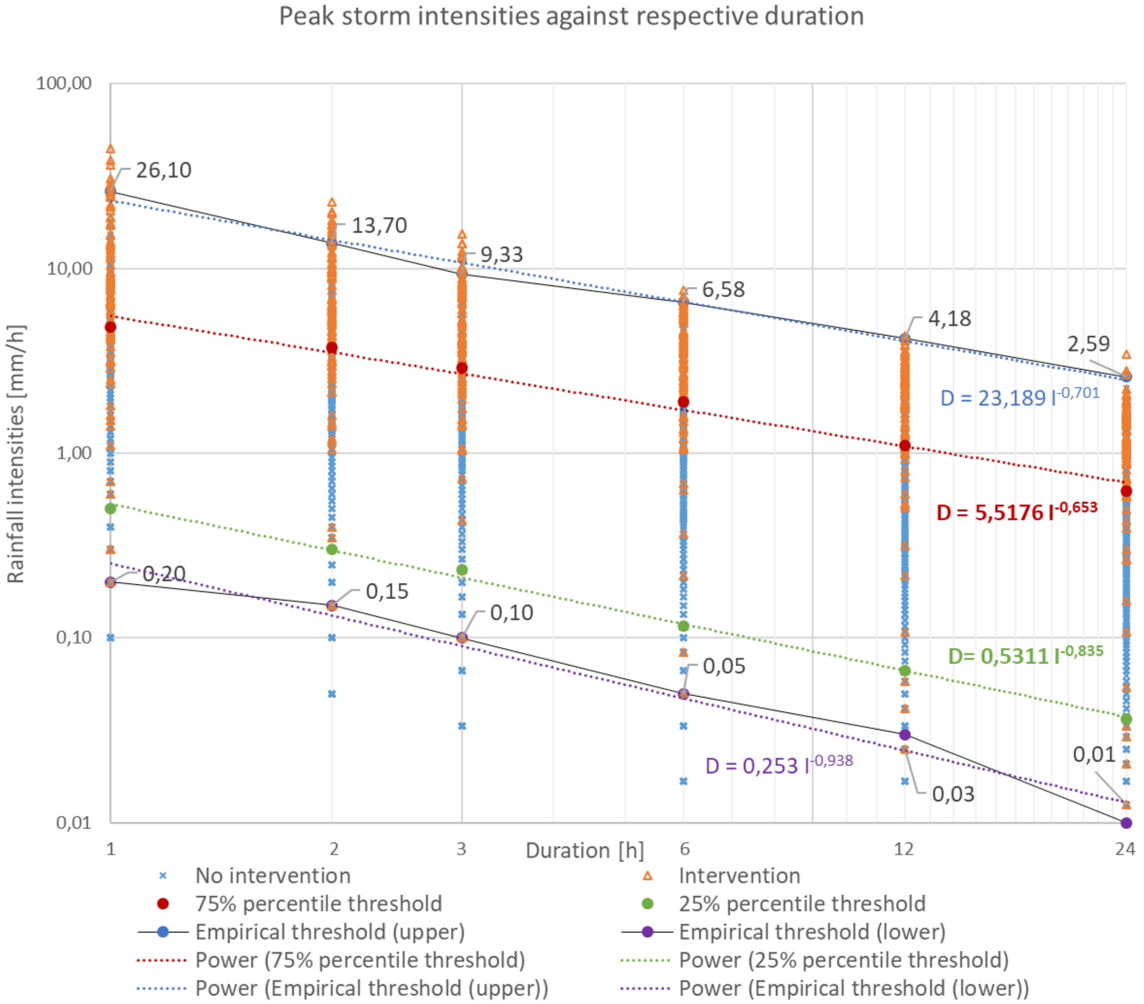

Figure 34. Intervention threshold indicator based on different approaches.

By fitting a trendline the upper and lower thresholds based on percentile rainfall data, an equation can be determined.

- For upper percentile threshold (75%)

$$I = 5{,}5176 \cdot D^{-0{,}653} \tag{3}$$

- For lower empirical threshold

$$I = 0{,}5311 \cdot D^{-0{,}835} \tag{4}$$

A rudimentary calculation can be performed to assess the correctness of threshold values by looking at previous rainfall events and analyze how many correct predictions can be made using calculated thresholds.

5.3. Overall threshold correctness

The correctness of threshold values can be analyzed based on rainfall events by determining what percentage of predictions would correctly predict a flash flood event. The same principle can be applied to predictions that no flood will happen. Lastly, the percentage of combined correct prediction called overall prediction correctness can be calculated.

To determine the prediction correctness, rainfall events were separated in four groups ***h***, ***m***, ***f*** and ***c***. ***h*** and ***c*** are categories with correct prediction. ***h*** are all intervention events above the threshold line, while **c** are all rainfall events, without interventions, below the threshold. When calculating wrong predictions, two categories are present. ***m*** are all interventions below threshold, i.e. their rainfall was lower and they didn't trigger a warning, but they resulted in an intervention. Similarly, ***f*** represents all rainfall events without interventions but above the threshold, i.e. they triggered a flood warning but no interventions were recorded. ***h*** and ***m*** together equal 88 which is the number of rainfall events that resulted in floods.

The overall correctness, hit rate and false alarm rate are calculated as ratio of correct and all predictions, by utilizing following formulas (Jang, 2015; Mason, 1982):

$$\text{Hit rate} = \frac{h}{m + h}, \tag{5}$$

$$\text{False alarm rate} = \frac{f}{c + f}, \tag{6}$$

$$\text{Overall correctness} = \frac{h + c}{h + m + f + c}. \tag{7}$$

764 rainfall events were analyzed in this paper (*h*+*m*+*f*+*c*). Of that number 88 rainfall events were related to interventions (*h*+*m*), while 676 were not related to interventions (*f*+*c*). To obtain the best overall correctness the hit rate should be kept as high as possible while simultaneously the false alarm rate should be kept as low as possible.

Table 5. Correctness of upper empirical threshold values

Pmax	1h	2h	3h	6h	12h	24h
Empirical threshold upper [mm]	23,189	28,529	32,206	39,623	48,748	59,974
h	11	11	9	5	2	3
m	77	77	79	83	86	85
f	1	0	0	0	1	1
c	675	676	676	676	675	675
hit rate	**12,5%**	**12,5%**	**10,2%**	**5,7%**	**2,3%**	**3,4%**
false alarm rate	**0,1%**	**0,0%**	**0,0%**	**0,0%**	**0,1%**	**0,1%**
overall correctness	**89,8%**	**89,9%**	**89,7%**	**89,1%**	**88,6%**	**88,7%**

Table 6. Correctness of lower empirical threshold values

Pmax	1h	2h	3h	6h	12h	24h
Empirical threshold lower [mm]	0,253	0,264	0,271	0,283	0,295	0,308
h	87	88	88	88	88	87
m	1	0	0	0	0	1
f	551	576	579	584	585	561
c	125	100	97	92	91	115
hit rate	**98,9%**	**100,0%**	**100,0%**	**100,0%**	**100,0%**	**98,9%**
false alarm rate	**81,5%**	**85,2%**	**85,7%**	**86,4%**	**86,5%**	**83,0%**
overall correctness	**27,7%**	**24,6%**	**24,2%**	**23,6%**	**23,4%**	**26,4%**

Table 7. Correctness of upper percentile threshold values

Pmax	1h	2h	3h	6h	12h	24h
Percentile (75%) [mm]	5,518	7,018	8,078	10,275	13,069	16,622
h	58	64	67	69	69	64
m	30	24	21	19	19	24
f	107	138	151	137	126	97
c	569	538	525	539	550	579
hit rate	**65,9%**	**72,7%**	**76,1%**	**78,4%**	**78,4%**	**72,7%**
false alarm rate	**15,8%**	**20,4%**	**22,3%**	**20,3%**	**18,6%**	**14,3%**
overall correctness	**82,1%**	**78,8%**	**77,5%**	**79,6%**	**81,0%**	**84,2%**

Table 8. Correctness of lower percentile threshold values

Pmax	1h	2h	3h	6h	12h	24h
Percentile (25%) [mm]	0,531	0,595	0,637	0,714	0,800	0,897
h	85	85	85	84	84	84
m	3	3	3	4	4	4
f	476	500	493	487	485	489
c	200	176	183	189	191	187
hit rate	**96,6%**	**96,6%**	**96,6%**	**95,5%**	**95,5%**	**95,5%**
false alarm rate	**70,4%**	**74,0%**	**72,9%**	**72,0%**	**71,7%**	**72,3%**
overall correctness	**37,3%**	**34,2%**	**35,1%**	**35,7%**	**36,0%**	**35,5%**

Based on the values of overall correctness, it can be concluded that the empirical approach gives a good threshold value but with low number of floods predicted (less than 13%). The lower empirical threshold has the lowest correctness rate with high hit rate but also many false positives. The upper percentile threshold has sufficient correctness with many correct flood predictions, but also higher false alarm rates than the upper empirical threshold. Lower percentile threshold has a slightly better correctness than the lower empirical threshold, but eliminates many false positives.

6. Discussion

The methodology and calculated threshold values can contribute and can be used in the development of Atlas of climatological extremes, which is planned to be developed by Croatian Meteorological and Hydrological Service (DHMZ).

Given that rainfall prediction relies on the analysis of previous rainfall events and intervention data, it is important that they are reliable and correct. During the preliminary analysis of intervention events some specific problems occurred such as notation of flood events, missing or incomplete data etc. To use such data as basis for future research it would be very helpful to standardize a noting system to categorize intervention events.

Rainfall data was available for the meteorological station Maksimir. There were 764 rainfall events distinguished during the observed period. During that time more than 900 interventions, relatable to rainfall events, were recorded by public services, throughout Zagreb. Spatial analysis was performed and it was determined that 331 interventions occurred within the set boundaries of the analyzed watershed. By crosslinking them to rainfall events it was determined that 88 rainfall events were relatable to intervention data. Further spatial analysis led to the conclusion that 89% of interventions occurred at predominantly developed areas. By further analyzing the data it was determined that most of the interventions occurred at residential and traffic areas, 85% in total. Such values strongly suggest that urbanization and flash flood events are linked. Care should be taken however, since the available impact data i.e. interventions could be influenced by survivorship bias, where only events that caused material and financial damage (e.g. at residential or traffic areas) were recorded, and events which caused floods at green areas weren't recorded.

Analysis of the rainfall data and flood impact of multiple meteorological stations would bring more certainty and improve the threshold values for the whole city of Zagreb. Data from the meteorological station Maksimir was measured as hourly precipitation. Flash floods often occur in a short period and hourly precipitation data may not be sufficient to model such occurrences. Since urban areas are more susceptible to flash floods it would help to determine thresholds resulted from precipitation data of shorter timespans e.g. 10 minutes should be analyzed. Additionally, this method takes into consideration only accumulated rainfall which could be a major drawback.

The empirical analysis of available data resulted in an upper threshold for accumulated rainfall intensity above which almost all rainfall was relatable to flood impact indicators. It was determined that the most influential parameter for flood prediction is the maximal accumulated rainfall intensity during 1 hour. By obtaining and analyzing max accumulated rainfall intensities of shorter duration a better predictor value could be calculated. Lower empirical threshold was not conclusive and a different approach at determining thresholds was briefly considered. The statistical analysis appears promising in determining threshold values and further research in this area should be considered. Calculation of prediction correctness parameter for introduced thresholds developed in this thesis provides numerical measure and feedback for level of “accuracy” in indicating flood events.

The thresholds presented here can provide guidance for rudimentary warning systems and planning for emergency response to significant runoff in similar settings. By comparing precipitation forecasts and measurements made during storms with the appropriate threshold lines, decisions on warning and emergency response can be made. The calculated threshold values are not a definitive predictor of flood events but rather a warning flag that could put emergency response units in a state of alertness at e.g. lower thresholds, and a state of high readiness at e.g. high thresholds. As a storm develops, it is important to compile measurements of peak intensities of different durations (as was done for the definition of the thresholds) as well as cumulative storm rainfall intensities and durations. Each rainfall measurement should be compared with the thresholds. When any combination of rainfall intensity and duration approaches or exceeds the threshold line that pose significant risks to life and property become likely. Less destructive floods can be expected before storm rainfall reaches the thresholds (Cannon *et al.*, 2008). Various institutions, primarily the firefighting departments and state administration for protection and rescue can benefit from such work. Based on here calculated threshold values a timely response to flood events throughout the city can be planned and executed. A map with areas marked as potential risk zones would be beneficial for urban planning and development. Based on land use data these risk zones should be analyzed to plan and implement water resilient infrastructure to prevent floods or reduce the risk.

There are many factors that should be considered in flash flood prediction such as geomorphological and meteorological conditions, level of urbanization, surface permeability, antecedent soil moisture conditions, infrastructure, etc. That is why different approaches and methodologies are used which can be computationally intensive. Methodology used in this Master Thesis provides much simpler approach. It cannot be said that the presented approach is a correct and complete one, but it provides guidelines and can be a part of more complex calculations and a tool in possible prediction of future flash floods. Combining precipitation forecast and threshold methods would provide additional benefit to establish an effective warning system.

7. Conclusion

Today, urban environments are increasingly endangered due to unplanned and increasingly intensive construction of impermeable surfaces, but also inadequate project solutions. Because of such actions flash flood events occur more often in urban environments. In the future more precipitation in the city of Zagreb is expected, especially in winter period and a slight increase in Autumn (*Strategija prilagodbe klimatskim promjenama u Republici Hrvatskoj za razdoblje do 2040. godine s pogledom na 2070. godinu*, 2020)

The aim of this thesis was to determine a reliable indicator to predict flood events caused by heavy rainfall in the city of Zagreb. It was determined that maximal accumulated rainfall during 1 hour most accurately correlates to the flood events indicators in the observed area in the city of Zagreb. From the crosslinked rainfall and intervention data, an empirical threshold was determined above which all rainfall events relate to interventions. The lower empirical threshold was inconclusive and other approaches were briefly introduced for future research guidelines. Verification of calculated values determined that the empirical threshold accurately predicts flood events in the observed area. From the peak storm intensity graph, it was determined that the upper threshold value for accumulated rainfall intensity above which almost all rainfall was related to flood events, i.e. to the flood impact indicators as

$$I = 23{,}189 \cdot D^{-0{,}701}$$

For events with a maximal accumulated rainfall over 1 hour of 23 mm or more, this would mean high risk of flood and a possible alarm trigger to set public services in a state of high readiness. Such prediction would be of great assistance to public services such as the Firefighting department, the State administration for protection and rescue or Local authorities, i.e. City administration. Adequate response could be planned and conducted in a timely manner. It should be noted that this is not a definitive threshold, but merely an indicator that presents a high likelihood of flood events. A more detailed analysis and evaluation should be done, and other approaches should be considered, before implementing such thresholds within public services. Also, link between flood impact indicators and flood hazard parameters should be established with field measurements of flood indicators in order to additionally validate results obtained in this approach.

Further research should be aimed at analyzing rainfall data of other meteorological stations to determine threshold values for floods throughout the city. Rainfall data should be obtained for shorter time intervals (e.g. 10 min) for more precise results. Additional statistical analysis would also greatly contribute to the advancement of this research.

It is important is that precipitation extremes are included in creation of norms, especially ones considering new infrastructure in order to avoid flooding events in the future. Predicting whether a flood event will happen, appropriate response can be planned. By applying smarter solutions in the city planning, floods could be mitigated or even prevented. Conventional hydrotechnical solutions should be used together with new approach such as implementation of green infrastructure. These measures should be approached on a multidisciplinary level.

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9. Curriculum Vitae

Tena Kovačić was born 3rd February 1993 in Varaždin. She lives in Ludbreg where she finished elementary school. From 2007 to 2011 she went to secondary school Druga gimnazija Varaždin. She obtained her bachelor degree as Professional Bachelor of Sustainable Development with main field of study Environmental Engineering at The Polytechnic of Međimurje in Čakovec which she attended from 01.10.2015. to 04.09.2018. She has enrolled Faculty of Agriculture, University of Zagreb 1st October 2018 with main field of study Environment, agriculture and resource management (INTER-EnAgro). She has a past experience in multiple projects such as Rotary youth camp in Copenhagen, Denmark (01.02.2017. – 01.03.2017.), Youth exchanges (Erasmus+) project Inspiration in Vindfjell, Norway and Green movement project in Diyarbakir, Turkey (01.10.2018. – 10.10.2018.). She attended EIT Climate-KIC Journey summer school held in Berlin, Utrecht and Budapest (04.08.2019. – 31.08.2019.) She was also a part of an international student exchange through CEEPUS program at University of Natural Resources and Life Sciences (BOKU), Vienna (01.03.2020. – 30.06.2020.). She is advanced user of Word and Excel and has an experience in working in Quantum GIS software. Her hobbies are reading and dancing as she is a member of Folklore ensemble Anka Ošpuh in Ludbreg.

LANGUAGE SKILLS:

Croatian Native language

	UNDERSTANDING	SPEAKING	WRITING
English	C1	B2	B2
German	B1	A2	A2