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Short-Term Rainfall Distribution in Space and Time Conditions in Southern Sweden

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ABSTRACT: Since short-term rainfall data are not available for all cities or are of short-duration, probabilities of extreme events and intensity-duration-frequency relations may have to be determined from observation from other places. Variations of the climate may have to be considered. In this paper, daily precipitation over 89 years are compared for three cities, and for 30 years for more than 200 stations in the very south of Sweden. It is not possible to fit any probability distribution to observations from a single station. The most extreme events are found to be independent of annual precipitation and to have the same character at all stations; the general extreme value distribution can be fitted to a combination of extreme data from all stations. When the full 89 year period is considered, there is no trend of the daily high precipitation. Very short-term storms of duration 10 to 60 minutes are analyzed for six cities. The extreme storms have the same character at all the cities. An idf-curve is determined from a sample of observations from all stations. The fit between observations and the Gumbel distribution is good.

INTRODUCTION

Urban drainage system must be designed to be able to handle the storm water produced by short-term intense storms. From precipitation measurements with high resolution intensity-duration frequency curves can be derived and used for design. However, short-term rainfall data are not available for all cities; and when they are, it is for most places for rather few years. Then, design storms must be derived on data from other places and from mean rainfall over long periods. In a changing climate the present values used for design may have to be changed. In this paper, storms in southern Sweden of duration 10 minutes to 1 day are analyzed. Spatial distribution and correlation are considered. General Extreme Value (GEV) distribution is fitted to station values as well as to regional data. The number of station years is prolonged by treating many stations as independent. Intensity-duration-frequency curves are derived. It is investigated, when observations can be transferred from one place to another. Trends are investigated.

DATABASE

The daily precipitation data analyzed in this paper are from official SMHI (Swedish Meteorological and Hydrological Institute) stations in the cities Malmö, Halmstad and Göteborg along the southern part of the west coast of Sweden. The data series extend from 1919 to 2007. Data after 1961 are obtained in digitalized form from SMHI, while older data are found from old notes. The observation period is 89 years. The distance between Malmö in the very south and Halmstad is about 150 km. There is another 150 km to Göteborg. The precipitation is caught in accumulating gauges, called SMHI gauges. The regional analysis of daily precipitation is based on 30 years of observations (1961–1990) from 230 stations over an area of about 10,000 km^2 in the southern-most country of Sweden, Skåne. The station net was organized by Hon. Dr. Jan Ellesson. Official SMHI-gauges were used.

The very short-term storm data, minutes to hour, are from the cities Malmö, Helsingborg, Halmstad, Göteborg and Uddevalla along the Swedish west coast and from the city of Växsjö on the Southwest Highlands (altitude 100 m) of Sweden. Helsingborg is 50 km north of Malmö, Uddevalla is about 100 km north of Göteborg. Växsjö is 150 km from the coast, directly east of Halmstad. The data can be obtained from the homepage of the Swedish municipal organization Swedish Water (Svenskt Vatten) and have been organized by Hernebring (2006). There are observations from all the cities for the period 1992–2004. For Göteborg and Malmö the records extend into the 70's, although the type of gauges has been changed and the position of the gauges changed slightly. Comparison is made with old short-term rainfall statistics. Rain with short-time resolution is measured with tipping bucket. The rain depth resolution of the tipping buckets used today is 0.2 mm. For some observation prior to 1992 tipping buckets with resolution 0.5 mm were used. Old Swedish idf-curves are based on observations using Hellman gauges. The accumulated precipitation as increasing depth in a gauge was registered versus time on paper. With tipping buckets the time resolution at high rain intensities can easily be 1 minute. Too low accumulated precipitation can hardly be observed in any gauge. However, care must be taken when analyzing very short-term rain intensities. There might be some debris hindering water from running into the bucket, so that water is accumulating in the funnel leading to the bucket. When the debris is removed by high water pressure, much water reaches the bucket and high rain intensity is registered for a short-period. When the 5 minutes, 10 and 20 minutes volumes are the same, more information than the data from the single tipping bucket are required before the observation data can be accepted. In the city of Malmö there are 6 precipitation stations with high time resolution. At five of them the series are almost complete for the last 12 years; at one for almost 30 years. The data were used for a study of local variations of short-term intense storms.

The data have been used to determine extreme values by fitting to extreme value distributions. Events exceeding threshold values have been included. The parameters have been determined using weighted moments (L-moments). The statistical analysis was done for individual stations and also for many stations lumped together. When extending the number of station years, only one rain event was included, if high precipitation occurred the same day at more than one station. The probability of high rain intensity was related to annual precipitation and altitude.

OBSERVED EXTREME EVENTS

The highest observed daily rainfall in the SMHI official station net for Skåne (the country of the southern-most Sweden) is 159 mm (from the town of Båstad in between Helsingborg and Halmstad) from 1936. However, there is an observation reported by Ellesson and Persson (1961), who 1960 measured 237 mm north-east of Kristianstad in the north-eastern part of Skåne peninsula. This is where the annual mean precipitation in Skåne is the lowest, only about 450 mm. In the period 1961 to 1990 the maximum daily rainfall recorded at any of the 230 stations was 114 mm. The rainfall in the three cities Malmö, Halmstad and Göteborg did not exceed 100 mm during any day in 89 years.

The highest observed 1 hour rainfall is 43 mm at one of the stations, Limhamn, in Malmö; at the station (Turbinen) with records over 30 years the highest hourly storm depth is 38 mm. At the other cities the highest rainfall is in the range 25–30 mm. However, the highest 30 minutes rainfall is almost the same in all the cities, 22–25 mm, except at the station Limhamn in Malmö; the same rain event that produced 43 mm in an hour produced 41 mm in 30 minutes. Hernebring (2006) has gone through old very short-term rain data collected by Swedish municipalities. There is an observation in 1916 from Stockholm on 25 mm over 5 minutes. An accumulating gauge was used so the measurement can not be very exact. Still, even if this rain volume occurred over 10 minutes this would be a very extreme event for Swedish conditions. The highest observed 10 minutes rainfall is in the range 12–16 mm for all the investigated cities. Only at the station Limhamn (not at the other stations in Malmö) the rain intensity is close to that in Stockholm, 28 mm in 10 min. The highest observed 5 minutes volume in Limhamn is 17 mm, but the second highest storm at any other station is only 11 mm. There are observations from all stations, which are about 10 mm in 5 minutes.

SPATIAL DISTRIBUTION OF EXTREME DAILY PRECIPITATION

The Ellesson data of 230 stations for the period 1961 to 1990 was used to analyze the regional distribution of extreme daily rainfall. The rain gauges are distributed over an area of about 10,000 km^2. Skåne is a peninsula, Figure 1, so no station is further away from the sea than 50 km. There are three ridges or small mountains with altitude up to 200 m within the region. The annual precipitation is more than 800 mm at the high altitudes, but only about 450 mm near the sea in the north-east.

The extreme daily precipitation has a different distribution than the annual distribution. There are 8 events of daily rainfall larger than 100 mm and 10 larger than 80 mm. They are distributed evenly over the whole region. The annual maximum daily precipitation for the 30 years is from 28 different stations, which are shown on Figure 1 together with the full station net. It seems that the very extreme rainfalls are distributed by chance all over the region. It has already been pointed out that the most extreme daily event has been recorded, where the annual precipitation is the lowest.

Considering the modest extremes there is a difference between stations with different geographical position. SMHI defines extreme precipitation as 40 mm/day. In Malmö at the western coast such or larger events

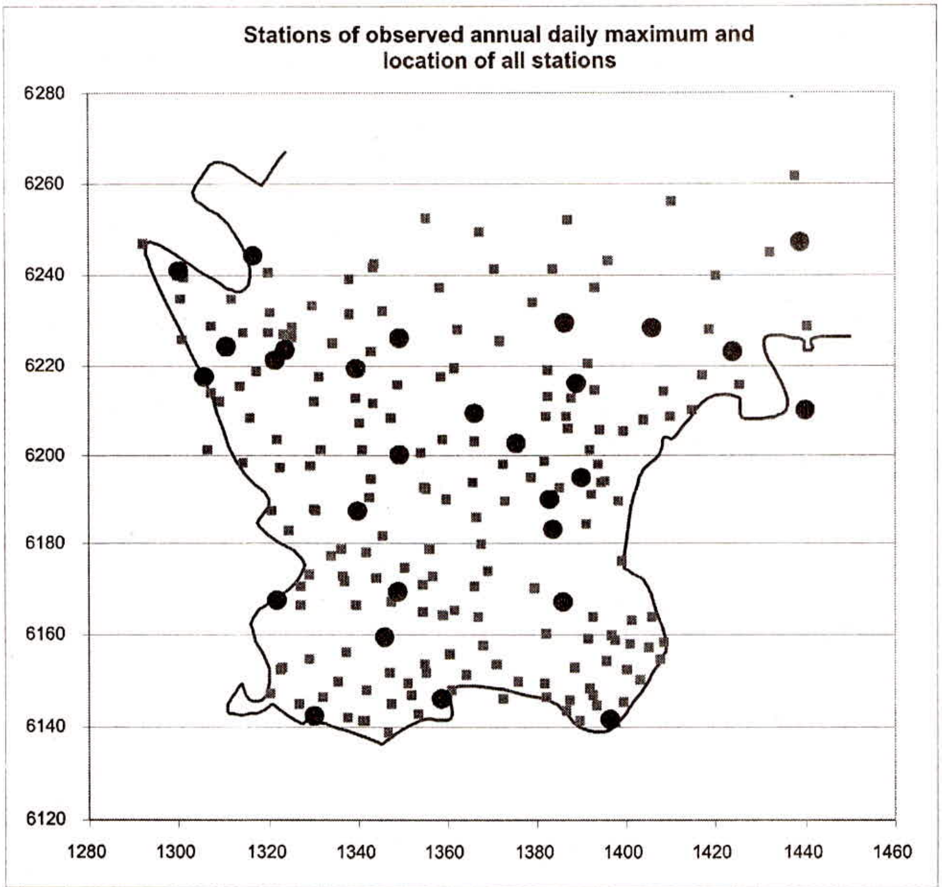

Fig. 1: Location of stations where annual maximum has been observed and location of all precipitation stations in Skåne

have occurred 20 times since 1919. The return period is thus 5 years. On the ridge Linderödsåsen and on its eastern slope towards the eastern coast of Skåne the return period for such events is 2 years, as found from the observations over the period 1961 to 1990. The probability for modest extreme events is weakly related to altitude, but more related to geographical positions. Rains from the south-east release their water while ascending over the small ridge.

It is possible to relate modest daily precipitation to annual precipitation. Madsen *et al.* (1998) have shown a relation between daily precipitation and mean annual precipitation in Denmark. Since there is a relation between altitude and annual precipitation and a weak relation between altitude and high daily precipitation, there is also such a relation in the region of Skåne. However, the slope of the regression curve is small and there is no relation with the very largest storms. In Sweden, what is called Z-values, Dahlström (1979) are used to relate mean summer precipitation to very short-term rainfall. Although there is a significant relation for storms of 1 year and 2 years return period, the regression slope is small.

Frequency Analysis Daily Precipitation

The probability of an extreme event is estimated by fitting frequency functions to observations. The parameters are determined using weighted moments, since ordinary moments may give too much weight to single observations. The General Extreme Value function (GEV) and the Gumbel distribution are used. All independent observations above a given high threshold value are used. The return period is related to the ratio between observation years and the number of observations exceeding the threshold. The ranking position is $(i-a)/N$, where i is position and N number of included observations. Usually the value of a is set to 0.35, but when the threshold is high and few values included lower values has to be used for the computations to be consistent.

The precipitation has been measured daily at the station Bulltofta in Malmö since 1919. Every event (20) exceeding 40 mm has been used for frequency analysis. The relation between intensity and return period is shown in Figure 2. The observed intensity-frequency graph tends to flatten out. Daily rains of 100 mm seem to have a very long return period at this station. The observations were fitted to extreme value functions. As seen in Figure 2 the fit is poor. The highest values exceeding 60–70 mm can not belong to the same probability distribution as the values between 40 and 60 mm. The same extreme value analysis was applied to data from another station is Malmö (Turbinen) from which there are observations since 1929. The fit between observations and the theoretical functions are even worse than for the station Bulltofta, since at the station Turbinen there is an observed daily rainfall of 97 mm.

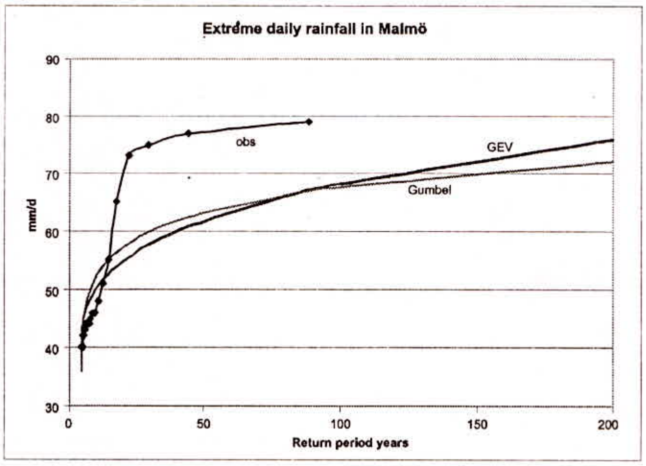

Fig. 2: Observed extreme events in Malmö and probability functions determined from L-moments

The daily rainfalls for the period 1919 to 2007 from Halmstad and Göteborg have been analyzed in the same way as those for Malmö. The results are similar, although the extreme daily rains are lower in Göteborg than in Malmö and Halmstad, as is shown in Figure 3. The conclusions are the same: observed extreme rains can not be fitted to an extreme value distribution; daily rains of 100 mm have a very long return period. The annual precipitation is about 800 mm in Göteborg and in Halmstad, while it is only 640 mm in Malmö. However, the highest observed rainfall is about 80 mm in Malmö and Halmstad, but less than 70 mm in Göteborg. The fourth highest observed value corresponding to a return period of 25 years is 65 mm in Malmö, 60 mm in Halmstad and a little more than 50 mm in Göteborg. Thus, there does not seem to be any relation between extreme daily precipitation and annual precipitation.

The same statistical analysis as for the three cities was performed also for the stations in the Ellesson precipitation net. The results are similar as for the three cities, although the analysis is based only on 30 years of data and therefore only on few values exceeding 40 mm. Therefore the corresponding analysis was done using data from the whole Ellesson net trying to determine the probability that very high rain intensity should occur at any of the stations. Only independent rainfalls were included, which means that only one value from a specific day was included. When the threshold value was put to 70 mm/day, 30 intense rainfalls could be included, which is exactly the number of observation years for the Ellesson data. The observed intensity frequency relation fits the GEV-distribution very well. The 100 year daily rainfall for occurrence at one place in Skåne is 135 mm.

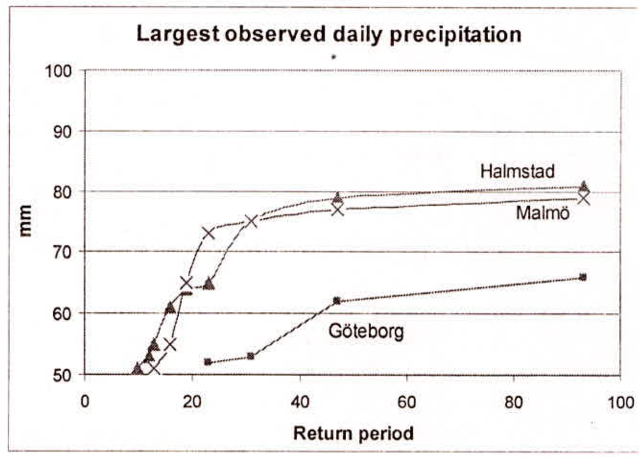

Fig. 3: Observed daily precipitation 1919–2007 in Malmö, Halmstad and Göteborg

When all observed daily rainfalls are included in the frequency analysis assuming daily rains at different stations to be independent, the number of station years and thus the return period increases very much, since the number of observation years is the number of stations times the observation period. The fit between observations and the GEV-distribution is very good. The return period of 100 mm daily rain at a specific station is more than 300 years. The 5000 year storm is 115 mm/day. The 100 year storm is about 80 mm per day. The actual return periods can be found only when there is a known correlation between extreme events between different stations. The 100 year storm for a station within the Ellesson net covering the Skåne peninsula should thus be in between 80 and 135 mm/day.

Short-Term Rainfall

Intensity-duration-frequency (idf) curves were derived for some Swedish cities more than 50 years ago, Svenskt Vatten (2004). Storm water systems are usually designed for 2 or 5 year return period. Thus, the most extreme events are not considered. When comparing idf-curves for different cities and for different periods, it is found that the curves are very similar indicating that the character of the short-term storms are of the same character over southern Sweden and that the character has no changed over time. A thorough investigation is done below. Observations with one minute resolution for the six southern Swedish cities Malmö, Helsingborg, Halmstad, Göteborg, Uddevalla and Växsjö were analyzed and idf-curves were derived. The station used for Malmö is the station with the longest short-term record, Turbinen. The highest observed intensities and the annual maximum for the six cities are compared in Table 1. The values are similar for the six cities except for the most extreme hourly rainfall in Malmö. The assumption that the mean rainfall depths of different durations are the same for the six cities was tested by comparing the monthly maximum rains of 30 minutes duration in Malmö and Växsjö for the months of May, June, July and August over 20 years (thus, 80 values), and between Malmö and Helsingborg for 12 years. There is no significant difference at any level. It was then assumed that rainfalls of shorter duration from all the cities belonged to the same probability distribution.

Table 1: Highest Observed Rainfall Depth and Storm of One-year Return Period

Duration Min	*10*	*20*	*30*	*60*	*Observation Period*
Malmö max	15.0	18.5	25	38	28
Helsngb max	12.0	17.5	22	31	12
Halmst max	14.6	18.8	23	26	12
Göteb max	18.7	24.1	29	31	32
Uddev max	14.4	22.0	24	31	12
Växsjö max	15.8	23.6	25	26	20
Malmö 1-y	6.8	8.8	10.6	14	
Helsngb 1-y	6.8	9.4	10.2	14	
Halmst 1-y	7.6	9.8	10.4	13	
Göteb 1-y	6.7			13	
Uddev 1-y	7.2	9.3	10.5	13	
Växsjö 1-y	6.5	9.0	10.8	13	

The cities Malmö and Helsingborg are closely situated, 50 km from each other, and both are at the sea. When comparing rainfall records it is found that it is rare that even such modest rainfall as 20 mm/day occurs the same day at both cities. High hourly rain volumes in the two cities within the same day are very rare indicating that probably all events at least those shorter than an hour are independent between the cities.

All independent rainfalls of duration 10 minutes to 1 hour from the six cites are combined into the same probability distribution. The events are considered independent if they occur at the same stations and there is a dry period of at least 4 hours in between the events, or if the events occur in different cities. There is at least 50 km between each station. The number of station years is 108. The observation data fit well to the theoretical intensity-duration function,

$$i = a\, t_d^{-0.56} \quad \ldots (1)$$

$$a = a_1\, T^{0.15} \quad \ldots (2)$$

where i is rain intensity, t_d is duration and T return period, with the coefficient a_1 for the 1 year storm being 3.0. The theoretical graph for 10 year return period is in Figure 4 compared with the observed data corresponding to 10 year return period. The Gumbel distribution was fitted to the observed data. The fit is rather good for all durations, as shown in Figure 4.

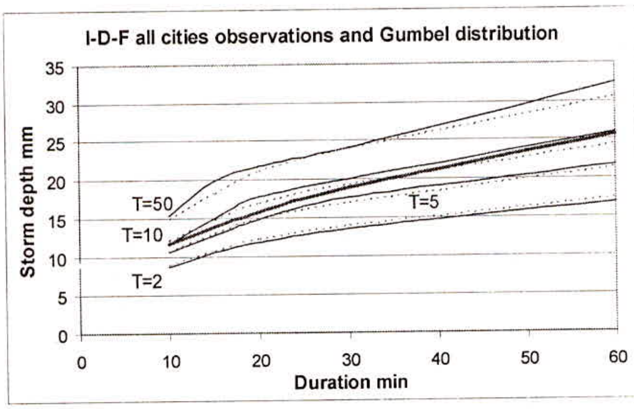

Fig. 4: Intensity-duration-frequency relation for six cities in southern Sweden. Dashed lines are the Gumbel distribution and solid lines observations for return periods 2, 5, 10 and 50 years. T = 50 years corresponds to the second highest value observed. Th thick line in the 10 year curve given by Eqns. (1–2)

Spatial Distribution of Extreme Rainfalls at Local Scale

In the city of Malmö there are 5 rainfall stations with continuous measurement with high time resolution since 1996 and another station with more sparse data. When data from all stations are used so the number of station years is 5 times 12 years there is a good fit to both the two extreme value functions, but not when considering the individual stations (only 12 years of data). Then there are extreme events that can not be

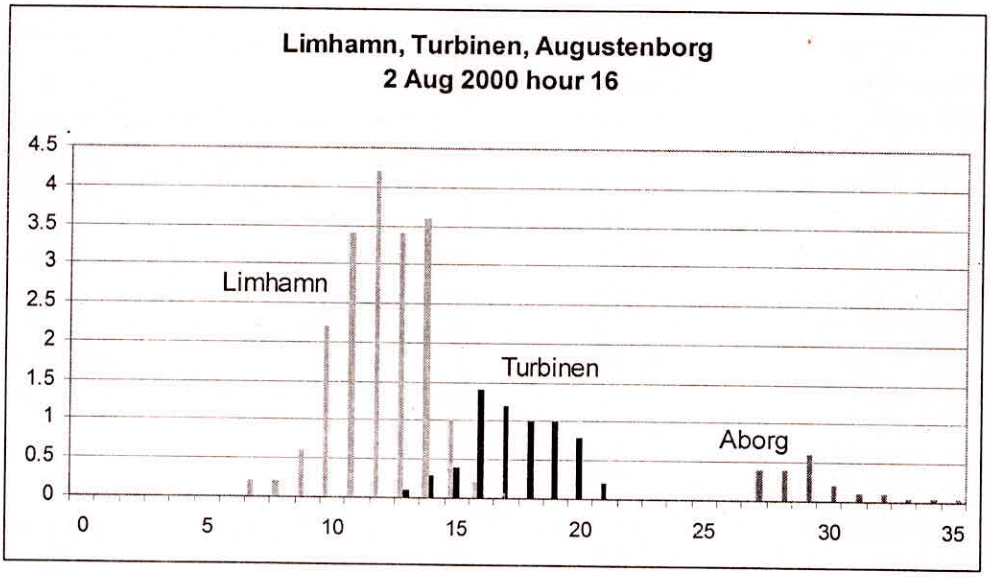

Fig. 5: Observed rainfall intensity (mm/min) at different stations in Malmö

fitted into the probability distributions. One such event is illustrated in Figure 5. At six stations in Malmö rain was during the whole day recorded to occur at only three stations and only for 5 minutes. At Limhamn this was by far the largest 5 minutes rainfall, 17 mm, ever recorded in Malmö. Since rain fell also only during 5 minutes but some minutes later and less intensity at the station Turbinen 500 m away, the record must be true although the daily storm depth is the same as the 5 minutes storm depth.

Trends of Daily Rainfall

In many regions including southern Sweden the annual precipitation has increased slightly over the last 100 years. Climate models show a further increase. Climate models also show increased rain intensities Räisanan and Joelsson (2001), Jones and Reid (2001). Based on down-scaling from global circulation models Skaugen *et al.* (2003) have computed that extreme daily precipitation should increase by 10–50% in large parts of Norway.

It is, however, hard to find trends in observed precipitation series. Häggström (2001) has analyzed high daily point precipitation in Sweden over the last 80 years. The return period for daily storms of 40 mm is 3–5 years. The fraction of stations having daily storms exceeding 40 mm was about 30% in the 1930's and early 1940's, but only 20% in the late 50's and in the 60's and 70's. During the 80's and 90's it has been 25% as it also was in the1920's.

For the United Kingdom, Osborne and Humble (2002) have found that high daily rainfalls during winter has increased, but that summer storms have become less intensive since 1960. The summer rains are still more intensive than the winter rains. Since there were many intense storms in the 1960's it is not possible to conclude that there is a trend toward lower intensities. Also Fowler and Kilsby (2003) have analyzed precipitation data for the UK. They did not find any change of the return period for high daily rainfall. However, they found an increase of the 5 and 10 day precipitation in southern England and a corresponding decrease in Scotland.

Gellens (2000) did not find any trend of the daily precipitation in Belgium since 1910. There are studies from Italy, where 200 year data series have been used, Brunetti *et al.* (2000) and Cislaghi *et al.* (2005). There is a trend towards less number of rainy days and longer dry periods. The mean precipitation of a rainy day, not the extreme, has increased. Only for the city of Genoa there is an increase of the extreme precipitation. Schmidli and Frei (2005) have used 100 years of observations from 104 stations Switzerland. They found an increase of intensive winter storms but no trend of the high summer storms. Hundecha and Bardossy (2005) came to the same conclusion for Germany; they even found that the summer storms had decreased in intensity.

Trends of daily precipitation have been investigated for North America. Although the annual precipitation has increased over almost the entire Canada, there is no trend of changed daily precipitation, except that the number of days with high precipitation has increased in the very north of the country, Kunkel (2003). A study by Akinremi and McGinn (1999) showed that the number of days with precipitation exceeding 25 mm has decreased on the Canadian prairie. Kunkel finds an increased daily intensity for the US compared to 1920/30, which also was shown by Karl and Knight (1998), but not if the investigation is extended to 1880.

In conclusion it may be stated that no trends toward changed high daily precipitation can be found in observations series in Europe or North America. However, the very extreme rains can not easily be statistically analyzed.

The daily rain series from Malmö, Halmstad Göteborg from 1919 including 2007 have been used to try to find trends of the extreme events. In Figure 6 the annual daily maximum precipitation in Malmö has been plotted. There is no trend. The regression curve is slowly decreasing, but is not significant. The four highest values (more than 20 mm higher than the fifth highest value) are from 1930 (73 mm), 1931 (75 mm), 1941 (79 mm) and 2007 (77 mm). Also for Halmstad and Göteborg the regression is mildly negative. There in an increase since 1985 of daily extremes in Halmstad since 1985, but not over a longer period.

Instead of considering the very largest events, the return period for less extreme events can be investigated. The number of events in Malmö exceeding 40 mm/day during different decades was determined. The frequency (no of events per year) was 0.4 in the 20's, dropped to 0.2 in the period 1930–60, was more than 0.3 in 1960–90 and has again dropped to 0.20. At a first glance there is a weak trend towards higher frequency but it is not significant.

Trends of Very Short-term Rainfall

Since storm water systems have had to be designed based on expected rainfall, there are old design storms based on old measurements. When comparing old idf-curves from 1940 with the ones derived on the new observations, the curves are found to be very similar indicating that the character of the storms has not changed much. For most stations the records are too short to allow trend analysis. The longest record is from Göteborg and extends over 34 years. The number of storm events exceeding 5 mm/10 minutes is shown in Figure 7. There is no significant trend; nor is there any trend for the storms of duration 20 to 60 minutes.

Also from Turbinen in Malmö there is a long series, almost 30 years. The observations prior to 1995 when a tipping bucket of volume 0.5 mm was used are significantly different, lower, from the observation after 1995 when a bucket of 0.2 mm. Up to 1995 the annual maximum short-term precipitation is constant, and also after 1995 but at a higher level. It is always difficult to analyze very short-term storms.

CONCLUSIONS

The return period of daily rain exceeding 40 mm is 2–5 years at different stations in southern Sweden. The probability of daily rains exceeding 70–80 mm is the same at all places in the region independent of the general precipitation climate. Daily storms exceeding 100 mm are very rare with return period exceeding 100 years. For individual stations the most extreme

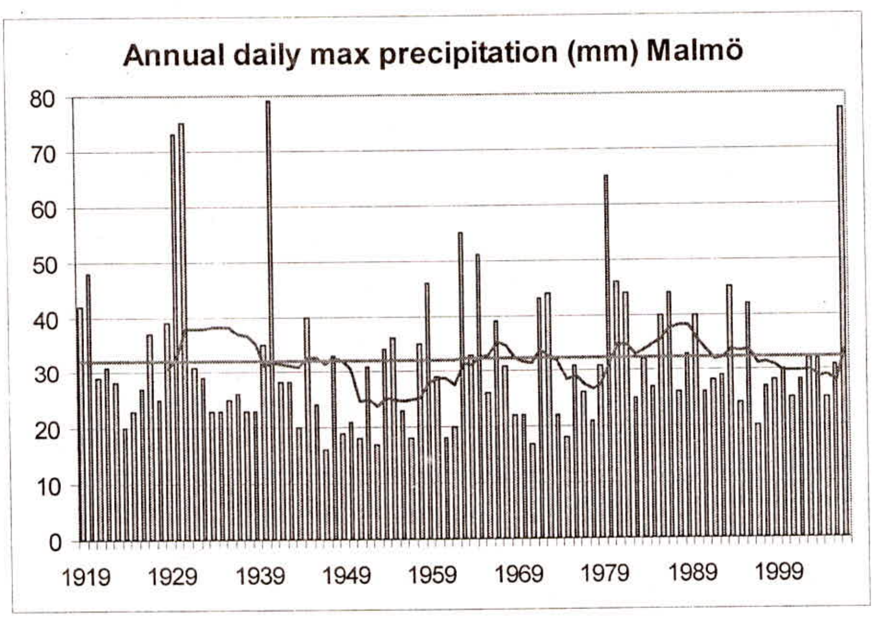

Fig. 6: Annual maximum daily precipitation in Malmö, 10 years running mean and trend line for the period 1919–2007

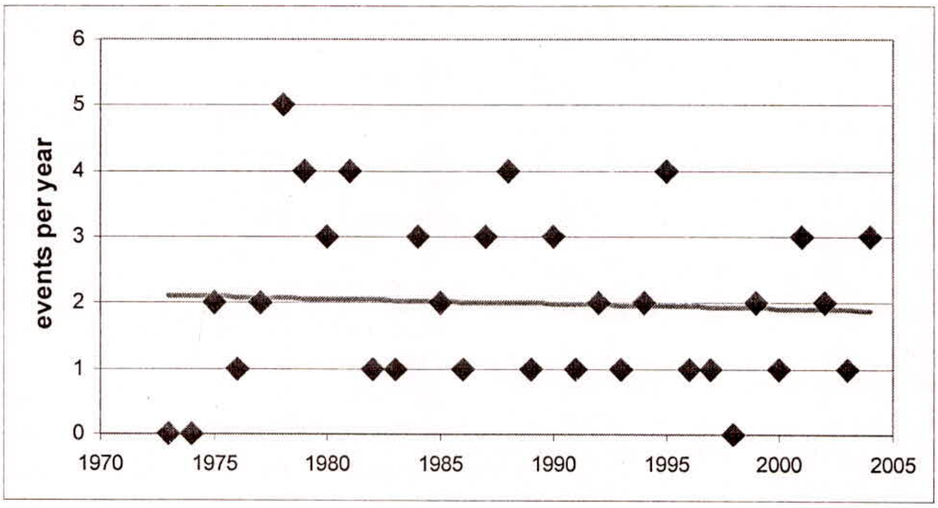

Fig. 7: Number of storm events in Göteborg exceeding 5 mm/10 min and trend line

rains can not be fitted to any theoretical probability distribution. However, since the most intensive storms have the same character at different places, the observations from many stations can be combined and the series prolonged to include many station years. These very long series can be fitted to GEV-distribution. Also short-term precipitation of duration less than an hour from different cities can be combined. From these a theoretical intensity-duration-frequency valid for all cities in southern Sweden can be derived. When long time series are investigated there is no trend of increased or decreased rain intensity.

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