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The intensification of short-duration rainfall extremes due to climate change – Need for a frequent update of intensity–duration–frequency curves

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HIGHLIGHTS

- Diverse short-term duration extreme rainfall intensities were analyzed for trends.
- Annual maximum rainfall intensities have increased at a rate of 4% per decade.
- The frequent update of IDF is required for the region.
- Climate change effect should be reported as a change per decade for practitioners.
- A stress test should be carried out to identify the possible flooding risk areas.

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ABSTRACT

Numerous studies have investigated future changes in extreme precipitation by employing climate models. However, trends in extreme short-duration (20–180 min) rainfall intensities, that is, design storm rainfall intensities used for stormwater infrastructure design, have received considerably less attention despite their importance. This study quantified the effect of climate change on design storm intensity based on observations. Trends were investigated for diverse short-term rainfall durations, ranging from 20 to 180 min, at 11 meteorological stations in Northern Europe, Estonia. The Mann-Kendall test and Sen's slope estimator were used to detect trends and calculate the trend magnitudes by analyzing a 70 year period of high-resolution temporal observed rainfall data. The Sen's slope indicated a positive magnitude of slopes for all the durations and stations investigated, and two stations in Northeast Estonia showed significantly increasing trends ($p < 0.05$). Unsurprisingly, the spatial distribution of trends revealed notable variations from station to station, as extreme rainfall events are heavily localized due to cloudburst. Despite this variety, it can be generalized that the annual maximum rainfall intensities in Estonia have increased at an average rate of 4 % per decade due to changing climate conditions, invariant of the rainfall duration analyzed. The use of decades enables to easily keep the intensity–duration–frequency curves updated, and it is more practical and relatable for engineers as well. The findings of this study provide critical knowledge for urban water management decision-makers, indicating the need to frequently update urban design criteria to design climate resilient urban infrastructure.

Practical implications

Climate change projections have been the primary tools for providing critical understanding of the future climate. However, the future projections of sub-daily precipitation extremes by climate models are known to be uncertain, as they are highly dependent on the climate model and emissions scenario employed. Moreover, the climate projections are provided for a

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certain time period, usually a period at the end of the 21st century (2071–2100) is available, which is then compared to the baseline period (1971–2000). These projected period differences in climatic behavior cannot be directly used in the infrastructure planning and designing process, as the lifespan of urban drainage system elements vary. For instance, there is no clear guidance for engineers on how to design a climate resilient (considering climate change) culvert with a lifespan of 40 years. Additionally, although the trend direction is mostly known in different regions in the world, the intensification magnitude of short-duration rainfall extremes is still highly uncertain.

Decision-makers require reliable and easily understandable information for effective adaption actions in urban water management planning. This is even more true with the continuing urbanization in Europe, what could further emphasize the possible under sizing of urban stormwater systems in some parts of Europe. Observed climate trends are one of the most reliable and easily understandable climate information of the past, which trend magnitude and direction can be transferred to the future. Although the uncertainty increases as one goes further into the future, trend analysis for the near- and mid-future still provides more reliable information compared to climate models. This is especially true for intense short-duration extreme rainfall events, which are still poorly described by the climate models.

Based on the study results, the added climate change stress magnitude to urban stormwater system is approximately 4 % per decade. This directly indicates that the intensity–durationfrequency curve (IDF), which is the basis in designing urban stormwater systems, is non-stationary. Thus, if the IDF is not frequently updated, the future precipitation events will be underestimated, resulting more pluvial flooding events in urban areas. Interestingly, since the trend magnitude is invariant of the rainfall duration analyzed, it is relatively easy to update the IDF curves, and it is also more practical and relatable for engineers. For example, designing a culvert with a lifespan of 40 years requires the calculation of the climate factor. The annual maximum extreme rainfalls are increasing 4 % per decade in Estonia. Thus, the multiplication of this percentage with the culvert lifespan (4 decades) gives the climate change magnitude for the culvert. This results a climate factor of 1.16 (16 % increase), which is then multiplied by the design storm depth, obtained from the IDF curve. The final value is then used as input to hydrological-hydraulic calculations.

The added stress of climate change to urban stormwater system makes the designing process more challenging since some parts of the stormwater system has already been built. Thus in order to evaluate the response of the system to climate change and to identify possible bottlenecks in the urban stormwater system, a stress test approach should be carried out. This approach can then help to quantify the capacity value needed to avoid flooding events in the identified bottlenecks. One of the most common solutions to increase the water detention and retention capability in the system is the implementation of various SUDS techniques to achieve a more climate resilient system. However, the applicability of these practices should be economically and socially justified for a specific location.

Decision-makers are overwhelmed by the diverse array of information available on the climate change impact of infrastructure, including urban stormwater systems. To aid this confusion, the following measures are suggested:

1) A stress test should be carried out to identify the possible flooding risk areas in the urban stormwater system;

2) Trend analysis of measured extreme precipitation data should be frequently carried out if such data is available;

3) Based on the trend analysis, the climate change effect for designing urban stormwater systems should be reported as a change per decade;

4) Due to the possible non-stationarity of the climate, there is a need for a frequent update of IDF curves based on precipitation measurements.

Data availability

Data will be made available on request.

1. Introduction

Climate warming is driving an increase in extreme rainfall across most of the globe, increasing the likelihood of extreme rainfall events occurring (Donat et al., 2016). This increase has been explained by statistical models accounting for only the warming of air, which is associated with an increase in water holding capacity (Lehmann et al., 2015) and water (moisture) availability (Tabari, 2020). As air temperature is projected to continue to rise (IPCC, 2014), this phenomenon is expected to continue. Thus, there will likely be a higher frequency and intensity of extreme rainfall in the future, leading to an increased risk of urban flash floods. This, in turn, can have serious negative impacts on the design, operation, and maintenance of urban drainage systems, for example, storm water culverts and pipes. However, the magnitude of the intensification is highly uncertain, which complicates the planning and design of climate resilient stormwater infrastructure.

The design standards for urban drainage systems are typically based on the concept of a design storm. The design storm average intensity is derived from the intensity–duration–frequency (IDF) curve, which describes the frequency of occurrence of extreme rainfall events. IDF curves are typically generated using historical annual maximum rainfall data under the assumption that future extreme rainfall has the same statistical characteristics as historical rainfall (Peck et al., 2012). The assumption of a stationary climate may lead to a notable underestimation of IDF curves, increasing the risk of flooding and failure of urban drainage systems (Cheng and Aghakouchak, 2014). Thus, due to climate change-induced shifts in extreme rainfall, revisions to existing design practices are required worldwide (Willems, 2013). Understanding changes in extreme rainfall intensity is an important issue in climate change adaptation and resilience.

A precipitation event is considered extreme if a certain threshold is exceeded (e.g., a 24-hour event exceeding a total amount of 50 mm) or if it is considered sufficiently rare according to a percentile-based threshold (e.g., upper 99th percentile of precipitation) (Seneviratne et al., 2012). The first global overview and estimation of extreme precipitation trends revealed an increasing probability of intense precipitation events for many extratropical regions, including Fennoscandia (Groisman et al., 2005). Due to the very high spatiotemporal variability of precipitation, specifically of extreme precipitation, large territorial variations in trends have been observed. The latest comprehensive study on a global scale confirmed the earlier conclusions on changes in extreme precipitation during the last 60 years, and precipitation totals and extremes have increased in humid regions since the mid-twentieth century (Donat et al., 2019). Sub-daily rainfall extremes have also been analyzed in North-Europe, which revealed the highly heterogeneous rainfall climate in the region (Olsson et al., 2022).

Extreme precipitation trend analysis for Poland is showing inconsistent signals in scientific literature, where results are highly dependent on the indices used and periods analyzed. Decreasing trends in extreme precipitation have been detected in Poland from 1951 to 2006 (Lupikasza, 2010), which was challenged by a more recent study, where most extreme precipitation indices showed increasing trends (Pińskwar et al., 2019). Regardless of the trend analysis result in Poland, an increase in extreme flash flood events is already evident in Poland (Pińskwar et al., 2020). The extreme precipitation index R95p has a statistically significant increasing trend in northern and eastern Europe during 1950–2010 (Donat et al., 2013). Extreme precipitation events have also been investigated in Estonia, where the number of days with precipitation totals above the 95th and 99th percentiles at 40 stations during 1961–2008 showed a clear increasing tendency (Päädam and Post, 2011). This finding was also supported by a later study showing that extreme precipitation events have become more frequent and intense in Estonia by applying a method of moving precipitation totals (Tammets and Jaagus, 2013).

Most global and local trend estimations are based on indices of extreme precipitation, which are calculated using daily (24 h) values. During the design of urban drainage systems, sub-daily precipitation is needed as the critical response time of urban drainage systems is in the order of minutes to a few hours (Ntelekos et al., 2008; Smith et al., 2002). Depending on the urban stormwater system elements (e.g., sewers, storm water management ponds or detention basins, street curbs and gutters, catch basins, and swales), diverse short-term design storm intensities are required. However, the climatological features of these sub-daily precipitation extremes have not been systematically analyzed across different climate zones due to observational limitations (Lewis et al., 2019).

As the development of IDF curves is based on the statistical analysis of historical annual maximum rainfall data, trends in annual rainfall maxima induce changes in the IDF curves (Cook et al., 2020). Based on the premise that climate change will alter the spatial and temporal variability of extreme sub-daily rainfall patterns, the design criteria of urban drainage systems must be revised to account for the impact of climate change. Ignoring the nonstationary assumption could lead to underestimation, which increases flood and failure risk in stormwater infrastructure (Cheng and Aghakouchak, 2014).

Future changes in IDF curves have been assessed in the city of London, Canada, by applying a weather generator algorithm to synthetically create future time series of weather data (Peck et al., 2012). Global climate modeling has been the basis for updating and incorporating climate change impacts into IDF curves owing to the lack of locally relevant climate change impact information (Simonovic et al., 2016). Additionally, there are no clear guidelines for engineers on how to account for climate change in the design process of urban stormwater systems.

This study quantifies long-term trends in annual maximum rainfall intensities in Estonia, focusing on short-term rainfall, which is the basis for designing urban stormwater systems. The impact of climate change on design storm intensities were analyzed at nine short-term rainfall durations (20 to 180 min) at 11 stations. As stormwater systems have a long design life, they are sensitive to changes in climate, especially to increasing rainfall intensities. To improve the climate resiliency of existing infrastructure, this study provides recommendations on how to consider climate change in the process of designing urban stormwater systems. Understanding the trends and magnitudes of short-term rainfall intensities can aid in the mitigation of associated climate change risks and damages.

2. Material and methods

2.1. Study area and rainfall data

The study was conducted in Estonia, which is located on the eastern coast of the Baltic Sea, between 57.5° and 59.5° N and 21.5° and 28.1° E (Fig. 1). The terrain in Estonia is flat, with an average elevation of approximately 50 m. Estonia is located in the transition zone from the maritime to the continental climate, with notable climatic differences being observed throughout the country. Compared to continental regions, less rainfall is expected on the coast and islands, especially during spring and the first half of summer. The inland areas are more susceptible to higher extreme precipitation events associated with higher air temperatures; therefore, changing climate conditions have different impacts on separate parts of Estonia, including extreme rainfall.

The average annual precipitation and actual evaporation in Estonia are approximately 650 mm and 350 mm, respectively. The highest precipitation amounts are usually recorded during the summer months and autumn, while the winter and spring months are drier. The monthly precipitation amounts vary considerably from year to year. The highest and lowest monthly precipitation amounts have been recorded in August, with values of 351 mm and 0 mm, respectively. The highest daily precipitation amount of 148 mm has been measured in July at the Metsküla station in Saaremaa. An extreme precipitation event in Estonia is defined by the Estonian Environment Agency by using two thresholds: a rainfall event exceeding the threshold of 50 mm in 12 h or 30 mm in 1 h. Because extreme precipitation is characterized by high spatial variability, the detection of trends induced by changing climate conditions is highly dependent on the quality and quantity of observed rainfall data.

Fig. 1. Location of the meteorological stations in Estonia used in the study.

High-resolution temporal rainfall data from Estonia are available from 1950 onwards and can be divided into three distinct periods according to the measurement method and time resolution. The pluviograph data from 11 meteorological stations are available until 1990. Pluviograph rainfall data were collected from the physical archive of the Estonian Weather Service (EWS) and digitalized. The time resolution of these pluviograph measurements ranges from 360 min up to 1 min, where higher rainfall intensities are measured with a finer time resolution, and vice versa (Kotowski et al., 2011). Rainfall data with varying time resolutions is available. The EWS physical archive contains an aggregated time series with a time resolution of 10 min. Pluviograph rainfall data is available during the warm season from May to September. Because annual maximum rainfall intensities occur in the warm period, the detection of trends is unaffected by this data limitation.

Digitized rainfall time series for the period 1991–2003 is available in the EWS digital database (MS Excel), containing pluviograph recordings from a total of 15 meteorological stations. The time resolution of this rainfall dataset is equivalent to that of the previous period, an aggregated 10-minute time resolution is available for rainfall during the warm period.

The meteorological station network in Estonia was automated in September of 2003. During the period of 2004–2010, time series with an aggregated time resolution of 60 min (clock hour) are available. This data limitation can strongly impact trend detection, as a coarse time resolution introduces more uncertainties to the trend analysis. Therefore, these data were excluded from further analysis. Since the beginning of 2011, precipitation data are available throughout the year, with a 10-minute aggregated time resolution at 29 meteorological stations.

The inclusion criteria for stations was set to a minimum requirement of 30 years of data. The stations selected for the trend analysis are shown in Fig. 1 and listed in Table 1. The period 2004–2010 is lacking for all

Table 1
Characteristics of the meteorological stations used in the study.

Station name	Elevation (m a.s.l.)	Data period	Average annual precipitation (mm)
Jõgeva	70.3	1950–1955, 1957–1987, 1991–2003, 2011–2021	650
Jõhvi	72.7	1955–2003, 2011–2021	657
Lääne-Nigula	23.9	1965–2003, 2011–2021	666
Ristna	6.9	1950–2003, 2011–2021	626
Sõrve	2.7	1955–1992, 1995–2003, 2011–2021	547
Tallinn	33.2	1951–1980, 1983–2003, 2011–2021	668
Tartu	70.2	1950–1953, 1955–1986, 2011–2021	620
Tiirikoja	32.6	1950–2003, 2011–2021	601
Väike-Maarja	120.7	1962–2003, 2011–2021	653
Viljandi	86.3	1965–2003, 2011–2021	710
Vilsandi	5.7	1955–1989, 1992–2003, 2011–2021	582

stations. Other data are also missing: 1954 and 1988–2003 in Tartu, 1993 and 1994 in Sõrve, 1981 and 1982 in Tallinn, 1956 and 1988–1990 in Jõgeva, and 1990 and 1991 in Vilsandi. The missing years were omitted from the data analysis, resulting in discrete time series for each station. Data quality control was conducted after data collection, where suspicious values (extremely high or low) were manually checked. As a result, short-term rainfall data from 11 stations were selected and collected in the database with an average length of approximately 57 years per meteorological station.

2.2. Stormwater design criteria

The concept of a design storm is widely used for the dimensioning of an urban drainage structure. The design storm is a synthetic rainfall event which intensity corresponds to a given duration and return period. The design storm intensity (i.e., the amount of rainfall occurring in a unit of time) is derived from the IDF curve. The IDF curve describes the relationship between rainfall intensity, duration, and return period (frequency). According to the type of structure designed, various combinations of design storm durations and return periods are employed. The design storm duration is typically equal to the time of concentration, which is the time required for rainfall water to flow from the most hydraulically remote point to the point under investigation. The design storm return period value is dependent on the level of acceptable risk for the urban hydraulic structure in question. Once the design storm duration and return period are chosen, the design storm intensity can be obtained from an IDF curve.

According to the national design guidelines in Estonia, a design storm with a duration of 20 min is typically used to design conventional urban drainage structures (e.g., storm water culverts and pipes) in Estonia (EVS_843, 2013). The design principle of a sustainable urban drainage system (SUDS) is dependent on the type of water retention or buffering technique employed. Design storm intensities for durations from 20 min to 3 h are typically used. The choice of a return period is dependent on the extent of the consequences of pluvial flooding (surface water flooding) in a given location. Typically, return periods of up to 10 years are employed in Estonia.

The development of IDF curves requires a frequency analysis of the historical extreme rainfall series. This is carried out by calculating annual maximum values or defining an extreme value threshold, which is either percentile or magnitude-based. This study uses the annual maximum value analysis for each duration, as it is the most typical approach to develop an IDF curve. First, rainfall data processing is carried out to obtain the annual maximum intensities for various short-term rainfall durations. Second, the obtained annual maximum intensities corresponding to each duration is fitted to a theoretical probability distribution (e.g., Gumbel Extreme Value Type-I). The fitted theoretical distribution is a mathematical function of an IDF, relating rainfall intensity with duration and return period. The development of IDF curves is based on historical data, with the assumption that the temporal structure of extreme rainfall events remains unchanged (Cheng et al., 2014; Vasiliades et al., 2015).

2.3. Rainfall data processing

A uniform discrete data format is required for analyzing the annual maximum rainfall intensity trends for various short durations. Therefore, as the rainfall data format varies depending on the measurement method used, data processing is performed. As a first step, a new rainfall event is defined using the concept of minimum inter-event time (MIT) (Dunkerley, 2008), which is a certain time threshold for a rain-free period after the preceding event is detected. The EWS uses an MIT value of 3 h as the definition of a new rainfall event, and for data consistency, the same value was used in the current study for the whole period.

The collected rainfall time series have an aggregated 10-minute time resolution, representing a period of 10 min (00–10, 10–20, 20–30, 30–40, 40–50, and 50–60) each hour. Rainfall data processing and trend analysis were conducted in the R environment (Ihaka and Gentleman, 1996). Rainfall data for a given rainfall event were linearly interpolated into an equal time interval of 1 min, corresponding to the maximum precision of the pluviograph. As a result, a fine-scale rainfall time series with a time interval of 1 min for each meteorological station and event was obtained.

This study analyzed trends in annual maximum rainfall intensities for the following durations: 20, 30, 40, 50, 60, 90, 120, 150, and 180 min. The maximum intensity of a given rainfall event and duration was computed by applying the moving time window approach, where the time window size corresponds to the length of the time duration analyzed. The maximum value was selected from the computed values for each rainfall event. The annual maximum rainfall intensity for each year is the maximum value of all rainfall events in the given year. As a result, a dataset of annual maximum intensities for each station was obtained, which was used as the input for trend analysis.

2.4. Trend analysis

Various statistical approaches have been developed to distinguish natural variations from those caused by climate change. The most commonly employed approach for detecting monotonic trends in hydrological variables is the Mann-Kendall (MK) non-parametric test (Kendall, 1975; Mann, 1945). This study uses the rank-based MK nonparametric test because it is robust against non-normality and missing values, which is relevant for study stations where sub-daily rainfall data are not discrete. The null hypothesis (H0) assumes that the maximum annual rainfall intensities are independently and identically distributed (no monotonic trend). The alternative hypothesis (Ha) states that the data follow a monotonic trend, which is either an upward monotonic (increasing) or downward monotonic trend (decreasing). In this study, a 5 % significance level was chosen as a threshold for trend detection (e.g., p values less than 0.05, were considered statistically significant, and H0 was rejected).

The MK test is complemented with Sen's slope estimator (Sen, 1968) to assess the magnitude of the trend. Sen's slope is a non-parametric procedure that calculates the median slope between all data pairs in the time series. The computed sign of the median slope shows the data trend (increasing or decreasing), whereas the value indicates the magnitude of the trend. Sen's slope is a popular non-parametric technique among scientists for estimating a linear trend, as no underlying distribution assumptions are made about the data. Furthermore, with a breakdown point of approximately 29 % from the data points (Wilcox, 1998), the method is robust to outliers and missing data.

Trend analysis of maximum annual rainfall intensities in Estonia was carried out at 11 meteorological stations (Table 1) using more than 30 years of measurements over the period 1950–2021. Although some missing data at the stations are evident, the average data coverage is approximately 85 %, including the missing period of 2004–2010. The length of the time series varied between 47 and 65 years (with an average of 57 years).

3. Results

3.1. Sub-daily extreme precipitation climatology

The annual maximum precipitation amounts at the Estonian stations for different high temporal resolutions from 20 to 180 min are presented in Table 2. The maximum values for 20 and 30 min were recorded in Jõhvi on June 26, 2000 and for 40–180 min in Jõgeva on August 2, 1994. Interestingly, the second highest 180-minute intensity was recorded in Sõrve on May 18, 2013. The last number of 79.6 mm in the coastal station is nearly unbelievable, especially during springtime. The second highest rainfall intensity in Sõrve was only 56.2 mm per 180 min. This was a remarkable exception because coastal stations, such as Vilsandi and Ristna, have much lower maximum rainfall intensities of 44.9 mm and 52.9 mm per 180 min, respectively. On the other end of the temporal time scale, the highest rainfall intensity in Estonia was recorded in Tiirikoja on June 20, 1980, with a value of 5.4 mm/min for 1 min.

The cumulative frequency of occurrence of accumulated precipitation depth in annual maximum 60 min rainfall events was binned according to the thresholds of 10, 20, 30, 40, and 50 mm (Table 3). Although these numbers are not fully comparable between stations due to different measurement time periods, it is clearly evident that the intensity of extreme rainfall is lower in the westernmost coastal stations (Ristna, Vilsandi, and Sõrve). In continental stations, it is considerably higher; however, it should be noted that the observation period and data coverage were much lower at some stations (Lääne-Nigula, Tartu, Väike-Maarja, and Viljandi) (Table 1). Consequently, the number of rainfall events in Table 3 was lower than that of the other stations.

Table 3
Cumulative frequency of occurrence of 60-minute rainfall events with precipitation amounts above 10, 20, 30, 40, and 50 mm.

Station name	Frequency occurrence				
	>50 mm	>40 mm	>30 mm	>20 mm	>10 mm
Jõgeva	1	2	3	25	129
Jõhvi	1	3	7	21	122
Lääne-Nigula	0	0	1	16	92
Ristna	0	0	1	8	76
Sõrve	0	0	2	8	59
Tallinn	0	2	2	20	152
Tartu	0	1	3	17	115
Tiirikoja	0	0	5	19	116
Väike-Maarja	0	1	3	17	103
Viljandi	0	2	4	17	117
Vilsandi	0	0	5	6	67
Total	2	11	36	174	1148

There have been almost 40 extreme rainfall events, where the average intensity for one hour has been over 0.5 mm/min (30 mm/60 min). The highest 60-minute rainfall event ever measured in Estonia exceeded the average intensity of 1 mm/min (precipitation amount of over 60 mm in 60 min), which took place in Jõgeva, with a precipitation amount of 78.6.

Besides the occurrence frequency of high intensity rainfall events, the distribution of these events according to the month of occurrence is also a topic of interest as it as it helps to determine the rainfall type (conventional or frontal). Annual maximum precipitation for rainfall durations of 20 and 60 min over the study stations in Estonia are presented in Figs. 2 and 3, respectively.

The highest number of events with annual maximum 20-minute rainfall amounts has been recorded in July (35 % of all cases), which is the warmest month in Estonia on average. The frequency of such rainfall has been slightly lower in August (31 %) and June (21 %). The occurrence of annual maximum rainfall in September and May has been much lower, at 8 % and 6 %, respectively.

It is interesting that the most severe rainfall cases have been observed not in July but in June and August, as was reported at the beginning of this section. The mean annual maximum 20-minute rainfall intensities have been approximately 0.5 mm/min, while the highest values have risen up to 2 mm/min.

Another peculiarity of the monthly distribution of annual maximum 20-minute rainfall is the highest median; the 1st and 3rd quartile values were obtained in May, although the number of such cases was low. This can be explained by the occurrence of extremely intense rainfall events in May. Thus, if annual maximum 20-minute rainfall occurs in the month of May, it is likely to be more severe compared to other months. At the same time, the median intensity of the annual maximum rainfall in July was even lower than in June and August.

Table 2
Maximum precipitation amounts for various time resolutions from 20 to 180 min.

Station name	Time resolution (minutes)								
	20	30	40	50	60	90	120	150	180
Jõgeva	39.0	49.1	64.5	74.6	78.6	88.9	90.6	94.7	99.4
Jõhvi	40.4	50.4	52.6	53.8	54.6	58.9	63.1	65.2	66.2
Lääne-Nigula	26.6	30.1	32.3	34.4	35.7	38.9	47.0	48.9	50.7
Ristna	22.3	25.3	29.3	33.3	33.8	34.0	34.4	35.1	37.0
Sõrve	19.4	27.9	32.3	34.4	34.9	50.3	64.7	72.3	79.6
Tallinn	24.4	33.2	40.9	44.6	45.0	46.2	46.5	48.0	55.7
Tartu	21.0	27.2	34.6	37.8	40.6	41.6	51.1	61.7	67.4
Tiirikoja	22.9	28.9	34.0	36.9	38.6	48.1	50.6	53.4	54.2
Väike-Maarja	26.3	34.7	41.7	42.3	43.3	45.0	48.8	50.9	54.2
Viljandi	30.2	37.4	42.0	45.8	46.9	49.1	57.7	59.8	59.8
Vilsandi	27.6	37.0	39.1	39.7	39.8	42.5	43.4	44.1	44.9
Maximum	40.4	50.4	64.5	74.6	78.6	88.9	90.6	94.7	99.4

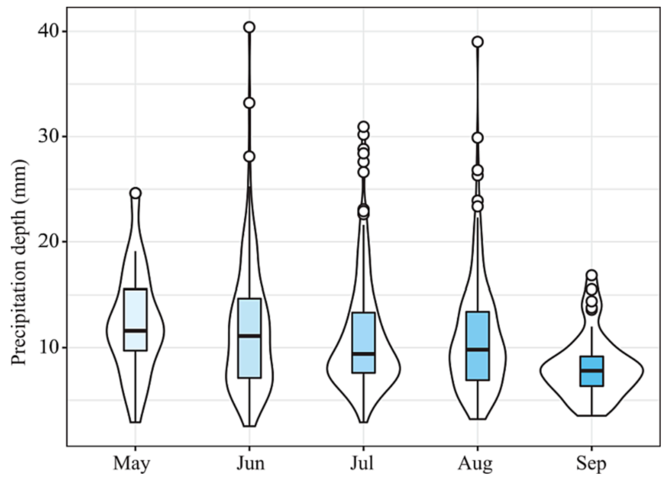

Fig. 2. Violin plot of annual maximum 20-minute rainfall occurrences over the study stations in Estonia by months, where the x- and y-axes indicate months and amounts of precipitation (mm), respectively.

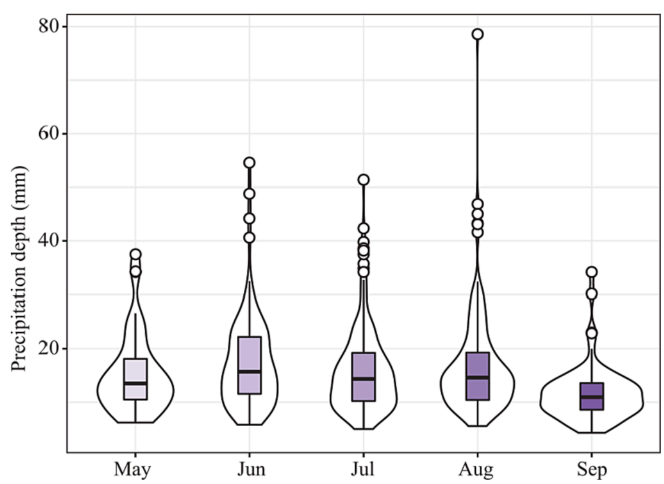

Fig. 3. Violin plot of annual maximum 60-minute rainfall occurrences over the study stations in Estonia by month, where the x- and y-axes indicates months and amounts of precipitation (mm), respectively.

Comparing the monthly distribution of annual maximum 20-minute rainfall statistics (Fig. 2) with 60-minute statistics (Fig. 3), it can be concluded that maximum rainfall events for a longer period are more evenly distributed. The percentages of September and May are higher (12 % and 8 %, respectively), while it is lower in June (19 %), July (32 %), and August (29 %).

It is natural that the intensity of rainfall in the case of 60-minute time duration is notably lower than for shorter durations. The median intensity of the annual maximum 60-minute rainfall has been approximately 0.2 mm/min, with the highest value in June. The record intensity measured on August 2, 1994, in Jõgeva was 1.3 mm/min, while all the other measured intensities were below 1 mm/min. For the annual maximum 60-minute rainfall intensity, the mean values in July are lower than those in June and August.

The calculation of the annual maximum rainfall intensity included a total of 628 years. Namely, there were 16 cases for 20-minute and 9 cases for the 60-minute duration rainfalls, which were recorded outside the period from May to September. These annual maximum rainfall events occurred in October, which is quite rare in Estonia. The highest rainfall amount in October was recorded in Tallinn on October 7, 1975, with values of 9.3 and 14.7 mm for time durations of 20 and 60 min, respectively. A similar 60-minute rainfall event was also recorded in Vilsandi (13.4 mm), where the majority of the October 60-minute annual maximum rainfall events have occurred.

3.2. Trends in short-term design storm intensities

The dataset from 1950 to 2021 was used for trend detection in the annual maximum short-term rainfall. The analysis was conducted for the warm period months (May to September), when the annual maximum rainfall intensities occur in Estonia. Rainfall intensities were investigated for nine short-term rainfall durations ranging from 20 to 180 min. Without loss of generality, the estimated trends and magnitudes of rainfall durations change linearly. Thus, for readability purposes, the results of annual maximum rainfall trend analysis are summarized in Table 4 only for the selected durations of 20, 60, 90, and 180 min. Trends were tested for significance using the MK non-parametric test, with a significance level of 0.05. The Sen's slope value, which represents the trend magnitude of rainfall depth (mm per decade), was consistently non-negative among all the meteorological stations and rainfall durations analyzed, except for Jõgeva station. This indicates an overall positive trend in the annual maximum short-term rainfall intensities in Estonia. Although a positive trend is evident, there are considerable differences between the meteorological stations. A more detailed overview of the calculated p values and Sen's slope values for short-durations from 10 to 60 min can be found in the Appendix: Table A1.

The MK test detected an increasing trend in annual maximum 20-minute duration rainfall at the Tiirikoja (0.95 mm/decade) and Jõhvi (0.92 mm/decade) stations at a confidence interval of 95 % (Table 4). Statistically significant trends were found in all the short-term rainfalls analyzed for the Tiirikoja and Jõhvi stations, with an increase of approximately 9 % per decade (recalculated by dividing trend magnitude by station average). Both meteorological stations are located in the northeast of Estonia. According to the results of the trend analysis, the trends in the other two north-eastern meteorological stations (Jõgeva and Väike-Maarja) are weak and statistically insignificant.

A significant positive trend was detected in the Lääne-Nigula station for the annual maximum rainfall with a duration of 60 min, where the Sen's value was 1.11 mm/decade. Interestingly, for the remaining durations and stations analyzed, no significant trend was detected at the 95 % level. These results indicate to the uncertainties associated with the trend analysis in short-term rainfall. It should be noted that the Sen's slope value was non-negative for all durations and stations investigated, with one exception, the Jõgeva station. Furthermore, the trend magnitude should be at least 7 % per decade to be considered statistically significant ($p < 0.05$).

Owing to the discrepancy among stations, the generalization of trends in short-term rainfall was performed. The interquartile range was used to assess the variability of the trend by focusing on the middle 50 % trend magnitude. An excellent power fit between the trends in annual

Table 4
Results of Mann-Kendall test and Theil-Sen's slope estimator.

Rain gauge	Sen's slope value (decade)			
	20 min	60 min	90 min	180 min
Jõgeva	−0.17	−0.3	−0.14	−0.14
Jõhvi	0.92*	1.50*	1.64*	1.87*
Lääne-Nigula	0.57	1.11*	1.14	0.85
Ristna	0.26	0.29	0.29	0.58
Sõrve	0.29	0.33	0.37	0.50
Tallinn	0.51	0.82	0.73	0.63
Tartu	0.17	0.67	0.55	0.58
Tiirikoja	0.95*	1.26*	1.27*	1.40*
Väike-Maarja	0.25	0.29	0.36	0.36
Viljandi	0.28	0.19	0.52	0.88
Vilsandi	0.27	0.33	0.44	0.69
Estonia	0.97*	1.23*	1.30*	1.67*

*Asterisks indicate a significant trend at the 95% confidence level.

maximum rainfall intensities and analyzed durations is evident, with high R2 values of 0.990, 0.973, and 0.975 for the first, second, and third quartiles, respectively (Fig. 4). Although the trend in rainfall intensity decreases over longer rainfall durations, the average trend magnitude is approximately 4 % per decade, which is invariant to the rainfall duration analyzed.

The number of stations in Estonia, containing long-term high-resolution temporal rainfall data, is quite low. According to the stations analyzed and the surface area of Estonia, one station describes an area of approximately 4100 km^2. Thus, trend detection is more complicated because of the low station measuring network in Estonia. To gain more confidence in the results, all 11 stations were aggregated into one station defined as Estonia, representing all long-term high-resolution rainfall measurements in Estonia. The annual maximum values for each year were computed for durations of 20, 60, 90, and 180 min. Then, trend detection was carried out for the Estonia station.

The MK test detected a statistically significant ($p < 0.05$) increasing trend in all the durations analyzed, with Sen's value (mm/decade) of 0.97, 1.23, 1.30, and 1.67, for short-term rainfall durations of 20, 60, 90, and 180 min, respectively. It should be noted that the calculated p values showed a confidence level > 99 percent ($p < 0.01$) for all durations analyzed. The findings clearly indicate that the maximum annual short–term rainfall intensities in Estonia are increasing (Fig. 5) owing to changes in the climate.

In summary, despite the clear spatial heterogeneity, it is evident that there has been an overall increasing tendency of extreme rainfall intensities during the period 1950–2021, although the increases were not significant at most stations (two stations were statistically significant at the 5 % significance level for all durations). The average trend in the annual maximum intensities has been approximately 4 % per decade, regardless of the design rainfall duration. The positive trend signal was also confirmed using all measurements as one station, Estonia.

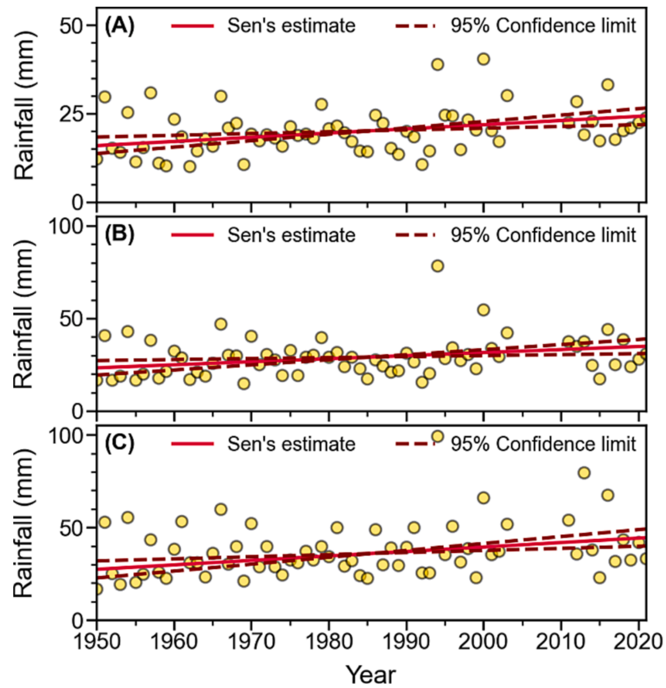

Fig. 5. Annual maximum 20- (A), 60- (B), and 180-minute (C) precipitation trend with Sen's slope value and its 95% confidence intervals in Estonia. Available data within the period 1950–2021.

4. Discussion

Increasing trends in design storm intensities due to climate change affect urban drainage system performance requirements and increase the risk of fluvial flooding. Annual maximum rainfall intensities in Denmark are likely to increase by 10–50 % within the next 100 years, and the magnitude of this increase is dependent on the duration and the return period (Arnbjerg-Nielsen, 2012). The calculated delta change (increase in maximum intensity) was higher for smaller durations and higher return periods. Similarly, the results of this study revealed an increasing trend in annual maximum rainfall intensities, in the order of 4 % per decade. Interestingly, this increase was invariant to the rainfall duration. These differences can be explained by the different methodologies and assumptions applied.

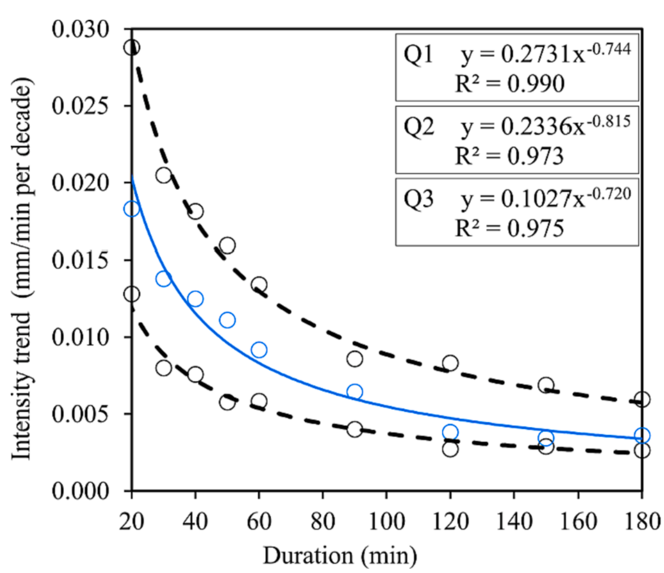

Fig. 4. Intensity trend of the maximum annual rainfall (mm $decade^{-1}$) on the design rainfall durations, where Q1 - 25th percentile, Q2 - 50th percentile, and Q3 - 75th percentile.

Various studies have focused on analyzing the effects of climate change on extreme precipitation by employing climate models. A comprehensive study used the HIRHAM4 RCM, with 12 km resolution covering Europe, to analyze future changes in extreme precipitation (1 h duration) intensities (Larsen et al., 2009). Scandinavia is expected to experience the highest increase in Europe, whereas southern Europe the lowest. The calculated climate factor was highest around the Baltic Sea (1.52 for a 1-hour duration); however, this result was doubted due to climate model limitations in simulating the heat exchange between the Baltic and the North Sea.

A similar study conducted in Sweden employed an ensemble of RCMs to investigate extreme precipitation depths for durations between 30 min and 1 d (Olsson and Foster, 2014). The results suggest that extreme precipitation increases by up to 25 % by the end of the 21st century. Recalculation of this increase to decadal basis shows an average change of approximately 2.6 %, revealing a magnitude similar to that in this study (average increase of 4 %). Contrary to the current study, the trend magnitude was inconsistent among durations (trend was more pronounced with shorter durations). This finding clearly indicates that uncertainties derived from employing climate models and future changes in RCM-simulated sub-daily precipitation extremes should be compared with alternative methods (Olsson and Foster, 2014).

The above-mentioned trends in extreme precipitation affect the evaluation and assessment of the hydraulic capacity of urban drainage systems. The lifespan of these systems is over 50 years; however, the current design practices (IDF relationship) do not consider future trends in design rainfalls. A number of studies have updated IDF curves by applying climate factors derived from climate modeling to account for future climate conditions (Madsen et al., 2009; Peck et al., 2012) which are then applied in hydraulic modeling.

Rainfall-runoff models have been widely employed to evaluate the effects of urbanization and climate change on urban drainage systems. These models are useful tools for assessing the effect of climate change on urban runoff (Berggren et al., 2014; Jung et al., 2015; Zahra et al., 2015) or to analyze the hydraulic performance of urban drainage networks (Berggren et al., 2012; Moore et al., 2016; Olsson et al., 2013). The calibration and validation of rainfall-runoff models are essential to reliably evaluate changes in the quantity and quality of urban stormwater considering climate change (Tuomela et al., 2019) and urbanization (Guan et al., 2016, 2015; Sillanpää and Koivusalo, 2015).

Various studies have shown the vulnerability of existing urban drainage networks to climate change by employing rainfall-runoff models (Berggren et al., 2012; Moore et al., 2016; Olsson et al., 2013).

These mathematical models can also be useful tools to carry out a stress test to identify the possible flooding risk areas in the near future due to the intensification of short-duration rainfall extremes. The upgrading of existing urban drainage systems is required, for example, upsizing of drainage pipes or implementation of SUDS elements to achieve a more climate resilient system. The implementation of nature-based solutions might prove to be difficult from the legal perspective, due to political aspects. For example, in Poland the lack of consistency and stability of legal regulations in sustainable stormwater management have considerably hindered the development of nature-based solutions (Kordana and Słyś, 2020). The applicability of SUDS practices should be also economically, socially (Hamann et al., 2020), and environmentally justified (Jayasooriya et al., 2020) for a given location. Several studies have analyzed the effects of installing SUDS elements to reduce urban runoff peaks (Bai et al., 2018; Guan et al., 2015; Zhu et al., 2019), showing the possible advantages of implementing SUDS techniques.

However, additional research is still required to evaluate the upgrade extent necessary to account for the increasing trend in the design storm intensities in the region. The lifespan of urban drainage system elements should be one design criterion to consider the effects of climate change. Thus, the results should be reported as a change over a decade, which facilitates the applicability among engineers. The results of the current study revealed an increasing trend in design storm intensities in the order of 4 % per decade. Based on the findings of this study, it is clear that there is a need for a frequent update of intensity–duration–frequency curves in Estonia, as well as in neighboring countries.

5. Conclusions

This study quantified the effect of climate change on short-term design storm intensity in Estonia.

The trend analysis of observations indicate an overall positive trend, with two stations showing statistically significant trends ($p < 0.05$) for all rainfall durations analyzed. The average trend in the annual maximum intensities has been approximately 4 % per decade, regardless of the design storm duration. Form the above, it is evident that there has been an increasing tendency of extreme rainfall intensities during the period 1950–2021.

The use of Sen's slope for climate change trend quantification gives the climate change magnitude, which can be directly used in the stormwater designing process. However, this approach assumes a constant design storm change rate, which is based on measurements. Thus, the further the future, the less reliable the future trend forecast based on the past. Despite this drawback, the study gives a unique possibility to identify possible flooding risk areas in the existing stormwater system. This can be carried out by stress testing the stormwater system, by gradually increasing the climate change factor.

Another limitation of the study was the number of meteorological stations used and the data quality. Although the data period used in the analysis is quite long, it is not continuous. This increases the uncertainty related to the trend magnitude. The development of new generation RCM's, capable of simulating deep-convection processes on high spatial and temporal resolution, could fill the cap in providing better understanding of the future extreme precipitation in Estonia, and the Baltic Sea region in general.

Regardless of the methodology used to assess the climate change impact on design storm, it should be reported as a change per decade rather than period averages, which are typical to climate modelling studies. This gives the ability to easily implement the future change to the design storm depth calculation process, which in turn makes it a useful index for practitioners in stormwater management. The lack of better climate model simulations in the region, the trend analysis based on observations should be carried out frequently enough to reduce the trend uncertainty. The findings of this study indicate the need to revise urban design rules in Estonia as well as in neighboring countries to prepare for heavy rainfall with higher intensities.

CRediT authorship contribution statement

Ottar Tamm: Conceptualization, Methodology, Visualization, Writing – original draft. **Egle Saaremäe:** Methodology, Data curation, Investigation, Writing – original draft. **Kristiina Rahkema:** Methodology, Data curation. **Jaak Jaagus:** Methodology, Writing – review & editing. **Toomas Tamm:** Project administration, Resources, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix: Table A1

Station	10 min			20 min			30 min			40 min			50 min			60 min		
	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen
Jõgeva	9.3	0.95	0.00	12.6	0.70	−0.02	14.4	0.57	−0.03	16.2	0.43	−0.04	17.4	0.45	−0.03	18.1	0.54	−0.03
Jõhvi	8.7	**0.03**	0.06	11.8	**0.01**	0.09	14.0	**0.00**	0.11	15.5	**0.00**	0.15	16.7	**0.00**	0.17	17.6	**0.00**	0.16
Lääne-Nigula	8.3	0.17	0.03	10.9	0.13	0.06	12.5	0.11	0.07	13.7	0.07	0.09	14.7	0.05	0.10	15.7	**0.04**	0.11

(continued on next page)

(*continued*)

Station	10 min			20 min			30 min			40 min			50 min			60 min		
	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen	$\overline{X}$	p	Sen
Ristna	6.3	0.34	0.02	8.7	0.28	0.03	10.2	0.13	0.04	11.2	0.13	0.04	12.1	0.13	0.04	12.9	0.23	0.03
Sõrve	6.6	0.21	0.02	9.3	0.18	0.03	11.0	0.16	0.03	12.2	0.15	0.03	13.2	0.22	0.03	14.0	0.25	0.03
Tallinn	7.9	0.50	0.01	11.0	0.11	0.05	12.7	**0.04**	0.06	13.7	**0.03**	0.07	14.5	**0.03**	0.09	15.2	**0.02**	0.08
Tartu	8.4	0.19	0.03	11.0	0.30	0.02	13.0	0.32	0.03	14.5	0.20	0.05	15.9	0.15	0.07	16.7	0.17	0.07
Tiirikoja	8.1	**0.00**	0.06	11.2	**0.00**	0.09	13.3	**0.00**	0.12	14.3	**0.00**	0.00	15.2	**0.00**	0.13	15.9	**0.00**	0.13
Väike-Maarja	8.9	0.22	0.04	12.3	0.53	0.02	14.1	0.67	0.01	15.2	0.62	0.03	15.8	0.52	0.04	16.3	0.55	0.03
Viljandi	9.1	0.76	0.01	13.0	0.64	0.03	15.0	0.86	0.02	16.1	0.78	0.02	16.9	0.89	0.01	17.4	0.78	0.02
Vilsandi	6.6	0.99	0.00	9.3	0.32	0.03	10.8	0.49	0.02	12.0	0.49	0.02	12.8	0.37	0.03	13.4	0.29	0.03

*Asterisks indicate a significant trend at the 95% confidence level, underlined values show the 90% confidence level.

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