TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

ANYLISIS OF TALLINN PRECIPITATION INTENSITY ACCORDING TO ESTONIAN WEATHER SERVICE DATA IN 2010-2018

TALLINNA SADEMETE INTENSIIVSUSE ANALÜÜS AASTATEL 2010-2018 RIIGI ILMATEENISTUSE TALLINN-HARKU AEROLOOGIAJAAMA ANDMETEL

MASTER THESIS

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Tallinn 2020

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THESIS TASK

Student: Inga Tennokese, 104983EABMM

Study programme: EABM03/09 – Environmental and Management

Supervisor: Karin Pachel PhD, Department of Civil Engineering and Architecture

Thesis topic:

(in English) *ANALYSIS OF TALLINN PRECIPITATION INTENSITY ACCORDING TO ESTONIAN WEATHER SERVICE DATA IN 2010-2018*

(in Estonian) TALLINNA SADEMETE INTENSIIVSUSE ANALÜÜS AASTATEL 2010-2018 RIIGI ILMATEENISTUSE TALLINN-HARKU AEROLOOGIAJAAMA ANDMETEL

Thesis main objectives:

1. Digitalization of the precipitation data of the Tallinn-Harku aerology plant in cooperation with the Weather Service.
2. Processing of precipitation data for Tallinn-Harku aerology plant 2010-2018.
3. Analysis of precipitation data for Tallinn-Harku aerology plant 2010-2018.

Thesis tasks and time schedule:

No	**Task description**	**Deadline**
1.	Digitalization of Weather Service precipitation data in 1923-1990	25.03.2019
2.	Aggregation, processing and analysis of precipitation data	22.10.2019
3.	Writing the Master´s thesis	25.05.2020

Language: english **Deadline for submission of thesis:** “25” May 2020

Student: Inga Tennokese .... “2” January 2020

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PREFACE

The Master thesis has been completed on the basis of data from the Tallinn-Harku aerology station of the Estonian Weather Service.

For receiving the data, I would like to thank Miina Krabbi Head of Meteorological Observation Department of Environment Agency. For processing data in Excel, I would like to thank Tanel Pihel a financial analyst at Euroapteek PLC.

I would like to thank Kaspar Tennokese a member of the council of the Estonian Society of Water Supply and Sewerage Engineers Association, for the discussing and co-thinking in the master´s thesis.

I would like to thank Karin Pachel, who was the supervisor of my master´s thesis, and who helped and was supportive in completing my master thesis.

In the Master's thesis, the precipitation of an 8-year observation series and their intensities have been studied, the analysis has been carried out using data from the Tallinn-Harku aerology station of the Estonain Weather Service. The aim of this Master's thesis is to find out what the share of intensvese precipitation has been and to study its possible changes over time.

INTRODUCTION

Climate change is already being felt in Europe as well as in the whole world. The average world temperature, which is already 0.8 °C higher than in the pre-industrial era, is still rising. During the last decade, the average temperatures on the European mainland have been 1.3 °C above the pre-industrial average, which means that in Europe temperatures have been rising more quickly than the world average. Due to climate change, land and ocean temperatures will rise, and the amount, intensity and distribution of precipitation will change, which will cause a rise in average sea levels globally, together with the risk of erosion along the coasts. In many regions, change in precipitation patterns, together with the melting of snow and ice, will change hydrological systems, which has a quantitative and qualitative impact on water resources. Natural processes will change and glaciers will melt, and in some regions (in Europe as well) this aggravates water shortage and expands the desertification process. [1]

In Estonia, the main factor influencing the climate is our geographical location. Estonia is situated in the boreonemoral zone of the Atlantic-Continental temperate zone between an oceanic and continental climate. According to the Köppen climate classification, Estonia belongs to type Dfb (warm summer humid continental climate), and only westernmost parts of Saaremaa and Hiiumaa belong to type Cfb (temperate oceanic climate).

Local variations are primarily caused by the Baltic Sea, which warms the regions and islands in winter and cools them down in spring. Terrain, especially in the south-eastern parts and in Pandivere Upland, plays important role in the distribution and duration of snow cover. [2]

Since in Estonia precipitation is almost two times higher than evaporation, the climate is very humid. Average annual precipitation is 550–700 mm, and the variation is from 520 mm on some islands to 740 mm in uplands. Seasonal variations in precipitation are similar all over the territory. The driest months are February and March; from then on, monthly rainfall numbers increase steadily. The most humid months are July and August, and towards winter, rainfall decreases. [3]

Climate is long-term average of the atmosphere in a particular location. To describe a climate, typically the average values of meteorological elements from decades of measurements are presented together with extreme values for different periods (months, seasons, etc.). It is important to assess the occurrence of dangerous types of weather and meteorological phenomena (e.g. extremal temperatures, storms, extremely dry or rainy summers). The World Meteorological Organization (WMO) has agreed upon 30-year periods for calculating climate parameters, the last of which was 1961-1990.

Although the average precipitation in Estonia for the period 1961-2008 is characterized by an upward trend (Figure 1), we cannot consider it reliable due to the great variation in precipitation. [4]

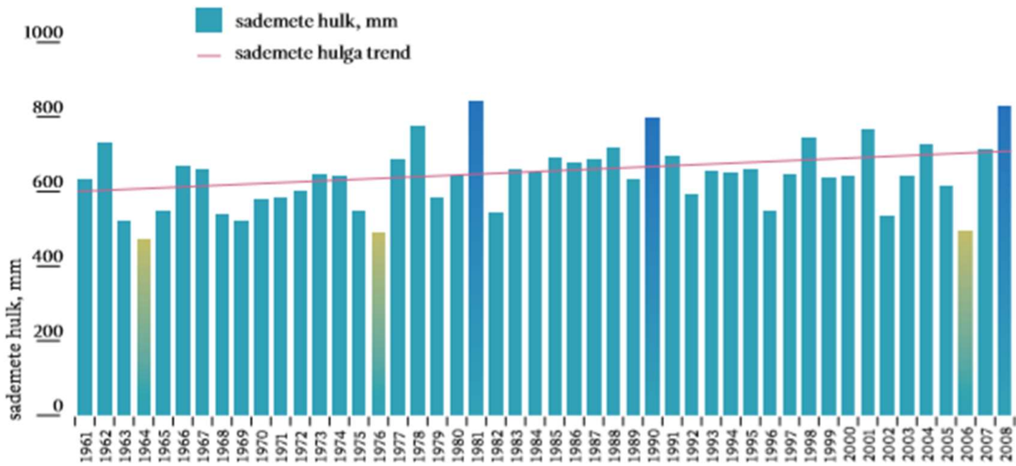


Figure 1. Annual average precipitation in Estonian meteorological stations together with trends for the period 1961-2008. Source: Estonian Weather Service. [4]

In Estonia, the average annual total precipitation is about 200-300 mm higher than evaporation or seepage. Various researchers have noticed the increase in high-intensity rainfalls; the general intensity of rainfall is increasing and the water volume of extreme rainfalls among the general amount of precipitation is also increasing. Measuring extreme rainfall is difficult, since these are rare and local events do not necessarily take place near present meteorological stations. Therefore, randomness plays an important role in obtaining information. In Estonia and in neighbouring countries, we foresee an increase of about 10 to 20 per cent in average precipitation as well as more even distribution throughout the year and a decrease in river flooding. Another possible scenario is that in the future (i.e. during the lifetime of stormwater drainage systems constructed now), the average annual precipitation in Estonia will decrease. Rainfall above 30 mm a day is considered a rare event also in the future (days with strong rainfall mean precipitation over 10 mm, and these usually occur in summer). [5]

According to the research presented in the article *A comparison of methods for estimating climate change impact on design rainfall using a high-resolution RCM*, the rise in precipitation is foreseen. Despite the variations between different methods, 20 to 35 per cent of increase in rainfall over the coastal region is consistently projected. This will pose significant challenges for existing infrastructure in that area. [6]

In Estonia, the basic standard for designing stormwater drainage systems for streets and territories is EVS 848:2013 *Sewer systems outside buildings.* The standard for public utilities as defined by EVS 843:2016 *Urban streets* must also be taken into consideration in designing streets. The methodology as defined by standard EVS 848 is used in many countries and described in many manuals. Before the 1990s, instructions based on SNiP ("construction norms and regulations", the guidelines used in the Soviet Union) and adjusted to Estonian climatic conditions were used to design stormwater and sewer systems in Estonia. In the present standard, the data and formulae for Estonia are from the early 1960s, from the dissertation by Arnold Kõiv (1965) published in extended version in the textbook *Veevarustus ja kanalisatsioon (Water supply and Sewerage)* (1968). When the present standard EVS 848:2013 was written, neither changes from the last 50 years in measuring precipitation nor other data considering climate change were taken into account. [7]

The standard EVS 848 needs updating due to expiration (renewal frequency for a standard is 5-7 years), but underlying data also needs updating. This work has already begun. Therefore, thorough analysis of the source data is very important, since the conclusions obtained influence the standards the designs are based on, and through that the risk of floods and financial costs. This gives practical value to the present thesis.

The aim of the thesis is to analyse the precipitation monitoring data collected from 2010 to 2018 by the Tallinn-Harku aerological station of the Estonian Weather Service. In spite of the short time series for metering, the intensity of precipitation for various durations of rainfall, the possible occurrence of a maximum point, probability based on rainfall intensity, and the occurrence of rainfalls with different length are analysed. Additional value is received by comparing rainfall tendencies with data collected and analysed by Tallinna Vesi AS.

1. OVERVIEW

1.1 Rainfall and floods

Intensive rainfall with a longer or shorter duration is one of the main environmental risk factors. It may cause rapid floods and rises in the ground-water table, and water may rise in rivers and lakes, which may cause floods. Strong rain may cause quickly emerging floods, so-called flash floods, while long-lasting rainy seasons may cause floods over larger territories, fill ditches and cause overload in sewer systems as well as the rise of water table in major water bodies and in groundwater. Floods may also be caused by rapid melting of snow when the ground is not able to absorb all the additional water and rivers carry it away. All over the world, flood risk caused by rainfall is considered to be the most important weather risk. Compared to many other countries, the risk of very heavy rain is significantly smaller in Estonia. [8]

To manage this risk, all the member states of European Union, including Estonia, are obliged to apply the basin-based Floods Directive. This means preliminary risk assessment concerning floods, danger lists and risk mapping as well as mitigation plans. [9]

According to models, the following climate changes are foreseen for Estonia for the 21st century:

- A rise in temperatures, which during the second half of the 20th century has been more rapid in Estonia than the world average, and the resulting diminishing of ice and snow coverage as well as longer heat-waves and droughts;
- An increasing amount of precipitation, especially in winter, with accompanying floods;
- A rise in sea level with accompanying erosion in coastal areas, pressure for relocation of buildings, etc.;
- More frequent storms with accompanying floods.

The aim of climate scenarios is to model the spatial and temporal variability of human-induced factors influencing the climate. We need several scenarios, since general development of the societies, especially the accompanying environmental effects could be modelled only ambiguously. [10]

1.2 Precipitation and methods for measuring them

The amount of precipitation is the depth of water on a horizontal surface measured in millimetres. Measuring the amount of precipitation is one of the main tasks of Estonian meteorological stations. For a half of a century, this has been done by using the Tretyakov precipitation gauge. Precipitation is recorded from 6 p.m. till 6 p.m. the next day (GMT). Until 2002, precipitation was measured four times a day: at 03:00, 06:00, 15:00 and 18:00 (GMT). Since transition to automatic precipitation gauges is taking place, in order to find better and more reliable models, parallel measurements are taken. Automatic gauges enable the determination of the amount of precipitation for any period.

Precipitation is classified according to its physical state:

- liquid (rain, shower, drizzle, ice-rain);
- solid (snow, snow shower, graupel, snow pellets, ice pellets, ice needles);
- mixed type (sleet, showers of rain and snow).

All the types are characterized by three intensities: weak, average and strong.

The meteorological stations, which work 24/7, record the time of the beginning and end of precipitation as an atmospheric phenomenon and these data enable us to calculate the duration of a rainfall/snowfall.

Rain intensity is the amount of precipitation in a time unit, usually millimetres per one minute. Until 2003, the rain intensity was measured with equipment called a pluviograph – an automated writer of rains. The ink-filled pen of the pluviograph drew the change in water level in the gauge onto a paper tape moving on drum driven by clockwork. By making measurements on these paper tapes, it was possible to find the rising water level and corresponding average intensity of rainfall for 10-minute interval. Modern electronic precipitation gauges record, in addition to the amount, the intensity of precipitation, but in order to support the reliability of the data it is necessary to solve some methodological problems. This is especially critical in countries where the precipitation occurs in liquid, solid and mixed forms.

Rainfall usually consists of several parts with different intensity. In warm seasons, the majority of rainfall occurs in short periods, with the final part of the rainfall being less intensive. The second increase in intensity within one and the same shower is caused by the arrival of the second cumulonimbus cloud. [8]

1.3 Strong rainfall and its causes

In the case of strong rainfall, precipitation is accumulated so quickly that exceeds the criterion typical to a particular geographical region. The value varies greatly across the globe. Here, strong rain is also described as so intensive that the soil does absorb the water. However, in numeric parameters, rain is considered intensive, if the amount of precipitation per minute is 1 mm or more.

The present official definition for Estonia is that severely hazardous precipitation is 30 mm or more per hour or a shorter period or 50 mm or more over 12 hours or a shorter period.

In Estonia, extremely intensive rainfalls are usually not long. A strong downpour usually lasts for less than an hour and the intensity varies greatly in time and space. Therefore, it is difficult to register the intensity of rain for every short period as well as its duration, location and the amount of precipitation.

Strong rainfall comes from large cumulonimbus clouds. These clouds grow to great heights due to upward air currents and may sometimes extend into the upper limit of the troposphere, which is at 12-14 km at our latitude. Favourable conditions for the formation of this cloud type are created by cyclones. Cyclones may be extremely deep and extensive and cause lasting and intensive rainfall over large territories. Often this type of rain is accompanied by strong winds. From 1961 to 2005 there were 199 days when 50 mm or more of the precipitation was measured in at least one of the meteorological, hydrological or precipitation measuring stations in Estonia. Of these, 54 per cent of such occurrences were created by cyclones with the centre passing directly over Estonia or very close; 34 per cent were caused by a passing atmospheric front; and 12 per cent were associated with local cumulonimbus clouds developing due to warming surfaces in the condition of high moisture without being connected to a cyclone or front (convective rain). [8]

1.4 History of the Tallinn-Harku Aerological Station

In 2000 the need for more modern equipment became apparent in Estonia beacause some of the weather stations were outdated and in poor condition; at the same time, interest had emerged in obtaining real-time high-quality weather information. The first automated station was installed on December 15, 2001: the Tallinn-Harku Aerological Station, MILOS 520 type equipment from Finnish company Vaisala started to collect

data. The next year, fifteen stations were replaced with automated stations; in 2003 six stations were replaced.
In addition to on-ground monitoring, remote monitoring is important. Radiosonde monitoring began in Tallinn in 1953. From 1953 to 1977, the station was situated in Kose, the eastern part of Tallinn. Since 1977, radiosonde monitoring has taken place at the Tallinn-Harku Aerological Station.
The first radar, which started operating at Tallinn-Harku Aerological Station in 1975, was replaced in 2000 with a special Meteor 500C (Doppler technology) weather radar. It enabled observation of weather from the station´s location up to central Estonia. The second new-generation radar (Dual-Pol technology), which started operating in 2008, is situated in Sürgavere. A year later, the Tallinn-Harku Station got itself a similar radar. These two radars belongs to several international networks: NORDRAD, BALTRAD and EUMETNET OPERA. [2]

1.5 Measuring precipitation on the ground

Precipitation is atmospheric water falling to the ground in liquid or solid form (rain, drizzle, sleet, snow, hail, snow pellets, ice pellets, graupel, ice-rain, freezing rain, freezing drizzle).
Often, products of atmospheric humidity that condensate on ground (dew, ground frost, glaze, white frost) are also called precipitation.
Precipitation is expressed through several parameters:

- Volume of precipitation;
- Intensity of precipitation.

The amount of precipitation is understood as the layer of rain water (in mm) forming on a horizontal surface that does not run off, seep into ground or evaporate.
Precipitation intensity is understood as the amount of precipitation within a certain time unit.
Units of the International System of Units (SI) are used to determine the amount and intensity of precipitation:

- Amount of precipitation: mm (= 1 kg/m^2 = l/m^2);
- Intensity of precipitation: mm/min (SI standard is mm/h).

In many countries, the precipitation gauge O-1 (Tretyakov gauge) is used to measure the precipitation amount manually. The set consists of:

- A receiver with a catching area of 200 cm^2;
- A base for the receiver;
- A wind shield;
- A CO-200 measuring glass.

A Tretyakov precipitation gauge.

The precipitation gauge is mounted on the meteorological field so, that the catching area of the receiver is 2 m from the ground. Water collected into the receiver is measured using the measuring glass; every division of the glass corresponds to the depth of 0.1 mm. To get the millimetres, the number of divisions is divided by 10. The amount of precipitation is measured throughout the year at 06:00 a.m. and 06:00 p.m. UTC.

Due to automatization of the stations, since September 2003, the first RG13H automatic tipping bucket-type rain gauges started to record the amount of precipitation. These rain gauges work like a scale – there are two small buckets with a storage capacity of 0.2 mm at the two ends of the scale. When one bucket is full, its content is discharged and the second bucket is turned under the funnel. The RG13H gives satisfactory measurements only during warm seasons. The RG13H and QMR-102 tipping bucket-type rain gauges are still in use in hydrometric stations.

From 2006 to 2011, the whole meteorological monitoring network switched over to VRG-101 scale-type automatic precipitation gauges (with a wind shield), and since the 2011 OTT PLUVIO2 (with and without a wind shield) has been used. Both precipitation gauges have a catch area situated 1.5 meters above the ground. The volume of precipitation is recorded every hour. Since 2010, the total volume of precipitation has also been recorded in 10-minute intervals. [11]

This is the reason why these data are analysed since November 2010; earlier data are given with the interval of one hour.

In 2017 the Environmental Agency’s Estonian Weather Service compared its precipitation data with the data from AS Tallinna Vesi. The Environmental Agency’s Estonian Weather Service uses the weighing bucket method, while AS Tallinna Vesi uses the tipping bucket method. Nine monitoring stations of AS Tallinna Vesi (Ädala 10, Rumbi 2B, Järvevana 3, Punane 38, Paldiski mnt 225, Tondi 40, Mahla 40, Voolu 13 and Meremehe 16) were analysed together with Harku Meteorological Station. The data from Harku Meteorological Station differed from the data of AS Tallinna Vesi. This difference was quite significant, and thus we can conclude that since the methods were different and the types of measuring device were different, this is the reason for the difference in the results. [12]

1.6 Tallinn-Harku Aerological Station

Location: Paldiski mnt. 245, Tallinn, Harjumaa

Latitude: N 59°23´53´´

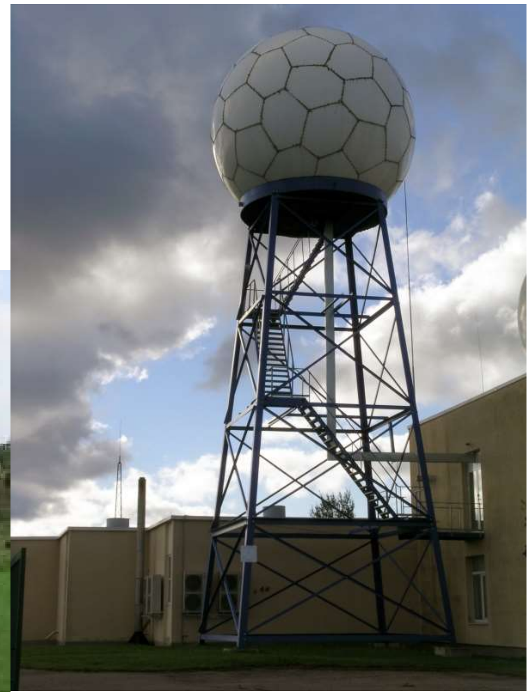
Longitude: E 24°36´10´´

The altitude of the observation field: 33.16 m (EH2000)

Beginning of aerological monitoring: 1946

Beginning of meteorological monitoring: 1805

Automatization of meteorological monitoring: 2003



Measured and observed parameters:

- Air temperature
- Ground temperature
- Minimal temperature of air at 2 cm above the ground
- Soil temperature: in the depth of 5, 10, 15 and 20 cm
- Soil temperature under a grass layer: in the depth of 0,2, 0.4, 0.8, 1.2, 1.6, 3.2 m
- Atmospheric humidity
- Atmospheric pressure
- Precipitation
- Wind: direction, speed
- Clouds: amount, types, altitude
- Range of vision
- Atmospheric phenomena
- Ground state
- Snow depth on the observation field
- The layer of frost/glaze
- Duration of sunshine
- UV index
- Total radiation
- Data from radiosonde
- Data from pilot balloon
- Radar [13]

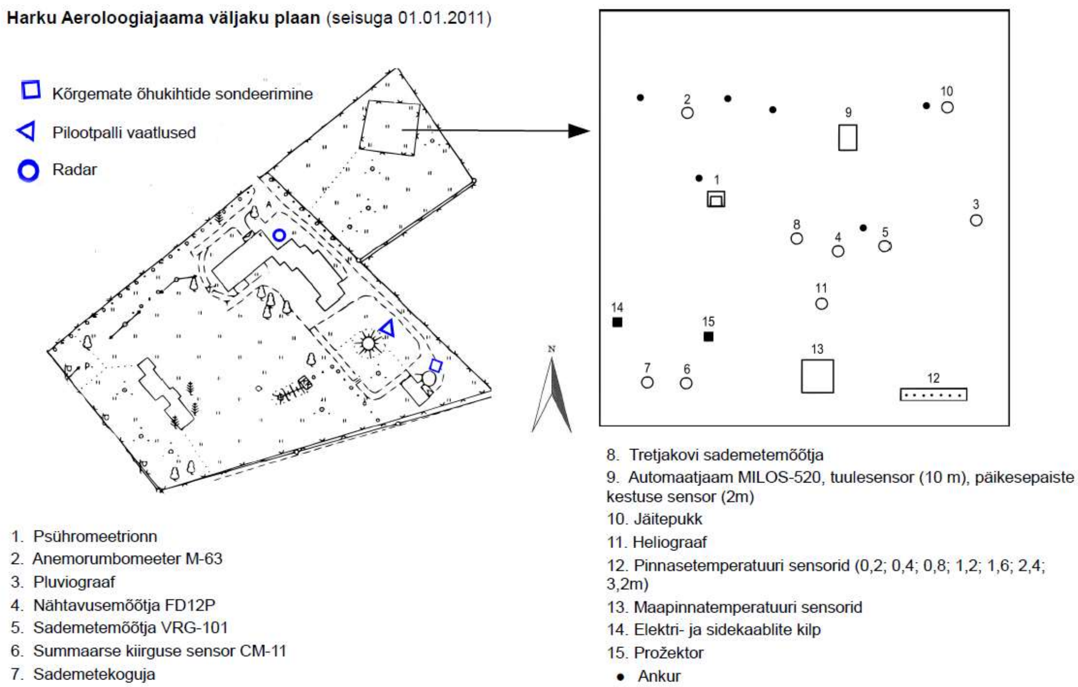


Figure 2. The plan of Harku Aerological Station [14]

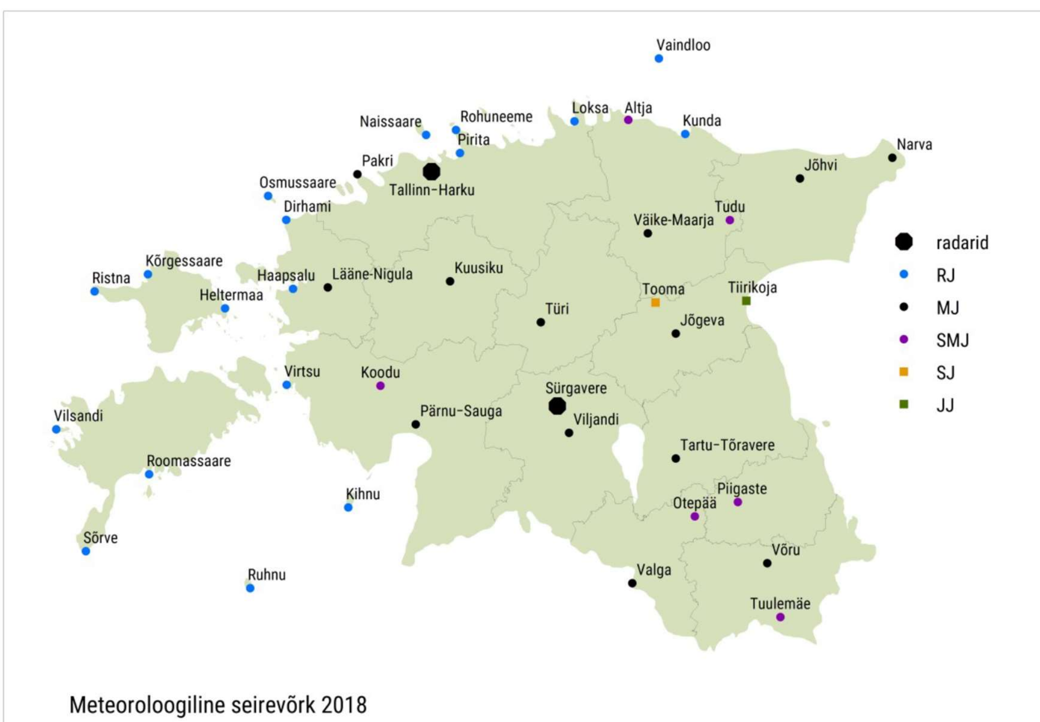


Figure 3. The network of monitoring stations in Estonia in 2018

The radars of monitoring network are situated in the aerological stations of Sürgavere and Tallinn-Harku. [14]

1.7 Legislation in Estonia and in other countries

In the countries of the European Union no unified requirements have been set for stormwater drainage systems. Helcom (the Baltic Marine Environment Protection Commission) is an organization for international environmental cooperation for the wellbeing of the Baltic Sea and has issued document 23/5 which gives general guidelines for controlling water pollution and stormwater in the Baltic Sea region. In Estonia, legislation, regulations and standards dealing with stormwater are the following: [15]

- "Water Act[1]";
- "Environmental Charges Act";
- "Public Water Supply and Sewerage Act";
- Regulation of the Minister of the Environment No. 61 from 2019 on *Requirements for wastewater treatment and discharging wastewater, stormwater, quarry water and cooling water to a receiving water body, compliance assessment measures and limit values for contaminants*[1];
- EVS 848:2013 *Sewer systems outside buildings*;
- EVS 846:2013 *Draining systems inside buildings;*
- EVS 843:2016 *Urban streets.*

1.7.1 Estonian Water Act and standard EVS 848:2013

The aim of the Water Act is to guarantee the cleanness of water and ecological balance in inland water bodies transboundary water bodies and groundwater. Accordingly, limit values for pollutant concentration of storm water for discharge into stormwater drainage systems must correspond to the Regulation of the Minister of the Environment No. 61, dated 08.11.2019. [16]

According to Regulation No. 61, a separate stormwater drainage system could be used only for discharging water with pollutant parameters not exceeding the limits set by Appendix 1 of this regulation for a wastewater collection areas with a pollutant load of 2000–9999 i.e., except suspended solids, which should not exceed 40 mg/l, and oil products, which should not exceed 5 mg/l.

In discharging wastewater, stormwater, quarry water and cooling water to a receiving water body, it must be guaranteed that the status of aquatic ecosystems and connected terrestrial ecosystems will not deteriorate. [17]

In this act, stormwater means water that has fallen as precipitation and that is collected and discharged through construction works, including ditches. [16]

The term calculated rainfall intensity in the standard EVS 848:2013 is defined as the theoretical intensity of rainfall determined by calculations. Rainfall intensity is the amount of rain falling over an area in time.

According to the standard EVS 848:2013, calculated intensity of rainfall depends on the duration of the rainfall. In the case of a lack of statistical data from monitoring stations and if

the duration T is 10 t0 60 minutes, the intensity can be calculated using the formula:

$q= B/T^n$,

where B is a variable calculated from the following formula

n is the exponent

T is the duration of the rainfall [min]

$B= 20^n * q_{20} * (1+c * \log p)$,

where q_{20} is rainfall lasting for 20 minutes and occurring once a year [l/s*ha],

n, c are empirical coefficients depending on the geographical location,

p is the recurrence period of calculated rainfall in years.

According to the standard, the parameters for Tallinn are: q_{20}=69,5, n=0,72 and c=0,8.

The recurrence period of calculated rainfall is defined as the average interval between two rainfalls with equal intensity. The rainfall recurrence period p depends on rainfall probability expressed in percent.

$p_b =(1-e^{-1/p}) * 100$ [%]

The approximate relationship between the recurrence period and probability are available in the table in this standard.

A short rainfall is rain lasting 5 to 10 minutes, and a long, lasting rainfall is rain that lasts 60 to 180 minutes. The standard gives corresponding formulas.

The formula for a short, 5-0-minute rainfall:

$q= aB/T^{n'}$

For a long, 60-180-minute rainfall:

$q=bB/T^{n''}$,

Where the values for the parameters a, b, n' and n'' are given in the table in the standard and depend on the meteorological zones of Estonia.

In calculating the rainfall intensity, we take the duration T equal to the rainwater flow time from the most distant point of the drainage area to the point of calculations.

Influx time is derived from the time the water flows over the surface and within the collector up to the point of calculations. [18]

1.7.2 Legislation in Finland

The main legislative acts organizing stormwater management in Finland are the following:

- "Land Use and Building Act" (222/2003, MRL);
- "Water Service Act" (119/2001, VHL);
- "Water Act" (587/2011, VL);
- "Flood Risk Management Act" (620/2010).

„Flood Risk Management Act" and the regulation (659/2010) based on this act stipulate: The planning of management of seawater and stormwater floods. The aim of the act is to reduce flood risk, prevent and mitigate unfavourable effects on human health, infrastructure, the economy and the environment; and improve preparedness for floods. According to the flood risk act, the risk from a rising sea and strong rainfall in the urban environment need more systematic assessment based on common, state-harmonized grounds. In addition to water management measures, special attention must be paid to land use planning and construction management, and to rescue missions. The aim of the law is also to harmonize the management of flood risks and other watersheds, taking into consideration the sustainable use and protection of the water resources. Flood risk and regulations are established by the state, which applies the EU directive on the assessment and management of flood risk (2007/60/EC). [19]

2. ANALYSIS OF PRECIPITATION INTENSITY

2.1 Raw data

Within the present master's thesis, data collected through measurements by the Estonian Weather Service during the 2010-2018 period was processed. The raw data came from the Environmental Agency in the form of the automatic readout of the measuring stations as an Excel table. Precipitation data are presented in 10-minute intervals from November 1, 2010 to November 30, 2018. The measured data are presented with 10-minute intervals regardless whether it rained or not (Table 1).

Table 1. An example of the raw data obtained from the Environmental Agency.

Tallinn-Harku				
Year	**Month**	**Day**	**Time (UTC)**	**Sum of precipitation for 10-minute, mm**
2018	1	1	00:00	0.0
2018	1	1	00:10	0.0
2018	1	1	00:20	0.0
2018	1	1	00:30	0.0
2018	1	1	00:40	0.0
2018	1	1	00:50	0.0
2018	1	1	01:00	0.0
2018	1	1	01:10	0.3
2018	1	1	01:20	0.1
2018	1	1	01:30	0.1
2018	1	1	01:40	0.1
2018	1	1	01:50	0.1
2018	1	1	02:00	0.1
2018	1	1	02:10	0.1
2018	1	1	02:20	0.1
2018	1	1	02:30	0.0

A rainfall is an event when precipitation (at least 0.1 mm) has occurred for at least 10 minutes and the interval between it and other rainfalls has been at least 10 minutes.
The raw data was not simplified, and rainfalls with low intensity were also not left out of the analysis. Also, no limits were set for the duration of rainfall, which is mainly expressed through the large number of rainfalls that occurred, and influences the probability of the occurrence of rainfall with various intensity.

2.2 Spreadsheet processing of the data

The first step was to filter out all the occurred rainfalls. The second step was to find the duration of the rainfall, i.e. determine the beginning and end of the rainfall. The third step was to calculate the intensities for the rainfalls.
In order to calculate the intensity, we need to know the amount of precipitation and the length of a rainfall. Meteorologically, rain intensity is calculated from the formula
$i=h/t$ mm/min, where
h – the thickness of precipitation layer (mm)
t – duration in minutes [20]

To find the rainfalls, the data was consolidated into one field (day, month, year, etc.) to get smaller a data volume for processing. Since we have data only for rainfall periods and the minimal length was set to 10 minutes, the automatic formula in Excel will search whether the series stand for continuing rainfall, the end of a rainfall or a new rainfall (Beginning, Continues, End). All continuing rainfalls are attributed to a unique number, the beginning and end of the rainfall. As appropriate, rainfalls with different duration (10 min, 20 min, etc.) were found among the continued rainfalls, together with precipitation amounts for the periods. Within all the continuous rainfalls, the period with highest rainfall was determined. The next step was to filter out from the dataset the maximum by the length of the period (10 min, 20 min, etc.) for the continuous rainfalls. Thus, we may have a 10-minute rainfall, 20-minute rainfall, 30-minute rainfall etc. all within the same rain.

Table 2. Example of searching for rainfall maximums

Year	Month	Day	Time (UTC)	Sum of precipitation for 10-minute, mm	Time period, min	Intensity, mm/min
2010	11	3	16:20	0.0		
2010	11	3	16:30	0.3	10	0.03
2010	11	3	16:40	0.7	10	0.07
2010	11	3	16:50	0.4	10	0.04
2010	11	3	17:00	0.7	10	0.07
2010	11	3	17:10	0.3	10	0.03
2010	11	3	17:20	0.7	10	0.07
2010	11	3	17:30	0.8	10	0.08
		20-minute rain max 1.5				

Table 2 shows how maximal precipitation was found for a 20-minute rainfall. For that, we need to take a rainfall with its beginning and end, and from there find the maximal sum precipitation of two addends. The condition was that these addends follow one another. In this rainfall, 20-minute maximal sum addends were 0.7 mm and 0.8 mm, which gave us the result 1.5 mm. The maximal result of the same, a 10-minute rainfall is 0.8 mm. Going on from there, we get that maximal result for the 30-minute rainfall is 1.8 mm, etc. Thus, in the case of this rain, we can find the maximal rainfall for the rain lasting up to 70 minutes.

2.3 Non-uniformity of aggregated data

The data for Tallinn-Harku rainfall is available in the environmental register of environmental information, from Estonian meteorological yearbooks, and from the web page of the Estonian Weather Service.

Table 3 presents the summed precipitation (mm) by months for the period 2010-2018 from Estonian meteorological yearbooks. These data conform to the data available in the public portal of the Environmental Register (http://register.keskkonnainfo.ee/envreg/main#HTTP3AISoioXcf7XKLSTSIFwQap9veWyxS). Looking at the total precipitation by months from the web-page of Estonian Weather Service (https://www.ilmateenistus.ee/ilm/ilmavaatlused/sademed/sademete-kuu-summad/), we can see there automatic measurements and manual measurements. All the reports present manually measured data. Data from the Estonian Weather Service for the period 2010-2018 are presented in Table 4. In Tables 3 and 4, the blue background indicates discrepancies in data. Discrepancies are not too large, but they are still noticeable. Since these are Estonian official registries, it indicates that some non-uniformity occurs in collecting and presenting the precipitation data.

Table 3. Summed precipitation data (in mm) from Estonian meteorological yearbooks for the Tallinn-Harku station

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
2018	41.6	27	23.2	35.8	12.4	51.7	8.8	66.6	116.6	92.5	28.8	34.3	539.3
2017	*24.4*	32.3	*43.6*	*45.8*	11.6	85.3	*22.6*	180	89.7	*154.2*	*87.6*	*89.7*	*866.8*
2016	81.3	84.6	14	61.7	11.3	117.3	54.2	179.5	32.2	45.3	61.5	30.8	773.7
2015	69.3	33.5	29.3	50.8	36.5	50.6	95.3	37.2	48.1	9.7	57.1	72.6	590
2014	54.4	26.8	27.7	11.1	47.1	80.9	47.4	114.8	*27.3*	26.9	*38*	73.5	579.9
2013	43.8	37.6	*12.1*	32.7	*21.3*	53.5	22.2	*122*	25.1	68.5	79.7	68	*586.5*
2012	71.6	*39.1*	50.6	66.8	53.2	98.7	121	82.3	131.6	101.1	66.8	53.4	936.2
2011	51.4	22.3	23.1	10.4	49.7	80.6	160.2	53.8	87.9	*68.6*	*48.1*	125.3	*781.4*
2010	*27.7*	49.5	*51.5*	35.6	*63.4*	*43.4*	146.8	53.8	55.9	38.5	*105.9*	74.7	*746.7*

Table 4. Summed precipitation data (in mm) from the web page of the Estonian Weather Service for the Tallinn-Harku station

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
2018	41.6	27	23.2	35.8	12.4	51.7	8.8	66.6	116.6	92.5	28.8	34	539
2017	*20.6*	32.3	*43.5*	*45.3*	11.6	85.3	*22.4*	180	89.7	*152.8*	*86.3*	*87.7*	*857.5*
2016	81.3	84.6	14	61.7	11.3	117.3	54.2	179.2	32.2	45.3	61.3	30.8	773.2
2015	69.2	33.5		50.8	36.4		89.5	37.2		9.7	57.1		
2014		26.8	27.7	11.1	47.1		47.4	114.8	*15.2*	*27.8*	*37.8*		
2013	43.8	37.6	*12*	32.7	*21.8*	53.5	22.2	*121.1*	25.1	68.5	79.7	68	*586*
2012	71.6	*39.4*		66.8	53.2	98.7	121	82.3	131.6	101.1	66.8	53.4	
2011	51.4	22.3	23.1	10.4	49.7	80.6	160.2	53.8	87.2	*67.4*	*45.5*	125.3	*776.9*
2010	*27.6*	49.5	*51.4*	35.6	*63.6*	*42.6*	146.8	53.8	55.9	38.5	*106*	74.7	*746*

2.4 Analysis of the rainfall

Figure 4 presents the summed precipitation data from Tallinn-Harku Aerological Station for the years 2007-2018. In addition, annual sums are given for the period 1981-2010. From this figure, great annual variations are clearly visible. The rainfall was most abundant in 2012 (approx. 940 mm), followed by 2017 (870 mm), 2011 (780 mm) and 2016 (744 mm).

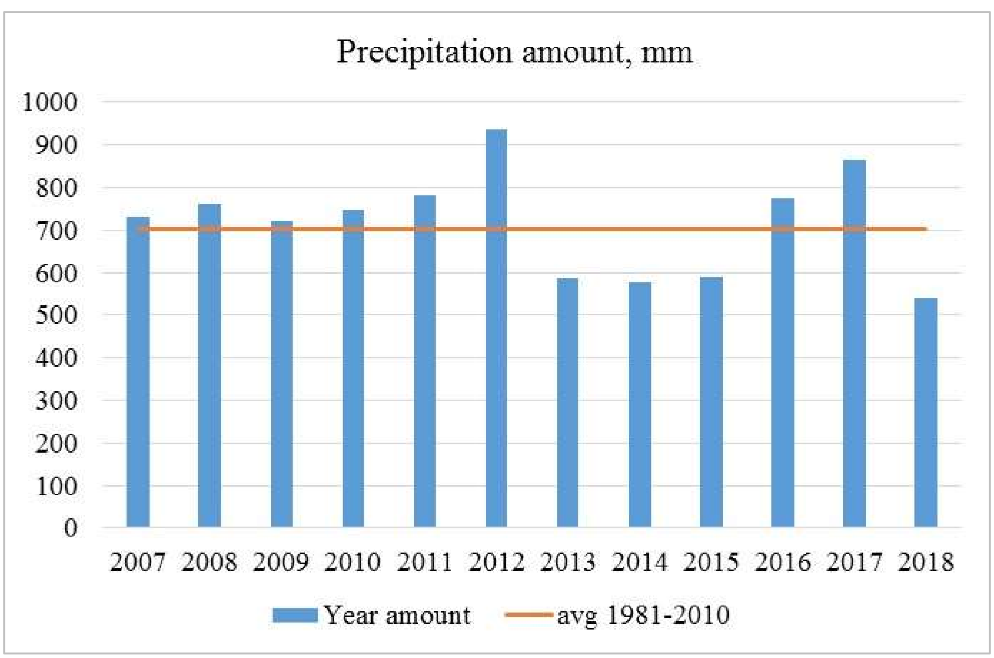


Figure 4. Precipitation at the Tallinn-Harku Aerological Station

In order to carry out more detailed analysis and characterize the rainfalls, I calculated minimums (min), maximums (max), means (avg), medians (median), and the limits for the 10th and 90th percentiles.

A deviation from the general pattern becomes an anomaly when the event is largely outside the general pattern of variation. If the anomaly is rare, i.e. when the frequency of the event occurring is in the 10th or 90th percentile (IPCC, 2001) the event is classified as extreme. [21]

The median is the average position of the distribution, with an equal number of elements on both sides. The median divides the statistical series into two equal parts.

In using statistical methods, the set of data is reduced into one, single value considered representative by the researcher, and this value is called either the statistical average or the arithmetic mean, and it describes the set as a whole.

Let the aggregate volume be N and the number of elements in it x_i. Then the arithmetic mean is:

$$\bar{x} = \frac{\sum x_i}{N}$$ [22]

In order to find the relationship between maximal rainfall intensity and rainfall duration, every period of rainfall occurrence must be analysed.

2.4.1 10-minute rainfalls

During the years 2010-2018, 7,329 rainfalls were registered with a duration of at least 10 minutes. The number of rainfalls was the largest in 2012 with 1048 rainfalls, followed by the year 2017 with 1042 rainfalls (Table 5). In these years, rainfall was also the most abundant (Figure 4). The 10-minute maximal intensity was the highest on 17 August 2017 with 1.03 mm/min, followed by 23 May 2011 with 1.2 mm/min. The next maximal intensities were on 28 November 2010 with 0.29 mm/min, 27 September 2012 with 0.82 mm/min, 08 August 2013 with 0.64 mm/min, 29 July 2014 with 0.9 mm/min, 17 July 2015 with 0.62 mm/min, 29 August 2016 with 0.94 mm/min and 2 August 2018 with 0.85 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer, with a few occurrences in late spring and early autumn.

The average values of the rainfall maximums are between 0.02 and 0.039. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 10-minute rainfalls 5,155 times, which makes up 70 per cent on the total number of rainfalls.

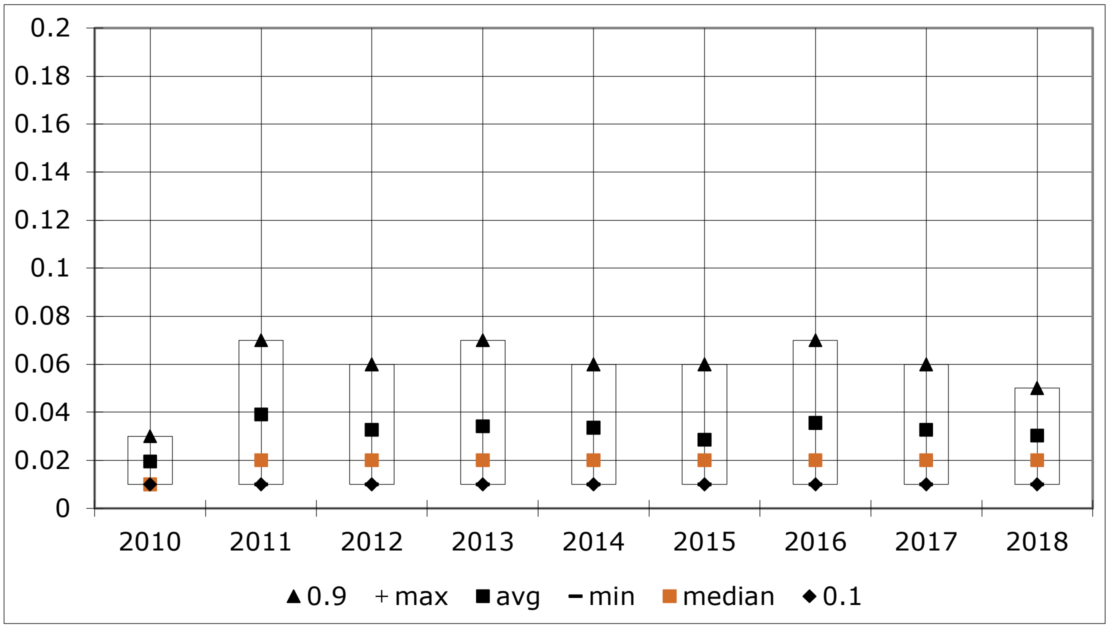


Figure 5. Differences in maximum intensities for 10-minute rainfalls in 2010-2018

A great variation in intensities are visible for all years except 2010, and this is also shown by the significant difference in the values of the median and the mean. The year 2010 has data from November.

Table 5. Differences in maximum intensities for 10-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	364	886	1,048	727	744	888	910	1,042	720
avg	0.020	0.039	0.033	0.034	0.034	0.029	0.036	0.033	0.030
max	0.29	1.02	0.82	0.64	0.90	0.62	0.94	1.03	0.85
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.9	0.03	0.07	0.06	0.07	0.06	0.06	0.07	0.06	0.05
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the period 2013-2014 and 2016.

2.4.2 20-minute rainfalls

During the years 2010-2018, 4,319 rainfalls were registered with a duration of at least 20 minutes. The number of rainfalls was the largest in 2017 with 636 rainfalls, followed by the year 2012 with 610 rainfalls (Table 6). In these years, rainfall was also the most abundant (Figure 4). The 20-minute maximal intensity was the highest on 17 August 2017 with 0.82 mm/min, followed by 29 August 2016 with 0.8 mm/min and 23 May 2011 with 0.79 mm/min. The next maximal intensities were on 7 November 2010 with 0.13 mm/min, 27 September 2012 with 0.55 mm/min, 08 August 2013 with 0.62 mm/min, 29 July 2014 with 0.51 mm/min, 17 July 2015 with 0.4 mm/min, 29 August 2016 with 0.8 mm/min and 23 September 2018 with 0.63 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer, with a few occurrences in late spring and early autumn.

The average values of the rainfall maximums are between 0.018 and 0.039. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 20-minute rainfalls 2,770 times, which makes up 64 per cent on the total number of rainfalls.

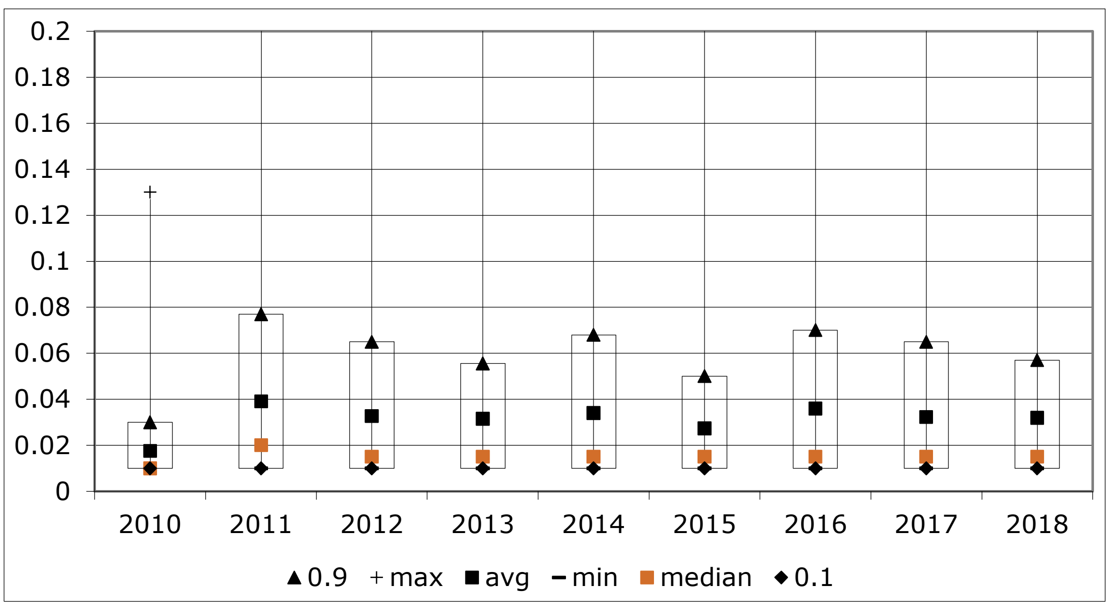


Figure 6. Differences in maximum intensities for 20-minute rainfalls in 2010-2018

A great variation in intensities are visible for all years except 2010, and this is also shown by the significant difference in the values of the median and the mean. The year 2010 has data from November.

Table 6. Differences in maximum intensities for 20-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	208	517	610	450	405	540	546	636	407
avg	0.018	0.039	0.033	0.032	0.034	0.027	0.036	0.032	0.032
max	0.13	0.79	0.55	0.62	0.51	0.40	0.80	0.82	0.63
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.9	0.03	0.08	0.07	0.06	0.07	0.05	0.07	0.07	0.06
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the years 2014 and 2016.

2.4.3 30-minute rainfalls

During the years 2010-2018, 2,874 rainfalls were registered with a duration of at least 30 minutes. The number of rainfalls was the largest in 2017 with 426 rainfalls, followed by the year 2012 with 423 rainfalls (Table 7). In these years, rainfall was also the most abundant (Figure 4). The 30-minute maximal intensity was the highest on 17 August 2017 with 0.7 mm/min, followed by 8 August 2013 with 0.62 mm/min and 11 July 2011 with 0.6 mm/min. The next maximal intensities were on 6 November 2010 with 0.11 mm/min, 27 September 2012 with 0.4 mm/min, 29 July 2014 with 0.37 mm/min, 17 July 2015 with 0.31 mm/min, 29 August 2016 with 0.56 mm/min and 23 September 2018 with 0.45 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.018 and 0.038. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 30-minute rainfalls 1,748 times, which makes up 61 per cent on the total number of rainfalls.

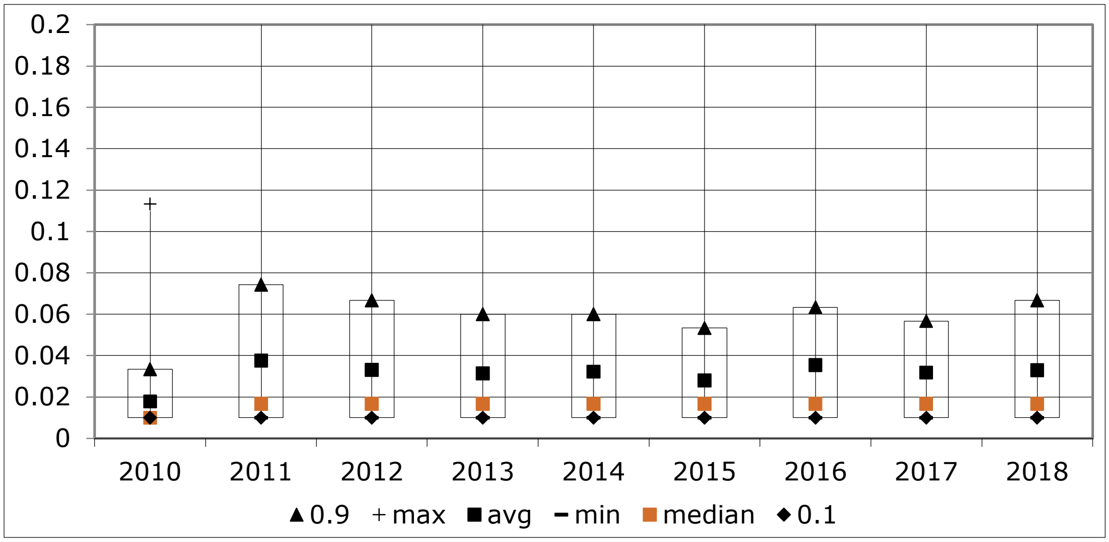


Figure 7. Differences in maximum intensities for 30-minute rainfalls in 2010-2018

A great variation in intensities are visible for all years except 2010, and this is also shown by the significant difference in the values of the median and the mean. The year 2010 has data from November.

Table 7. Differences in maximum intensities for 30-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	130	338	423	311	286	335	377	426	248
avg	0.018	0.038	0.033	0.031	0.032	0.028	0.035	0.032	0.033
max	0.11	0.60	0.39	0.62	0.37	0.31	0.56	0.70	0.45
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.9	0.03	0.07	0.07	0.06	0.06	0.05	0.06	0.06	0.07
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the years 2012, 2016 and 2018.

2.4.4 40-minute rainfalls

During the years 2010-2018, 2,046 rainfalls were registered with a duration of at least 40 minutes. The number of rainfalls was the largest in 2012 with 314 rainfalls, followed by the year 2017 with 307 rainfalls (Table 8). In these years, rainfall was also the most abundant (Figure 4). The 40-minute maximal intensity was the highest on 17 August 2017 with 0.57 mm/min, followed by 8 August 2013 with 0.53 mm/min. The next maximal intensities were on 7 November 2010 with 0.12 mm/min, 11 July 2011 with

0.46 mm/min, 27 September 2012 with 0.32 mm/min, 7 July 2014 with 0.29 mm/min, 17 July 2015 with 0.25 mm/min, 29 August 2016 with 0.45 mm/min and 21 June 2018 with 0.43 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.019 and 0.035. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 40-minute rainfalls 1,192 times, which makes up 58 per cent on the total number of rainfalls.

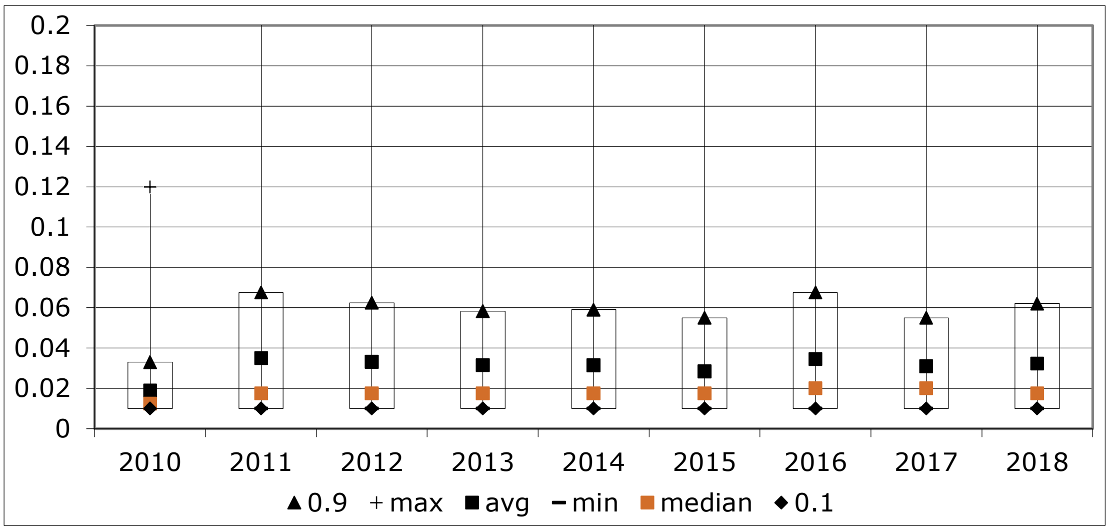


Figure 8. Differences in maximum intensities for 40-minute rainfalls in 2010-2018

A great variation in intensities are visible for all years except 2010, and this is also shown by the significant difference in the values of the median and the mean. The year 2010 has data from November.

Table 8. Differences in maximum intensities for 40-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	90	230	314	218	208	238	274	307	167
avg	0.019	0.035	0.033	0.031	0.031	0.028	0.035	0.031	0.032
max	0.12	0.46	0.32	0.53	0.29	0.25	0.46	0.57	0.43
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.9	0.03	0.07	0.06	0.06	0.06	0.06	0.07	0.06	0.06
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the years 2011 and 2016. Somewhat lower were the values for the period 2012-2014 and 2017-2018.

2.4.5 50-minute rainfalls

During the years 2010-2018, 1,517 rainfalls were registered with a duration of at least 50 minutes. The number of rainfalls was the largest in 2012 with 351 rainfalls, followed by the year 2017 with 229 rainfalls (Table 9). In these years, rainfall was also the most abundant (Figure 4). The 50-minute maximal intensity was the highest on 17 August 2017 with 0.47 mm/min, followed by 8 August 2013 with 0.45 mm/min. The next maximal intensities were on 6 November 2010 with 0.1 mm/min, 11 July 2011 with 0.37 mm/min, 15 July 2012 with 0.27 mm/min, 29 July 2014 with 0.24 mm/min, 17 July 2015 with 0.21 mm/min, 29 August 2016 with 0.41 mm/min and 21 June 2018 with 0.41 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer.

The average values of the rainfall maximums are between 0.019 and 0.035. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 50-minute rainfalls 844 times, which makes up 56 per cent on the total number of rainfalls.

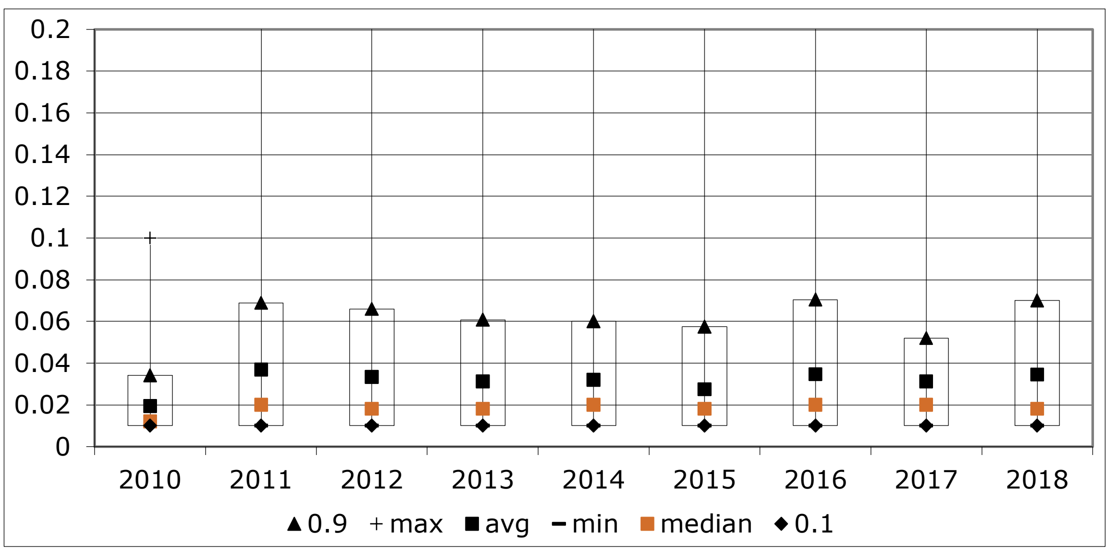


Figure 9. Differences in maximum intensities for 50-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011-2014 and 2016-2018, which is also indicated by a significant difference in the values of the median and mean. Smaller variations within a year have been seen only 2015, and these was the year of low rainfall.

Table 9. Differences in maximum intensities for 50-minute rainfalls in 2010-2018

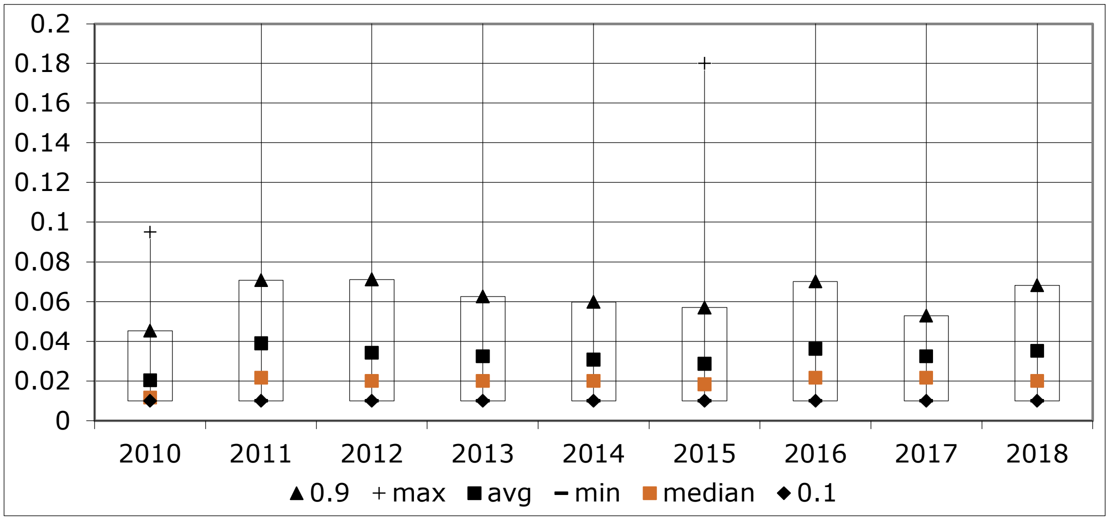
year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	61	167	251	157	147	184	210	229	111
avg	0.019	0.037	0.033	0.031	0.032	0.027	0.035	0.031	0.035
max	0.10	0.37	0.27	0.45	0.24	0.21	0.41	0.47	0.41
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.9	0.03	0.07	0.07	0.06	0.06	0.06	0.07	0.05	0.07
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the period 2012-2014 and 2016-2018.

2.4.6 60-minute rainfalls

During the years 2010-2018, 1,159 rainfalls were registered with a duration of at least 60 minutes. The number of rainfalls was the largest in 2012 with 204 rainfalls, followed by the year 2017 with 184 rainfalls (Table 10). In these years, rainfall was also the most abundant (Figure 4). The 60-minute maximal intensity was the highest on 8 August 2013 with 0.44 mm/min, followed by 17 August 2017 with 0.42 mm/min. The next maximal intensities were on 6 November 2010 with 0.1 mm/min, 11 July 2011 with 0.31 mm/min, 27 September 2012 with 0.26 mm/min, 22 August 2014 with 0.21 mm/min, 17 July 2015 with 0.18 mm/min, 23 August 2016 with 0.36 mm/min and 21 June 2018 with 0.38 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn. The average values of the rainfall maximums are between 0.02 and 0.039. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 60-minute rainfalls 598 times, which makes up 52 per cent on the total number of rainfalls.



10. Differences in maximum intensities for 60-minute rainfalls in 2010-2018

A great variation in intensities are visible for all years except 2010, and this is also shown by the significant difference in the values of the median and the mean. The year 2010 has data from November.

Table 10. Differences in maximum intensities for 60-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	48	116	204	113	112	140	160	184	82
avg	0.020	0.039	0.034	0.032	0.031	0.029	0.036	0.032	0.035
max	0.10	0.31	0.26	0.44	0.21	0.18	0.36	0.42	0.38
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.9	0.05	0.07	0.07	0.06	0.06	0.06	0.07	0.05	0.07
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the years 2012, 2016 and 2018.

2.4.7 70-minute rainfalls

During the years 2010-2018, 903 rainfalls were registered with a duration of at least 70 minutes. The number of rainfalls was the largest in 2012 with 157 rainfalls, followed by the year 2017 with 149 rainfalls (Table 11). In these years, rainfall was also the most abundant (Figure 4). The 60-minute maximal intensity was the highest on 8 August 2013 with 0.43 mm/min, followed by 17 August 2017 with 0.38 mm/min. The next maximal intensities were on 6 November 2010 with 0.09 mm/min, 30 July 2011 with 0.22 mm/min, 27 September 2012 with 0.23 mm/min, 22 August 2014 with 0.19 mm/min, 17 July 2015 with 0.16 mm/min, 29 August 2016 with 0.35 mm/min and 21 June 2018 with 0.34 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn. The average values of the rainfall maximums are between 0.019 and 0.039. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 70-minute rainfalls 437 times, which makes up 48 per cent on the total number of rainfalls.

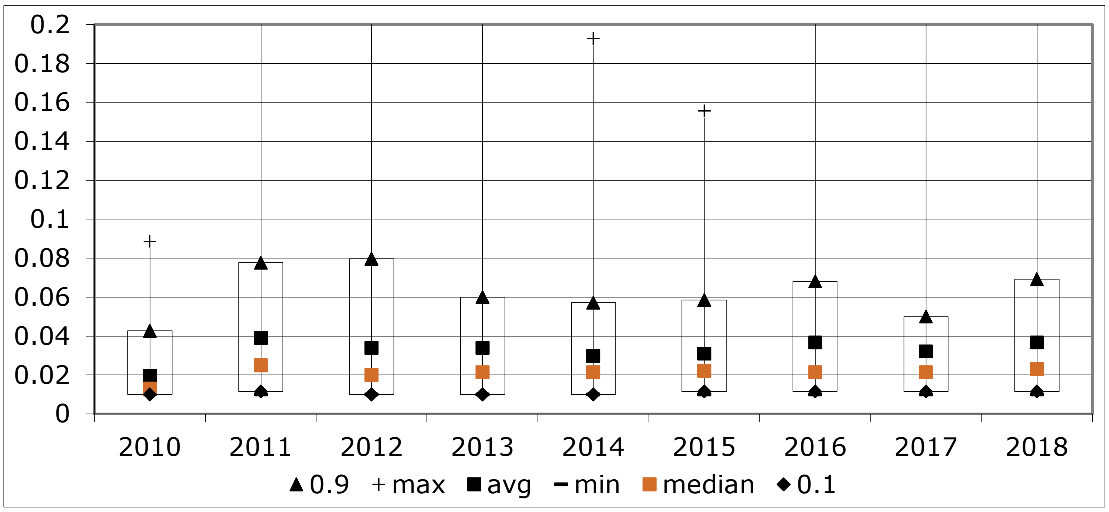


Figure 11. Differences in maximum intensities for 70-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011, 2012, 2016 and 2018, which is also indicated by a significant difference in the values of the median and mean. Smaller variations within a year have been seen for the period 2013-2015, and these were the year of low rainfall.

Table 11. Differences in maximum intensities for 70-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	38	80	157	90	91	102	129	149	67
avg	0019	0.039	0.034	0.034	0.030	0.031	0.037	0.032	0.027
max	0.09	0.22	0.23	0.43	0.19	0.16	0.35	0.38	0.34
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.01
0.9	0.04	0.08	0.08	0.06	0.06	0.06	0.07	0.05	0.05
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the period 2012-2013 and 2016.

2.4.8 80-minute rainfalls

During the years 2010-2018, 715 rainfalls were registered with a duration of at least 80 minutes. The number of rainfalls was the largest in 2012 with 123 rainfalls, followed by the year 2017 with 115 rainfalls (Table 12). In these years, rainfall was also the most abundant (Figure 4). The 80-minute maximal intensity was the highest on 8 August 2013 with 0.39 mm/min, followed by 17 August 2017 with 0.35 mm/min and 29 August 2016 with 0.32 mm/min. The next maximal intensities were on 6 November 2010 with 0.09 mm/min, 30 July 2011 with 0.22 mm/min, 27 September 2012 with 0.22 mm/min, 22 August 2014 with 0.18 mm/min, 22 September 2015 with 0.16 mm/min and 21 June 2018 with 0.3 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.021 and 0.039. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 80-minute rainfalls 322 times, which makes up 45 per cent on the total number of rainfalls.

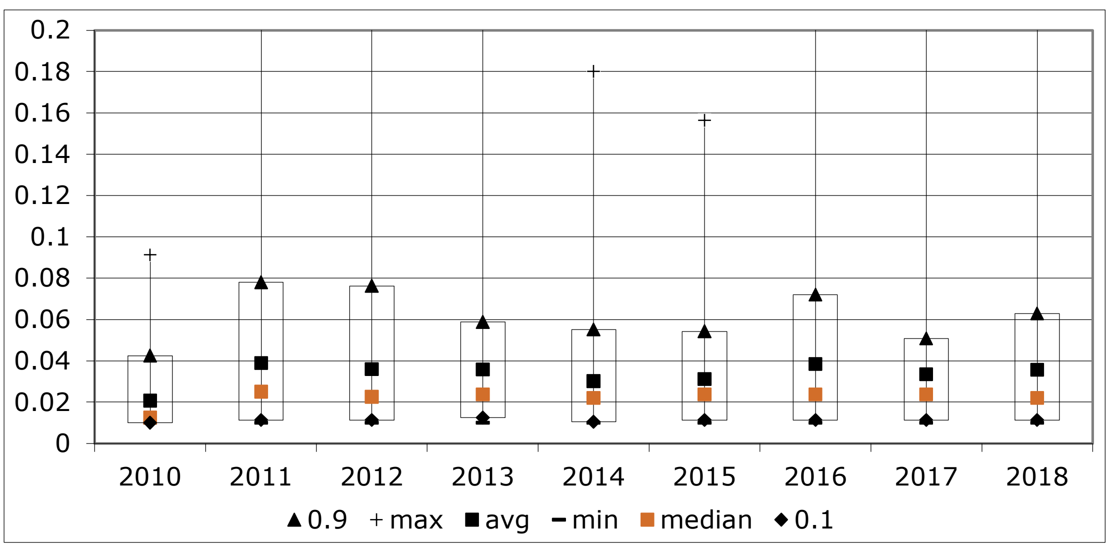


Figure 12. Differences in maximum intensities for 80-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011-2013, 2016 and 2018, which is also indicated by a significant difference in the values of the median and mean.

Table 12. Differences in maximum intensities for 80-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	26	59	123	71	74	84	105	115	58
avg	0.021	0.039	0.036	0.036	0.030	0.031	0.038	0.033	0.036
max	0.09	0.22	0.22	0.39	0.18	0.16	0.32	0.35	0.30
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.9	0.04	0.08	0.08	0.06	0.06	0.05	0.07	0.05	0.06
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the period 2012-2013, 2016 and 2018.

2.4.9 90-minute rainfalls

During the years 2010-2018, 563 rainfalls were registered with a duration of at least 90 minutes. The number of rainfalls was the largest in 2017 with 95 rainfalls, followed by the year 2012 with 90 rainfalls (Table 13). In these years, rainfall was also the most abundant (Figure 4). The 90-minute maximal intensity was the highest on 8 August 2013 with 0.35 mm/min, followed by 29 August 2016 with 0.3 mm/min. The next maximal intensities were on 6 November 2010 with 0.09 mm/min, 30 July 2011 with 0.22 mm/min, 27 September 2012 with 0.2 mm/min, 22 August 2014 with 0.16 mm/min, 22 September 2015 with 0.16 mm/min, 20 June 2017 with 0.16 mm/min and 21 June 2018 with 0.27 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.025 and 0.042. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 90-minute rainfalls 227 times, which makes up 40 per cent on the total number of rainfalls.

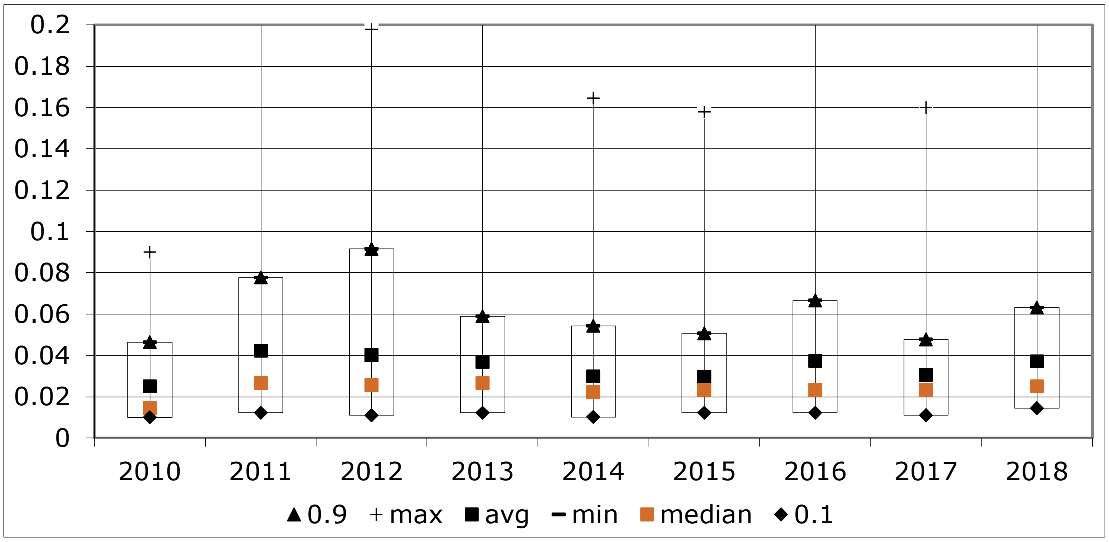


Figure 13. Differences in maximum intensities for 90-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011-2013, 2016 and 2018, which is also indicated by a significant difference in the values of the median and mean.

Table 13. Differences in maximum intensities for 90-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	17	43	90	60	63	65	88	95	42
avg	0.025	0.042	0.040	0.037	0.030	0.030	0.037	0.031	0.037
max	0.09	0.22	0.20	0.35	0.16	0.16	0.30	0.16	0.27
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.01	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.03
0.9	0.05	0.08	0.09	0.06	0.05	0.05	0.07	0.05	0.06
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the period 2012-2013, 2016 and 2018.

2.4.10 100-minute rainfalls

During the years 2010-2018, 451 rainfalls were registered with a duration of at least 100 minutes. The number of rainfalls was the largest in 2012 with 77 rainfalls, followed by the year 2017 with 75 rainfalls (Table 14). In these years, rainfall was also the most abundant (Figure 4). The 100-minute maximal intensity was the highest on 8 August

2013 with 0.31 mm/min, followed by 29 August 2016 with 0.29 mm/min. The next maximal intensities were on 6 November 2010 with 0.09 mm/min, 30 July 2011 with 0.21 mm/min, 27 September 2012 with 0.18 mm/min, 22 August 2014 with 0.15 mm/min, 22 September 2015 with 0.14 mm/min, 20 June 2017 with 0.15 mm/min and 21 June 2018 with 0.24 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.028 and 0.044. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 100-minute rainfalls 164 times, which makes up 36 per cent on the total number of rainfalls.

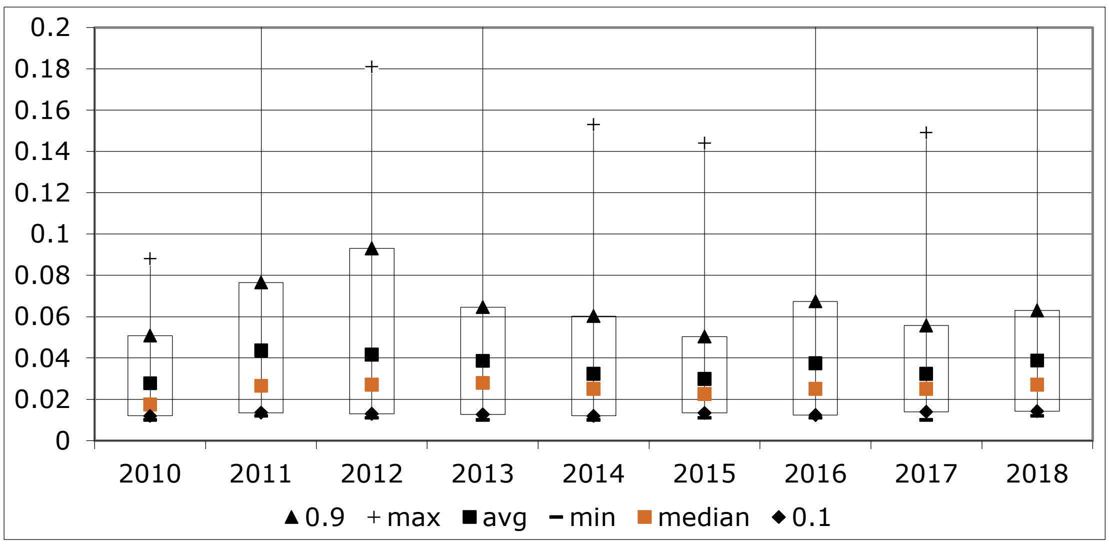


Figure 14. Differences in maximum intensities for 100-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011-2013, 2016 and 2018, which is also indicated by a significant difference in the values of the median and mean.

Table 14. Differences in maximum intensities for 100-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	12	36	77	47	49	58	64	75	33
avg	0.028	0.044	0.042	0.039	0.032	0.030	0.037	0.032	0.039
max	0.09	0.21	0.18	0.31	0.15	0.14	0.29	0.15	0.24
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03
0.9	0.05	0.08	0.09	0.06	0.06	0.05	0.07	0.06	0.06
0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the period 2012-2013 and 2018.

2.4.11 110-minute rainfalls

During the years 2010-2018, 372 rainfalls were registered with a duration of at least 110 minutes. The number of rainfalls was the largest in 2012 with 64 rainfalls, followed by the year 2017 with 62 rainfalls (Table 15). In these years, rainfall was also the most abundant (Figure 4). The 110-minute maximal intensity was the highest on 30 July 2011 with 0.21 mm/min, followed by 27 September 2012 with 0.18 mm/min. The next maximal intensities were on 6 November 2010 with 0.08 mm/min, 29 June 2013 with 0.11 mm/min, 22 August 2014 with 0.14 mm/min, 22 September 2015 with 0.13 mm/min, 26 June 2016 with 0.14 mm/min, 20 June 2017 with 0.14 mm/min and 17 September 2018 with 0.07 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.027 and 0.044. The minimums were the same, namely 0.01 mm/min for all the periods. Up to 0.02 mm/min occurred for 110-minute rainfalls 120 times, which makes up 32 per cent on the total number of rainfalls.

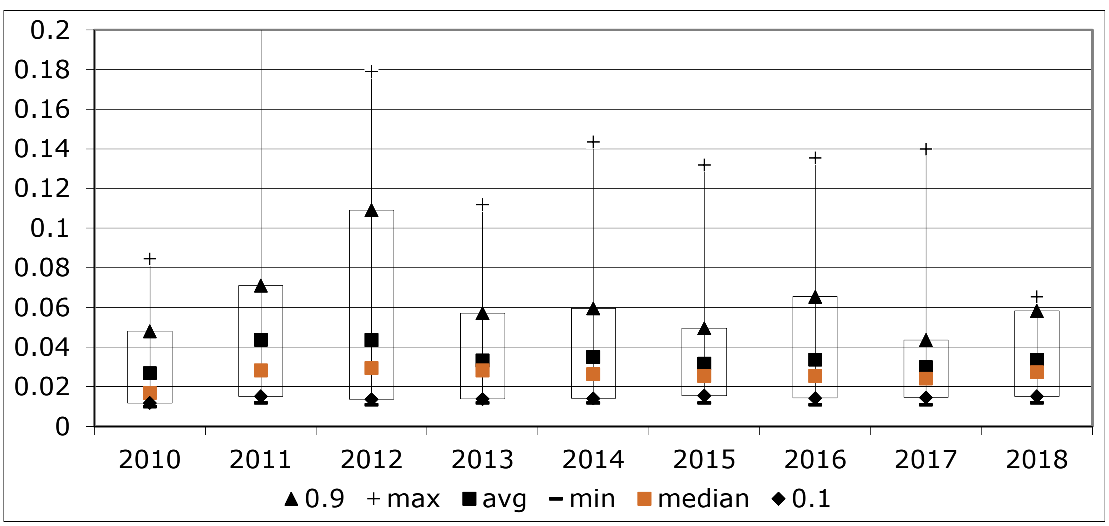


Figure 15. Differences in maximum intensities for 110-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011 and 2012, which is also indicated by a significant difference in the values of the median and mean.

Table 15. Differences in maximum intensities for 110-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	12	30	64	37	39	46	55	62	27
avg	0.027	0.044	0.044	0.033	0.035	0.032	0.034	0.030	0.034
max	0.08	0.21	0.18	0.11	0.14	0.13	0.14	0.14	0.07
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
median	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03
0.9	0.05	0.07	0.11	0.06	0.06	0.05	0.07	0.04	0.06
0.1	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.02

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the years 2011 and 2012. The remaining values are considerably lower.

2.4.12 120-minute rainfalls

During the years 2010-2018, 318 rainfalls were registered with a duration of at least 120 minutes. The number of rainfalls was the largest in 2012 with 55 rainfalls, followed by the year 2017 with 53 rainfalls (Table 16). In these years, rainfall was also the most abundant (Figure 4). The 120-minute maximal intensity was the highest on 30 July 2011 with 0.21 mm/min, followed by 27 September 2012 with 0.2 mm/min. The next maximal intensities were on 6 November 2010 with 0.08 mm/min, 29 June 2013 with 0.11 mm/min, 22 August 2014 with 0.14 mm/min, 6 July 2015 with 0.08 mm/min, 26 June 2016 with 0.13 mm/min, 20 June 2017 with 0.13 mm/min and 17 September 2018 with 0.07 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.03 and 0.047. The minimums for the period 2010-2017 were the same, namely 0.01 mm/min for all this periods and in 2018 the minimums of 0.02 mm/min. Up to 0.02 mm/min occurred for 120-minute rainfalls 91 times, which makes up 29 per cent on the total number of rainfalls.

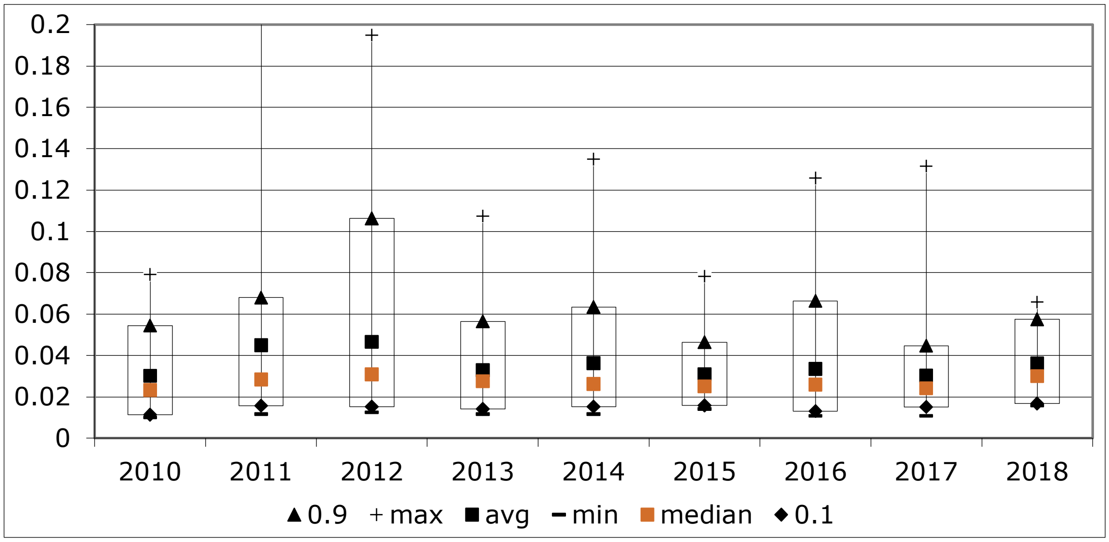


Figure 16. Differences in maximum intensities for 120-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011, 2012 and 2014, which is also indicated by a significant difference in the values of the median and mean.

Table 16. Differences in maximum intensities for 120-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	9	25	55	33	34	37	49	53	23
avg	0.030	0.045	0.047	0.033	0.036	0.031	0.033	0.030	0.036
max	0.08	0.21	0.20	0.11	0.14	0.08	0.13	0.13	0.07
min	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
median	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03
0.9	0.05	0.07	0.11	0.06	0.06	0.05	0.07	0.04	0.06
0.1	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2012. The remaining values are considerably lower.

2.4.13 130-minute rainfalls

During the years 2010-2018, 273 rainfalls were registered with a duration of at least 130 minutes. The number of rainfalls was the largest in 2012 with 51 rainfalls, followed by the year 2017 with 49 rainfalls (Table 17). In these years, rainfall was also the most abundant (Figure 4). The 130-minute maximal intensity was the highest on 30 July 2011 with 0.22 mm/min, followed by 27 September 2012 with 0.2 mm/min. The next maximal intensities were on 6 November 2010 with 0.08 mm/min, 29 June 2013 with 0.1 mm/min, 22 August 2014 with 0.13 mm/min, 6 July 2015 with 0.07 mm/min, 16 August 2016 with 0.09 mm/min, 20 June 2017 with 0.13 mm/min and 17 September 2018 with 0.07 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.031 and 0.049. The minimums for the period 2010 and 2012-2017 were the same, namely 0.01 mm/min for all this periods, but in 2011 and 2018 the minimums of 0.02 mm/min. Up to 0.02 mm/min occurred for 130-minute rainfalls 71 times, which makes up 26 per cent on the total number of rainfalls.

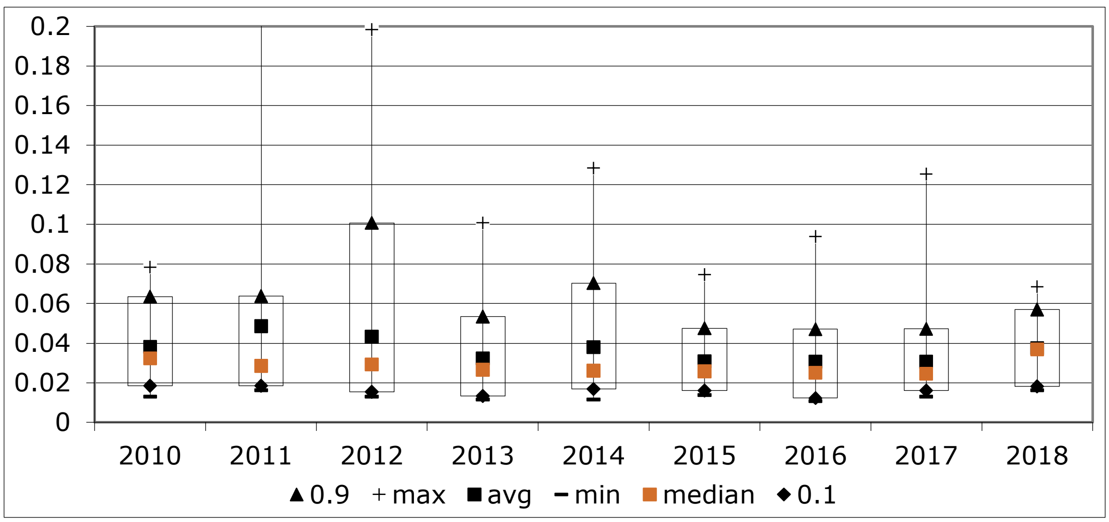


Figure 17. Differences in maximum intensities for 130-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011, 2012 and 2014, which is also indicated by a significant difference in the values of the median and mean.

Table 17. Differences in maximum intensities for 130-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	6	21	51	28	29	30	40	49	19
avg	0.038	0.049	0.043	0.032	0.038	0.031	0.031	0.031	0.038
max	0.08	0.22	0.20	0.10	0.13	0.07	0.09	0.13	0.07
min	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02
median	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.04
0.9	0.06	0.06	0.10	0.05	0.07	0.05	0.05	0.05	0.06
0.1	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011, followed slightly lower by the year 2012. The remaining values are considerably lower.

2.4.14 140-minute rainfalls

During the years 2010-2018, 239 rainfalls were registered with a duration of at least 140 minutes. The number of rainfalls was the largest in 2017 with 45 rainfalls, followed by the year 2012 with 42 rainfalls (Table 18). In these years, rainfall was also the most abundant (Figure 4). The 140-minute maximal intensity was the highest on 30 July 2011 with 0.22 mm/min, followed by 27 September 2012 with 0.2 mm/min. The next maximal intensities were on 6 November 2010 with 0.07 mm/min, 29 June 2013 with 0.09 mm/min, 22 August 2014 with 0.12 mm/min, 6 July 2015 with 0.07 mm/min, 16 August 2016 with 0.09 mm/min, 20 June 2017 with 0.12 mm/min and 17 September 2018 with 0.07 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.031 and 0.047. The minimums for the period 2012-2017 were the same, namely 0.01 mm/min for all this periods, but for the period 2010-2011 and 2018 the minimums of 0.02 mm/min. Up to 0.02 mm/min occurred for 140-minute rainfalls 55 times, which makes up 23 per cent on the total number of rainfalls.

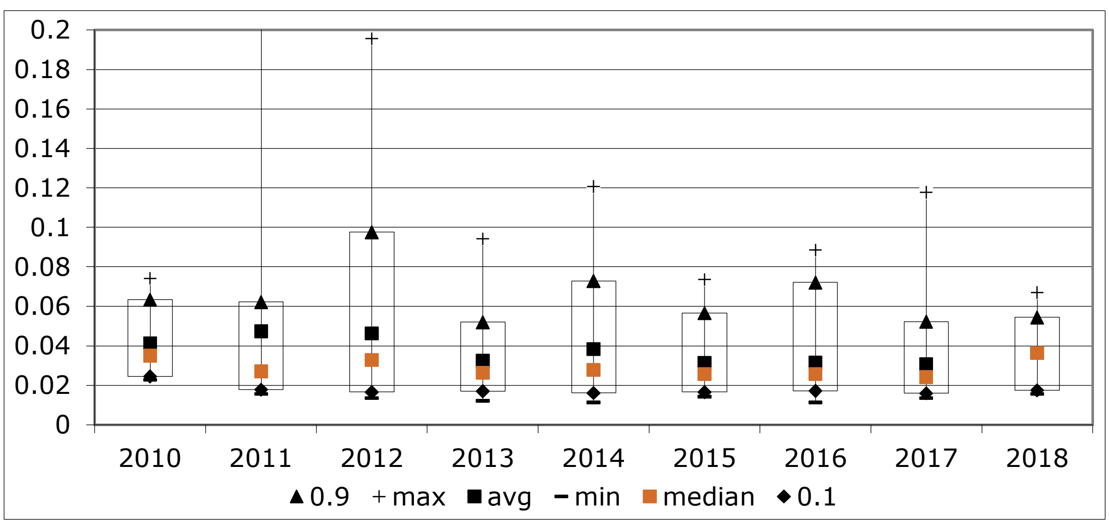


Figure 18. Differences in maximum intensities for 140-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011, 2012 and 2014, which is also indicated by a significant difference in the values of the median and mean.

Table 18. Differences in maximum intensities for 140-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	5	21	42	25	26	25	31	45	19
avg	0.041	0.047	0.046	0.032	0.038	0.031	0.032	0.031	0.036
max	0.07	0.22	0.20	0.09	0.12	0.07	0.09	0.12	0.07
min	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02
median	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.04
0.9	0.06	0.06	0.10	0.05	0.07	0.06	0.07	0.05	0.05
0.1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the years 2010 and 2012.

2.4.15 150-minute rainfalls

During the years 2010-2018, 204 rainfalls were registered with a duration of at least 150 minutes. The number of rainfalls was the largest in 2012 with 38 rainfalls, followed by the year 2017 with 36 rainfalls (Table 19). In these years, rainfall was also the most abundant (Figure 4). The 150-minute maximal intensity was the highest on 30 July 2011 with 0.21 mm/min, followed by 27 September 2012 with 0.19 mm/min. The next maximal intensities were on 6 November 2010 with 0.07 mm/min, 14 August 2013 with 0.07 mm/min, 22 August 2014 with 0.11 mm/min, 6 July 2015 with 0.07 mm/min, 16 August 2016 with 0.09 mm/min, 20 June 2017 with 0.11 mm/min and 17 September 2018 with 0.06 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.
The average values of the rainfall maximums are between 0.03 and 0.05. The minimums for the period 2012 and 2014-2017 were the same, namely 0.01 mm/min for all this periods, but in years 2011, 2013 and 2018 the minimums of 0.02 mm/min, in 2010 the minimums 0.03 mm/min. Up to 0.02 mm/min occurred for 150-minute rainfalls 46 times, which makes up 23 per cent on the total number of rainfalls.

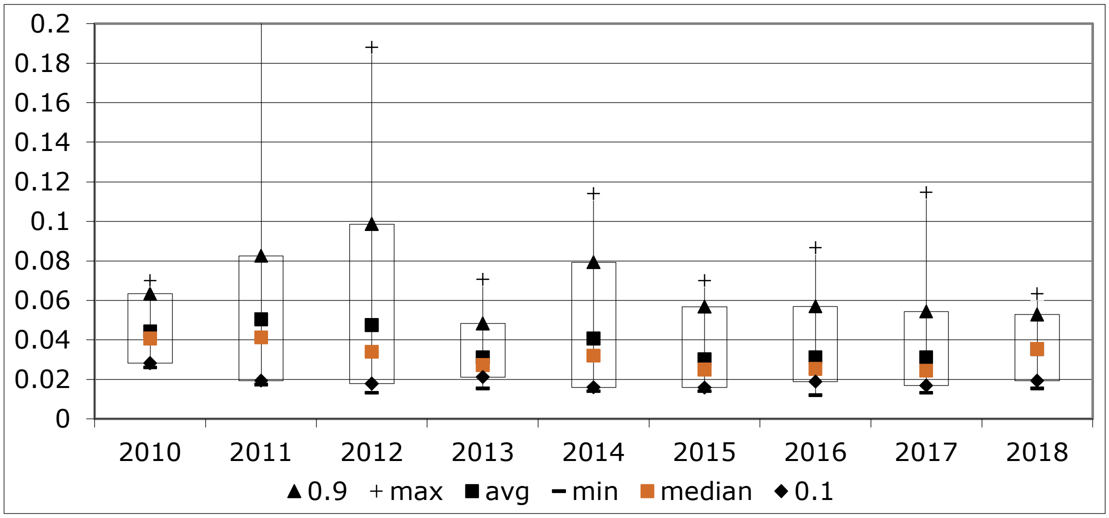


Figure 19. Differences in maximum intensities for 150-minute rainfalls in 2010-2018

A great variation in intensities are relatively large only for the 2012 year, which is also indicated by a significant difference in the values of the median and mean.

Table 19. Differences in maximum intensities for 150-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	4	17	38	20	21	24	25	36	19
avg	0.044	0.050	0.048	0.031	0.041	0.030	0.031	0.031	0.035
max	0.07	0.21	0.19	0.07	0.11	0.07	0.09	0.11	0.06
min	0.03	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02
median	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.04
0.9	0.06	0.08	0.10	0.05	0.08	0.06	0.06	0.05	0.05
0.1	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the year 2012.

2.4.16 160-minute rainfalls

During the years 2010-2018, 183 rainfalls were registered with a duration of at least 160 minutes. The number of rainfalls was the largest in 2012 with 36 rainfalls, followed by the year 2017 with 32 rainfalls (Table 20). In these years, rainfall was also the most abundant (Figure 4). The 160-minute maximal intensity was the highest on 30 July 2011 with 0.21 mm/min, followed by 27 September 2012 with 0.18 mm/min. The next maximal intensities were on 6 November 2010 with 0.07 mm/min, 14 August 2013 with

0.07 mm/min, 22 August 2014 with 0.11 mm/min, 6 July 2015 with 0.07 mm/min, 16 August 2016 with 0.08 mm/min, 20 June 2017 with 0.12 mm/min and 17 September 2018 with 0.06 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.03 and 0.05. The minimums for the period 2012 and 2014-2015 were the same, namely 0.01 mm/min for all this periods, but for the period 2011, 2013 and 2016-2018 the minimums of 0.02 mm/min, in 2010 the minimums 0.03 mm/min. Up to 0.02 mm/min occurred for 160-minute rainfalls 37 times, which makes up 20 per cent on the total number of rainfalls.

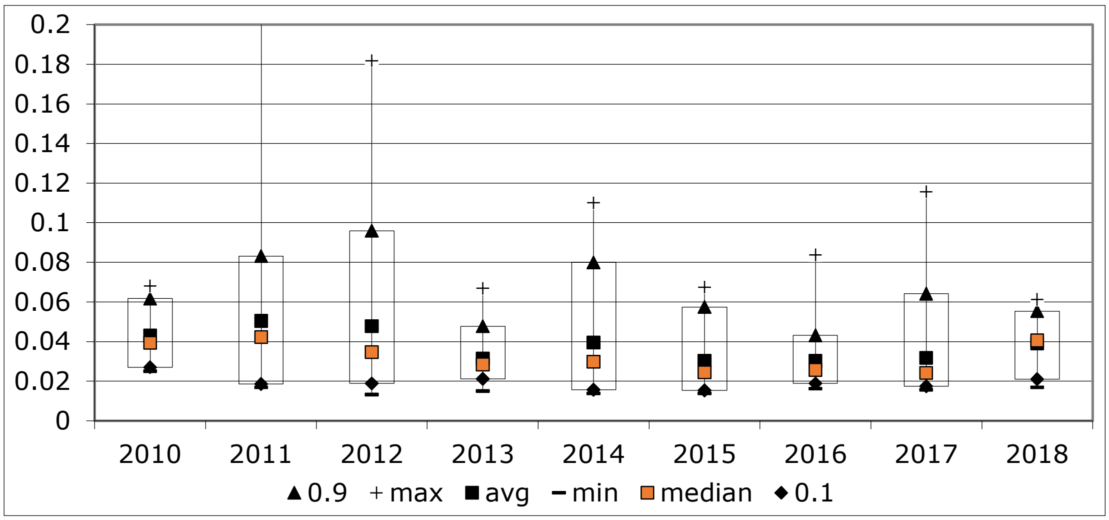


Figure 20. Differences in maximum intensities for 160-minute rainfalls in 2010-2018

A great variation in intensities are relatively large only for the 2012 year, which is also indicated by a significant difference in the values of the median and mean.

Table 20. Differences in maximum intensities for 160-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	4	16	36	18	20	23	19	32	15
avg	0.043	0.050	0.048	0.031	0.040	0.030	0.030	0.032	0.039
max	0.07	0.21	0.18	0.07	0.11	0.07	0.08	0.12	0.06
min	0.03	0.02	0.01	0.02	0.01	0.01	0.02	0.02	0.02
median	0.04	0.04	0.03	0.03	0.03	0.02	0.03	0.02	0.04
0.9	0.06	0.08	0.10	0.05	0.08	0.06	0.04	0.06	0.06
0.1	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the year 2012.

2.4.17 170-minute rainfalls

During the years 2010-2018, 159 rainfalls were registered with a duration of at least 170 minutes. The number of rainfalls was the largest in 2012 with 31 rainfalls, followed by the year 2017 with 30 rainfalls (Table 21). In these years, rainfall was also the most abundant (Figure 4). The 170-minute maximal intensity was the highest on 30 July 2011 with 0.2 mm/min, followed by 27 September 2012 with 0.17 mm/min. The next maximal intensities were on 6 November 2010 with 0.06 mm/min, 14 August 2013 with 0.06 mm/min, 22 August 2014 with 0.1 mm/min, 6 July 2015 with 0.06 mm/min, 16 August 2016 with 0.08 mm/min, 20 June 2017 with 0.12 mm/min and 30 September 2018 with 0.06 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer and with a few occurrences early autumn.

The average values of the rainfall maximums are between 0.031 and 0.053. The minimums for the period 2012 and 2014-2015 were the same, namely 0.01 mm/min for all this periods, but for the period 2010-2011, 2013 and 2016-2018 the minimums of 0.02 mm/min. Up to 0.02 mm/min occurred for 170-minute rainfalls 33 times, which makes up 18 per cent on the total number of rainfalls.

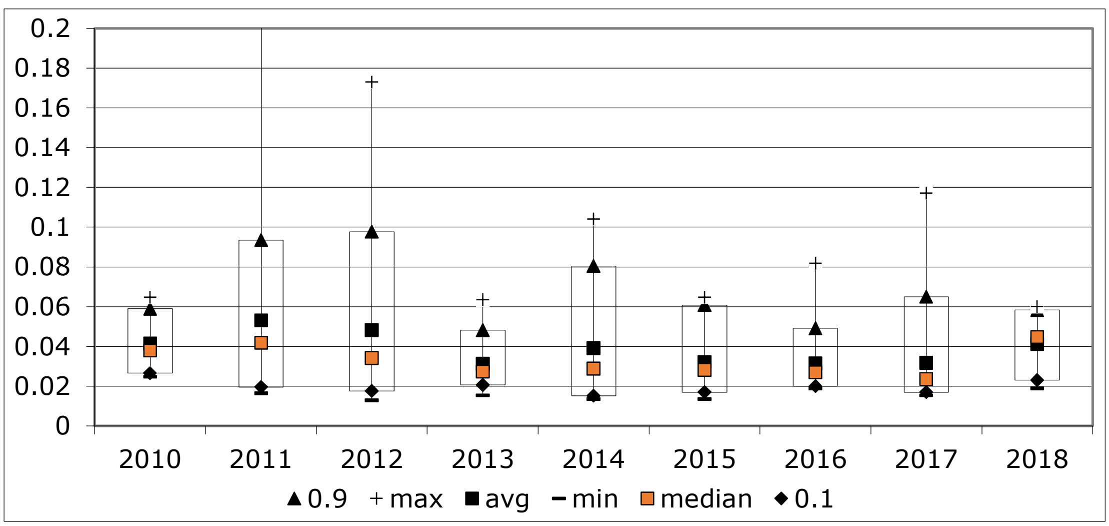


Figure 21. Differences in maximum intensities for 170-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011, 2012 and 2014, which is also indicated by a significant difference in the values of the median and mean.

Table 21. Differences in maximum intensities for 170-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	4	13	31	16	18	19	16	30	12
avg	0.041	0.053	0.048	0.031	0.039	0.032	0.031	0.032	0.041
max	0.06	0.20	0.17	0.06	0.10	0.06	0.08	0.12	0.06
min	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.02	0.02
median	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.04
0.9	0.06	0.09	0.10	0.05	0.08	0.06	0.05	0.07	0.06
0.1	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the year 2012.

2.4.18 180-minute rainfalls

During the years 2010-2018, 128 rainfalls were registered with a duration of at least 180 minutes. The number of rainfalls was the largest in 2012 with 28 rainfalls, followed by the year 2017 with 22 rainfalls (Table 22). In these years, rainfall was also the most abundant (Figure 4). The 180-minute maximal intensity was the highest on 30 July 2011 with 0.21 mm/min, followed by 27 September 2012 with 0.16 mm/min. The next maximal intensities were on 9 November 2010 with 0.04 mm/min, 4 November 2013 with 0.05 mm/min, 22 August 2014 with 0.1 mm/min, 29 April 2015 with 0.06 mm/min, 16 August 2016 with 0.08 mm/min, 20 June 2017 with 0.12 mm/min and 17 September 2018 with 0.06 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer, with a few occurrences early autumn and one spring time.
The average values of the rainfall maximums are between 0.031 and 0.053. The minimums for the period 2011-2014 and 2016-2018 were the same, namely 0.02 mm/min for all this periods and in 2010 the minimums of 0.03 mm/min. Up to 0.02 mm/min occurred for 180-minute rainfalls 24 times, which makes up 19 per cent on the total number of rainfalls.

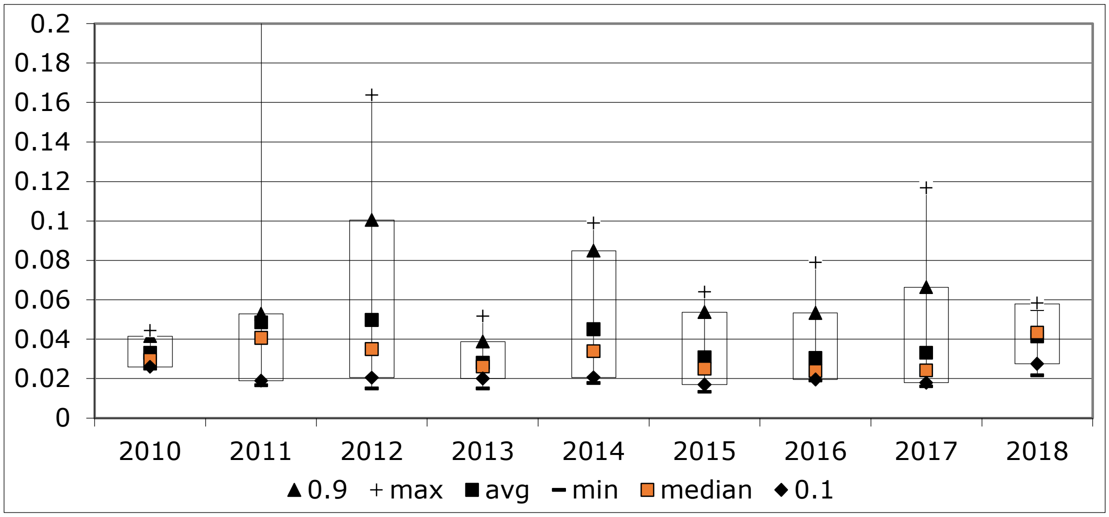


Figure 22. Differences in maximum intensities for 180-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2012 and 2014, which is also indicated by a significant difference in the values of the median and mean.

Table 22. Differences in maximum intensities for 180-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	3	11	28	14	13	15	13	22	9
avg	0.033	0.048	0.050	0.028	0.045	0.031	0.030	0.033	0.041
max	0.04	0.21	0.16	0.05	0.10	0.06	0.08	0.12	0.06
min	0.03	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02
median	0.03	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.04
0.9	0.04	0.05	0.10	0.04	0.08	0.05	0.05	0.07	0.06
0.1	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the years 2011 and 2014.

2.4.19 190-minute rainfalls

During the years 2010-2018, 111 rainfalls were registered with a duration of at least 190 minutes. The number of rainfalls was the largest in 2012 with 26 rainfalls, followed by the year 2017 with 21 rainfalls (Table 23). In these years, rainfall was also the most abundant (Figure 4). The 190-minute maximal intensity was the highest on 30 July 2011 with 0.21 mm/min, followed by 27 September 2012 with 0.16 mm/min. The next maximal intensities were on 9 November 2010 with 0.04 mm/min, 4 November 2013 with 0.05 mm/min, 25 August 2014 with 0.08 mm/min, 29 April 2015 with 0.06 mm/min, 16 August 2016 with 0.08 mm/min, 20 June 2017 with 0.11 mm/min and 30 September 2018 with 0.06 mm/min. Taking a look at these maximums by years, we see that they have typically occurred during summer, with a few occurrences early autumn and one spring time.

The average values of the rainfall maximums are between 0.028 and 0.051. The minimums for the period 2012-2013 and 2015 were the same, namely 0.01 mm/min for all this periods. The minimums for period 2010,2011, 2014 and 2016-2017 were the same, namely 0.02 mm/min for all this periods. In 2018 the minimums of 0.03 mm/min. Up to 0.02 mm/min occurred for 190-minute rainfalls 20 times, which makes up 18 per cent on the total number of rainfalls.

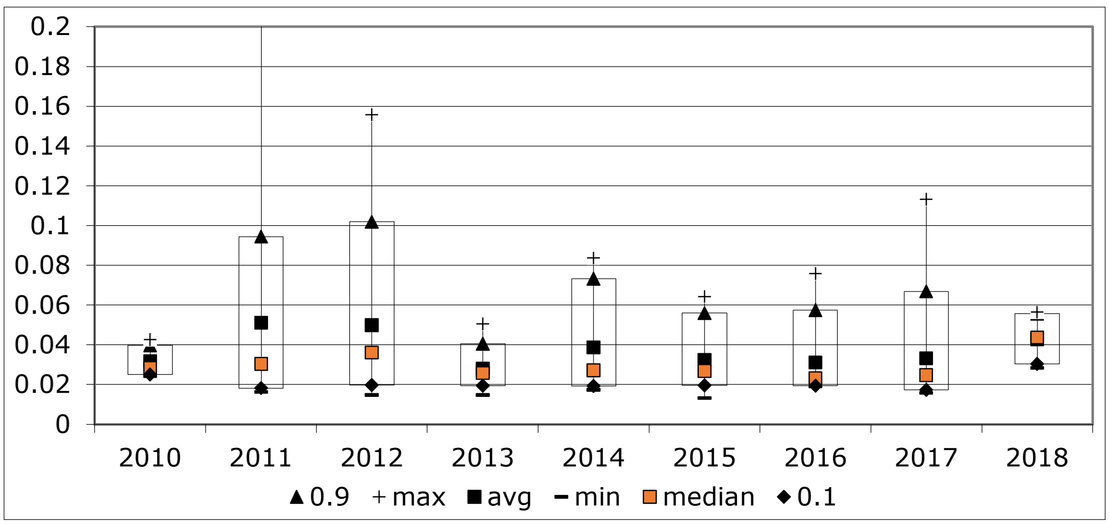


Figure 23. Differences in maximum intensities for 190-minute rainfalls in 2010-2018

A great variation in intensities are relatively large for the years 2011, 2012 and 2014, which is also indicated by a significant difference in the values of the median and mean.

Table 23. Differences in maximum intensities for 190-minute rainfalls in 2010-2018

year	**2010***	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018****
number of rainfalls	3	8	26	11	10	13	11	21	8
avg	0.032	0.051	0.050	0.028	0.039	0.032	0.031	0.033	0.043
max	0.04	0.21	0.16	0.05	0.08	0.06	0.08	0.11	0.06
min	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.03
median	0.03	0.03	0.04	0.03	0.03	0.03	0.02	0.02	0.04
0.9	0.04	0.09	0.10	0.04	0.07	0.06	0.06	0.07	0.06
0.1	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03

*incomplete year, data since 01.11.2010
** incomplete year, data until 30.11.2018

The highest maximal average was observed for the year 2011. Somewhat lower were the values for the year 2012.

2.4.20 200-430 minutes rainfalls

Since the number of 200-430-minute rainfalls is under one hundred, the data is aggregated for further analysis. All the rainfalls that lasted for 200-430 minutes are presented in tables 24, 25 and 26. The number of rainfalls is summary of the duration of the rain for the period 2010-2018. The rest of the parameters are taken as the average for the period 2010-2018.

The tables show that the trend of the number of rainfalls is constantly downward. The duration of 200-240-minute rainfalls, with data for the period 2010-2018. The longest rainfall during the period 1 November 2010 to 31 December 2010 lasted for 240 minutes on 26 December 2010, and its maximal intensity was 0.02 mm/min. The next are the data on 250-430-minute rainfalls for the period 2011-2018. The longest rainfall was on 29 April 2015 and lasted for 270 minutes, and its maximal intensity was 0.06 mm/min (Table 24). The next data are for 280-430-minute rainfalls for the periods 2011-2014 and 2016-2018 (Table 25).

The longest rainfall was on 16 August 2016 and lasted for 340 minutes, and its maximal intensity was 0.06 mm/min (Table 26). The next data are for 350-430-minute rainfalls for the periods 2011-2014 and 2017-2018.

The longest rainfall was on 13 July 2017 and lasted for 390 minutes, and its maximal intensity was 0.02 mm/min. The longest rainfall for the period 1 January 2018 to 26 November 2018 lasted for 390 minutes, and its maximal intensity was 0.03 mm/min. The next data are for 400-430-minute rainfalls s for the periods 2011-2014 (Table 26). The longest rainfall was on 7 January 2014 and lasted for 410 minutes, and its maximal intensity was 0.03 mm/min. The next data are for 420-430-minute rainfalls for the periods 2011-2013.

The longest rainfall was on 4 November 2013 and lasted for 420 minutes, and its maximal intensity was 0.04 mm/min. The next data are for 430-minute rainfalls for the periods 2011-2012.

In 2011 and 2012, the longest rainfalls lasted for 430 minutes. Maximal intensity was on 30 July 2011 at 0.15 mm/min, and on 17 October 2012 at 0.04 mm/min with a duration of 430 minutes (Table 26). In 2011 there were two rainfalls that lasted for 430 minutes. The second one was on 6 December 2011 and the intensity was 0.03 mm/min.

Table 24. 200-270-minute rainfalls

min	**200**	**210**	**220**	**230**	**240**	**250**	**260**	**270**
number of rainfalls	95	86	76	68	61	52	48	41
avg	0.036	0.037	0.038	0.039	0.037	0.039	0.040	0.042
max	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.07
min	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
median	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
0.9	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
0.1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03

Table 25. 280-350-minute rainfalls

min	**280**	**290**	**300**	**310**	**320**	**330**	**340**	**350**
number of rainfalls	37	29	26	24	22	18	14	12
avg	0.044	0.047	0.046	0.046	0.046	0.045	0.045	0.042
max	0.08	0.07	0.07	0.07	0.07	0.06	0.06	0.06
min	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
median	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03
0.9	0.06	0.07	0.06	0.06	0.06	0.06	0.06	0.06
0.1	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03

Table 26. 360-430-minute rainfalls

min	**360**	**370**	**380**	**390**	**400**	**410**	**420**	**430**
number of rainfalls	11	11	11	10	7	6	4	3
avg	0.041	0.040	0.040	0.039	0.047	0.045	0.056	0.063
max	0.06	0.06	0.06	0.06	0.07	0.06	0.08	0.09
min	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.03
median	0.03	0.03	0.03	0.03	0.04	0.04	0.06	0.06
0.9	0.05	0.05	0.05	0.05	0.06	0.06	0.07	0.09
0.1	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.04

The averages for 200-430-minute rainfalls were 0.036-0.063.

Minimums for 200-270-minute rainfall s were observed to be 0.02 mm/min for the period, while the minimum for rainfalls lasting for 280-390, 410 or 430 minutes was 0.03 mm/min, and for the rest of the rainfalls of 400 and 420 minutes the minimum was 0.04 mm/min.

Variability is not great, which is also seen from the small differences in the values for median and mean.

2.5 Maximal intensity values for the rainfalls

Figure 25 shows maximal values for 10-430-minute rainfalls for the period 2010-2018. This chart presents data for maximal intensity rainfalls for all the length (10 min, 20 min, etc.) for the period 2010-2018. The longer the rain, the lower is its maximal intensity. Very small are the differences in intensities for the rainfalls starting from 110 minutes.

The highest maximal intensities are for the rainfalls lasting for 10, 20 or 30 minutes.

The highest intensity for the whole period was for a 10-minute rain on 17 August 2017 – 1.02 mm/min. The second-highest in intensity was a rainfall on 23 May 2011 also lasting for 10 minutes and with the intensity of 1.02 mm/min.

Thus, we can conclude that very intensive rainfalls are usually short. The detailed data in tabular form in Figure 24 are presented in Appendix 1.

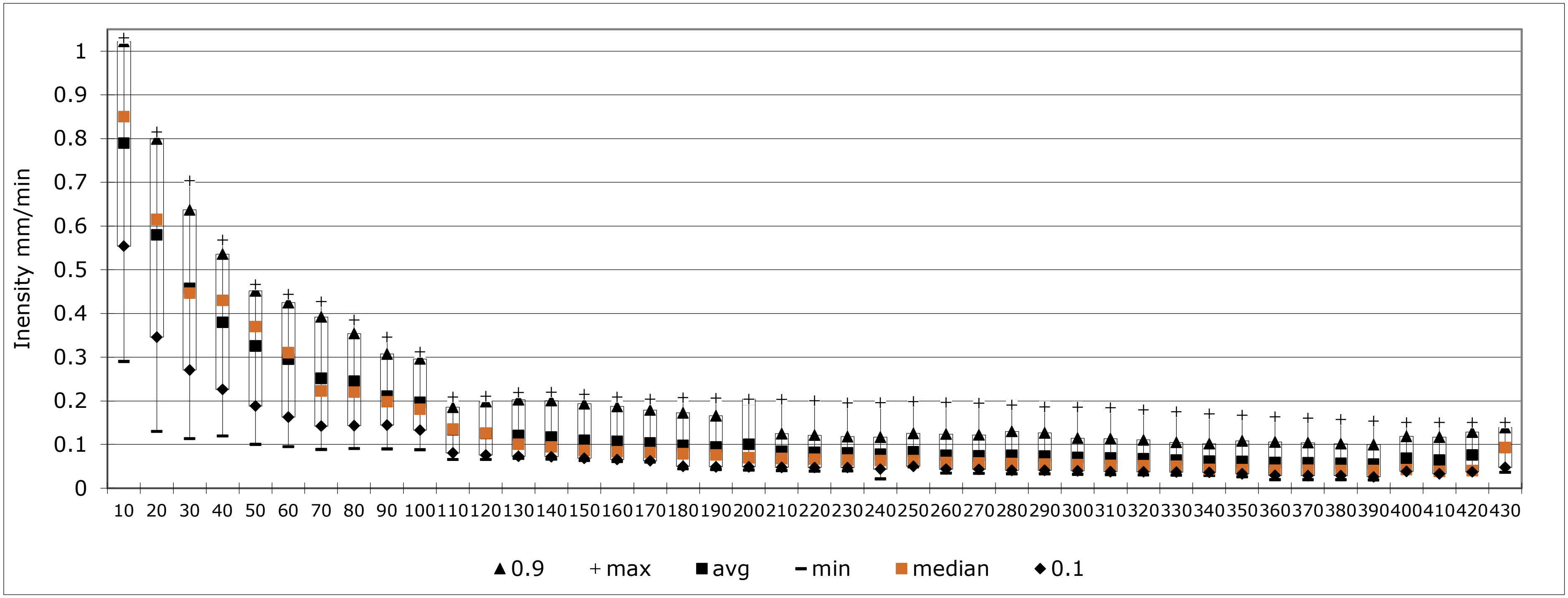


Figure 25. Summary table for maximal intensities in 10-430-minute rainfalls.

2.6 Comparison of maximal intensities with the dataset collected by AS Tallinna Vesi

For comparison, a dataset compiled by Riin Uus for analysing rainfall intensity based on data collected by AS Tallinna Vesi.

In her master's thesis, Riin Uus analysed information collected in the period 2013-2019. The meters recorded data with the interval of one minute. To decrease the volume of the data and improve processing speed, the data was aggregated into 5-minute steps. The start of a rainfall (Talgus) was defined as a situation where the total precipitation within five minutes was 1 mm or above, and at least 15 minutes had passed from the end (Tlõpp) of the previous rainfall. The end (Tlõpp) of the rainfall was defined as a situation where the total amount of precipitation measured over 5 minutes was below 0.2 mm/min. Since the measuring error of the gauge was 0.1 mm/min, 0.2 mm/min was chosen. Every rainfall received its own ID, to make it easier to connect it to the monitoring stations later. All rainfalls under 5 minutes of duration were left out. [12]

Figure 26 present an extract of the maximums for 5-60-minute rainfalls for the years 2013-2019. From the figure, it is seen that the intensities are the highest for the rainfalls lasting for 5 10, 15 or 20 minutes, and the longer the rain lasts, the less the intensity is.

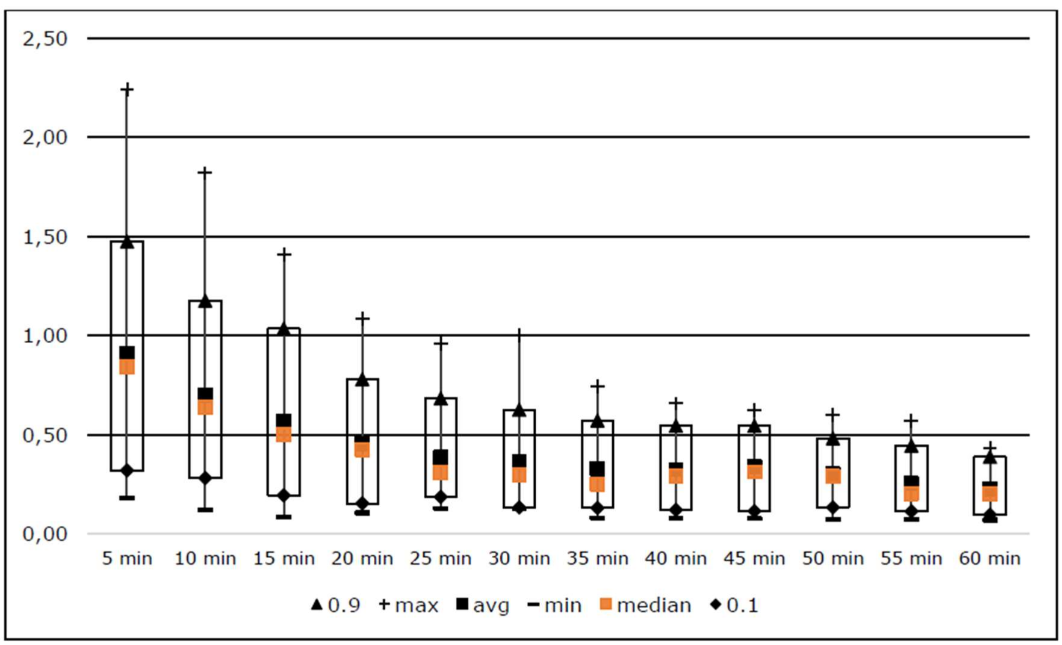


Figure 26. The analysis of precipitation intensity in Tallinn according to the monitoring data of AS Tallinna Vesi for the period 2013-2019 [12]

In comparing the maximum intensities from the datasets by AS Tallinna Vesi and the Estonian Weather Service, we can see that the shape of the diagrams is similar and that they describe the same result, namely that maximal intensities are higher with shorter rainfalls and longer rainfalls have lower maximal intensities.

We can also demonstrate that, while the maximal intensity values for the rainfalls lasting 60 minutes are practically the same (approx. 0.4 mm/min), the shorter the duration of the rain, the larger the discrepancy. It indicates that rainfalls with longer duration are steadier and are not much influenced by local geographical factors.

Since the Estonian Weather Service does not collect data for 5-minute intervals, we can only guess that the initial part of the chart would have also been sharper for the maximal intensities at the Tallinn-Harku station.

Discrepancies in maximal intensity data on the rainfalls with shorter duration come mainly from differences in recorded rainfall intensities in the stations. Figure 27 presents as an example of the differences for 10-minute maximal intensities in data collected by AS Tallinna Vesi and the Estonian Weather Service for the period 2014-2018.

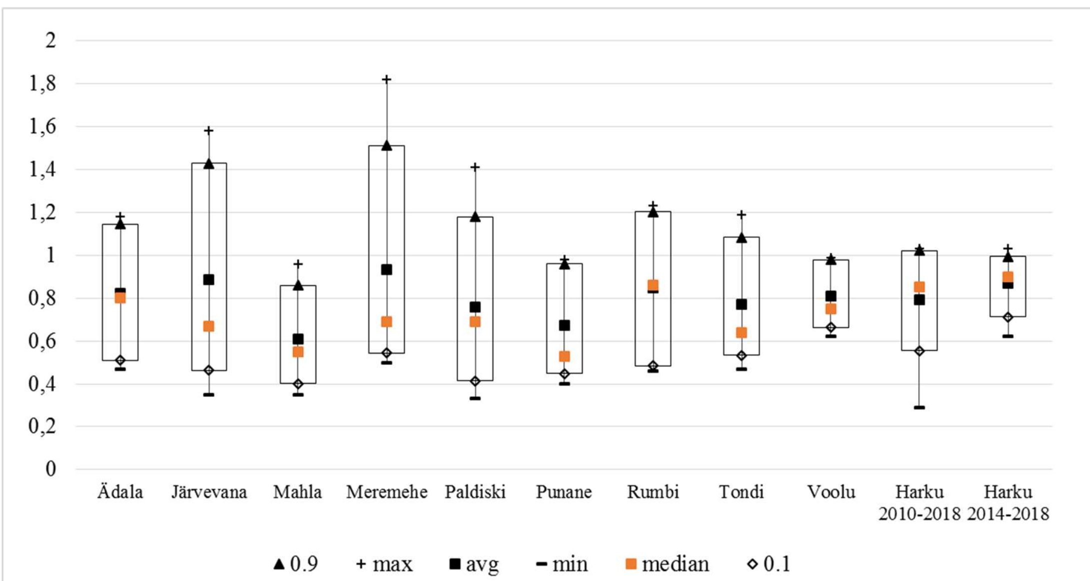


Figure 27. Differences for 10-minute maximal intensities collected from measuring stations of AS Tallinna Vesi during 2014-2018 [12], and at Tallinn-Harku station during 2010-2018 and 2014-2018

Ten-minute rainfalls with an especially intensive maximum have been recorded in the stations of Meremehe and Järvevana, where the intensity has been approximately 1.5 mm/min. The most similar maximal intensities have been measured at the stations of

Punane, Mahla and Tondi, where 10-minute rainfalls' intensive maximums have been approximately 1.0 mm/min.

The data from the Tallinn-Harku station are quite different, especially the extremal values. The averages are similar to those measured at the Rumbi and Ädala stations.

In addition, the figures show how great the variation in rainfall intensity may be in such a small area as Tallinn. It proves again that rain is not a geographically uniform phenomenon and that the important aspect is the location of the measuring point (randomness).

2.7 Probability of the occurrence of 10-minute rainfalls

Since the intensity may be the highest with 10-minute rainfalls, I analysed the probability of their occurrence during the period 2010-2018. Figure 28 shows that the probability of a low-intensity rainfall is significantly higher that the occurrence of a high-intensity rainfall. The probability of the occurrence of a 10-minute rainfall with high intensity is very small, about 0.1 per cent. The figure shows that for a longer period, the probabilities for rain become very similar.

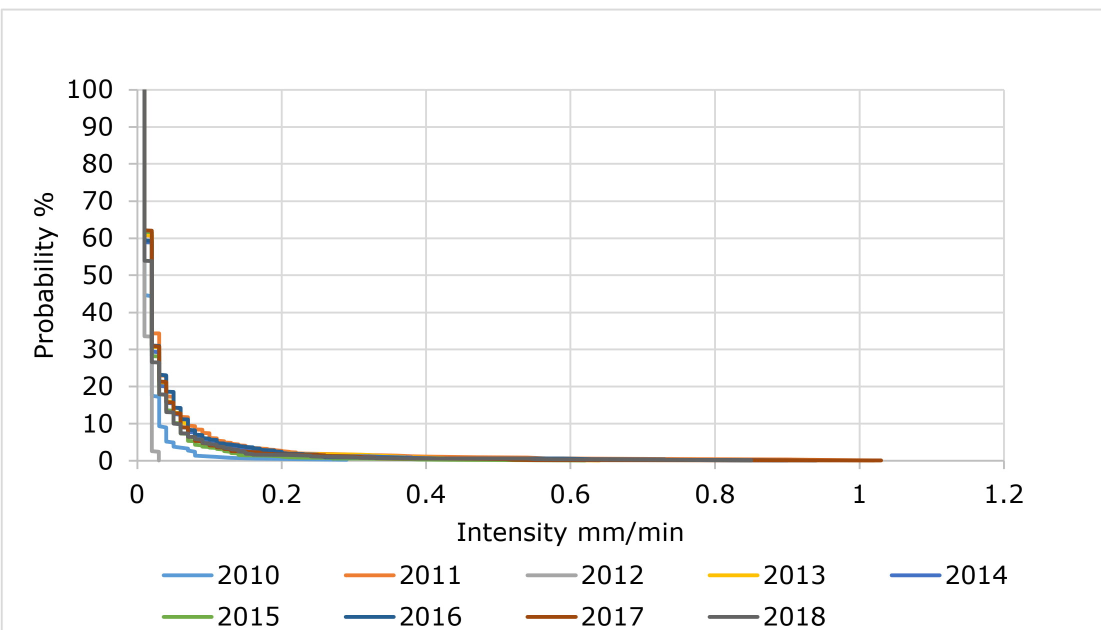


Figure 28. Probability curves for rain intensity

Since the occurrence of rainfalls with very low intensity have been taken into consideration, attention should be turned to the shape of the curve.

Table 7 in Standard EVS 848:2013 gives the relationship between calculated rainfall intensity and recurrence period, which makes the determination of calculated flow rate depend on the probability of rain, while the probability of rain itself is tied to the intensity of rainfall.

Table 7. Correlation between the probability of rain repetition period.

Recurrence period p (in years)	1/3	0,5	1	2	5	10	20	100
Probability of occurrence p_b (%)	95	86	63	39	18	9.5	4.9	1

Thus, the smaller the probability for calculated flow, the higher the intensity of the rain taken into consideration in the calculations.

2.8 Analysis of rainfalls by their duration

The number of rainfalls by their duration for the period 2010-2018 was 24,635. The occurrence of rainfalls during the period 2010-2018 is presented on Figure 29. The duration of rainfall is given in 10-minute intervals. The number starts from 10 minutes and ends with a rainfall of 430 minutes. Figure 29 and tables 27-30 show that the largest number of rainfalls last for 10 minutes, and the longer the rainfalls are, the smaller their number is.

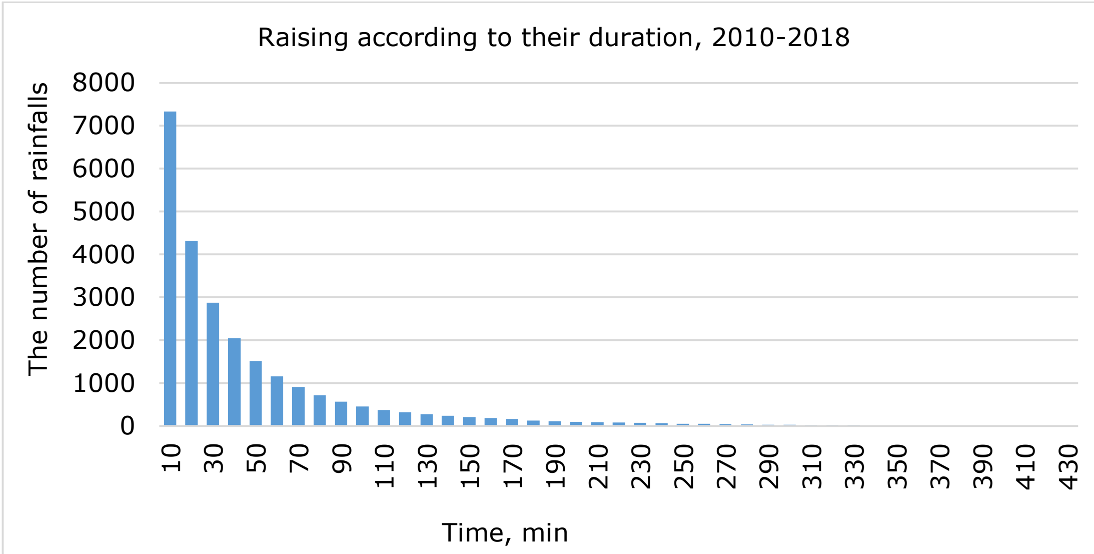


Figure 29. The number of rainfalls during 2010-2018

Table 27. The number of rainfalls, 10-100 minutes

Time (min)	10	20	30	40	50	60	70	80	90	100
Number of rainfalls	7,329	4,319	2,874	2,046	1,517	1,159	903	715	563	451
% of rainfall	29.8	17.5	11.7	8.3	6.2	4.7	3.7	2.9	2.3	1.8

Table 28. The number of rainfalls, 110-210 minutes

Time (min)	110	120	130	140	150	160	170	180	190	200	210
Number of rainfalls	372	318	273	239	204	183	159	128	111	95	86

Table 29. The number of rainfalls, 220-320 minutes

Time (min)	220	230	240	250	260	270	280	290	300	310	320
Number of rainfalls	76	68	61	52	48	41	37	29	26	24	22

Table 30. The number of rainfalls, 330-430 minutes

Time (min)	330	340	350	360	370	380	390	400	410	420	430
Number of rainfalls	18	14	12	11	11	11	10	7	6	4	3

Table 27 shows that the number of 10-minute rainfalls was 7,329, which is approximately 30 per cent of the total number of rainfalls. 20-minute rainfalls made up approximately 18 per cent. Rainfalls with a shorter duration and lasting up to 30 minutes make up more than half at 59 per cent. Rainfalls with a shorter duration and lasting up to 60 minutes make up approximately 78 per cent. The number of rainfalls lasting for at least 70 minutes is under a thousand occasions, and for 200 minutes or more, we have less than 100 occasions.

SUMMARY

Climate change is felt in Europe as well as in the whole world. Due to climate change, the sea and land temperatures are rising, and the volume, intensity and distribution of the precipitation will change.

According to observations by various researchers, high-intensity rainfalls are becoming more frequent and the number of extremal rainfalls will grow among the total amount of precipitation. Measuring extremal precipitation events is difficult due to the fact that they are local and rare events that do not necessarily occur near existing meteorological stations. Therefore, randomness plays an important role in obtaining information.

In Estonia and neighbouring countries, the average increase in precipitation is predicted to be 10 to 20 per cent and it is also predicted to have a more even distribution within the year, with a decrease in floods caused by melting snow.

The standard for designing systems for disposal of stormwater from the streets and territories in Estonia is EVS 848:2013. In writing the present standard EVS 848:2013, the changes in methodology that took place over the last 50 years to measure stormwater as well as data concerning climate change have not been taken into consideration.

In Estonia, very intensive rainfall is usually short in duration.

The present master's thesis studied data collected by the Estonian Weather Service at Tallinn-Harku Meteorological Station. The reference period was 2010-2018. Precipitation data is in 10-minute intervals from 1 November 2010 to 30 November 2018.

Major variations are visible within the years. The year with the highest precipitation was 2012 (about 940 mm), followed by 2017 (about 870 mm) and 2011 (about 780 mm).

In order to find the relationship between maximal rainfall intensity and rain duration, an in-depth analysis was carried out with rainfalls lasting from 10 minutes to 430 minutes. The highest maximal intensities were recorded for rain lasting for 10, 20 0r 30 minutes. The longer the duration of the rain, the lower its maximal intensity. Maximal intensities between rainfalls of 110 minutes long and longer show minimal differences.

In comparing maximal intensities between the data from AS Tallinna Vesi and the Estonian Weather Service, we must say that in spite of some differences, both curves describe the same result. The main difference is in rainfall intensities registered by the meteorological stations, which is more proof that precipitation is geographically uneven and the location of the station (i.e. randomness) plays an important role. Among the data of AS Tallinna Vesi, there were also stations (such as Punane, Mahla and Tondi) where maximal intensities of 10-minute rainfalls were very similar to the values obtained from the Tallinn-Harku station.

In addition, it is important to highlight that although maximal intensities of 60-minute rainfalls were almost the same as those of the data from AS Tallinna Vesi, the shorter the duration of a rainfall, the larger the discrepancy in values was. This indicates that the rainfalls with a longer duration are more even and not so strongly influenced by local geographical factors.

Since the Estonian Weather Service does not collect data in 5-minute intervals, data from the comparison only lets us suppose that the beginning of the curve drawn by the data on maximal intensities obtained from Tallinn-Harku may be even higher, similar to the curve based by the analysis of the data from AS Tallinna Vesi.

Since the 10-minute rainfalls may present the highest intensity, their probability was analysed for the period 2010-2018. It was demonstrated that the probability for the occurrence of a low-intensity rainfall is much higher than the probability of a high-intensity rainfall. In addition, the figure shows that over the years, the probabilities become more similar.

In analysing the rainfalls by their duration, it became obvious that the number of 10-minute rainfalls was 7,329, forming 30 per cent of the total number of rainfalls. Shorter rainfalls and rainfalls lasting up to 30 minutes formed over one half of the rainfalls, namely 59 per cent.

Thus, we can conclude that the most common rainfalls are of a duration of 10-30 minutes and are not very intensive. High-intensity occurs with short-duration (10 or 20 minutes or shorter) rainfalls, but the probability is smaller and the variation of the intensity may be great, depending on local conditions. If in designing we take into consideration only the data collected in Tallinn-Harku, they may not adequately reflect the real situation in the city of Tallinn.

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APPENDIX

Appendix 1. Maximal values for 10-430-minute rainfalls for the period 2010-2018

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min	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**
avg	0.79	0.58	0.46	0.38	0.33	0.30	0.25	0.25	0.21	0.20	0.13	0.13	0-12	0.12
max	1.03	0.82	0.70	0.57	0.47	0.44	0.43	0.39	0.35	0.31	0.21	0.21	0.22	0.22
min	0.29	0.13	0.11	0.12	0.10	0.10	0.09	0.09	0.09	0.09	0.07	0.07	0.07	0.07
median	0.85	0.62	0.45	0.43	0.37	0.31	0.22	0.22	0.20	0.18	0.14	0.13	0.10	0.09
0.9	1.02	0.80	0.64	0.54	0.45	0.42	0.39	0.35	0.31	0.30	0.19	0.20	0.20	0.20
0.1	0.55	0.35	0.27	0.23	0.19	0.16	0.14	0.14	0.14	0.13	0.08	0.08	0.07	0.07

min	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**230**	**240**	**250**	**260**	**270**	**280**
avg	0.11	0.11	0.10	0.10	0.09	0.10	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.08
max	0.21	0.21	0.20	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.19	0.19
min	0.06	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.03	0.03	0.03
median	0.09	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06
0.9	0.19	0.19	0.18	0.17	0.17	0.20	0.13	0.12	0.12	0.12	0.13	0.12	0.12	0.13
0.1	0.07	0.07	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.04	0.04	0.04

min	**290**	**300**	**310**	**320**	**330**	**340**	**350**	**360**	**370**	**380**	**390**	**400**	**410**	**420**	**430**
avg	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.08	0.09
max	0.19	0.19	0.18	0.18	0.18	0.17	0.17	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15
min	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.04	0.03	0.04	0.04
median	0.06	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.09
0.9	0.13	0.11	0.11	0.11	0.10	0.10	0.11	0.11	0.10	0.10	0.10	0.12	0.12	0.13	0.14
0.1	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.030	0.04	0.03	0.04	0.05