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WATCH

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Call 2015

WATer management for road authorities in the face of climate CHange

Climate and climate change: protocol for use and generation of statistics on rainfall extremes

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[1] In climate science one generally speaks of precipitation. This includes also snow and hail, whereas rainfall only refers to liquid precipitation. In this chapter we will use the term rainfall, since that type of precipitation is most relevant for WATCH.

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Executive summary

As part of the WATCH project a protocol for the use and generation of extreme rainfall data for the current and future climate was generated. This report includes an overview of available data on extreme rainfall, some background on extreme rainfall statistics and how one can deal with uncertainties about the future climate. In the chapter 4 and 5 the protocols for the current and future climate, respectively, are described. In chapter 6 the climate analogues tool is described. With this tool one can find locations in Europe, where currently already certain rainfall extremes occur, that one might expect in his/her region in the future.

Climate is the average weather in a given area over a longer period of time. A description of a climate includes information on e.g. the average temperature in different seasons, rainfall, and sunshine. Also a description of the (probability of) extremes is often included. Available information on the current climate and climate change is described in the tables in Chapters 1 and 2.

The most used probability distributions for generating extreme rainfall statistics are Generalized Pareto Distribution (GPD) and Generalized Extreme Value (GEV). They may give more or less the same statistics. For high return times (> about 100 years) these distributions may underestimate the extreme rainfall amounts. In many regions increases in extreme rainfall amounts are observed (or the frequency increases). In most countries included in this study, the available rainfall statistics are not corrected for these trends. This may result in underestimation of extreme rainfall amounts for the “current” climate.

The temporal resolution of the basic data used for deriving the extreme rainfall statistics determines the rainfall amounts that will be obtained for the various return levels. Most extreme rainfall statistics found for the countries in this study are based on station data (point statistics). These give the probability to exceed a certain amount of rainfall for a certain point.

In regions with hardly any regional differences in rainfall extremes Areal Reduction Factors can be derived from high spatial and temporal resolution data to transform point statistics into area statistics. However, in most countries there are clear regional differences in rainfall statistics. In these cases the areal statistics have to be derived separately for each location. Only for a few countries included in this study, areal statistics on extreme rainfall for the current climate could be found.

Research on observations of rainfall extremes shows that in several countries the rainfall extremes on hourly basis increase stronger with temperature increase than the rainfall extremes on daily basis. For higher temperatures increases of up to 14% per ˚C for hourly extremes are observed. The turning point is approximately at a daily average temperature of 10-14 ˚C or an average dew point temperature of 6-10 ˚C. Increases in rainfall extremes can be better explained when using dew point temperature than when using temperature, since dew point temperature directly measures moisture instead of the maximum water holding capacity (as with temperature).

Most currently available climate models have too coarse spatial resolutions and are unable to represent local convective processes dynamically. Especially at higher temperatures they may underestimate the short duration rainfall extremes. Due to the limited number of climate studies undertaken at convection-permitting scales, it is still not possible to draw broader conclusions from these models on how sub daily rainfall will change under future climate change. But, there is reasonably support that changes in sub-daily extremes could be as large as 14 % per degree temperature increase.

Information on changes in the future for the short duration rainfall extremes is often missing in countries. Therefore, scaling with available data such as temperature can be used. Based on the above information it seems most appropriate to use a scaling method whereby changes in rainfall extremes are set proportional to the change in dew point temperature.

When deciding how to take uncertainty about climate change into account, keep the following aspects in mind:
- What is the life cycle of the asset one is working on? Determine the time horizon to take into account.
- Does one wants to be prepared for the worst case or a more average situation? Determine which projection or range of projections for the future to take into account.

The protocol for extreme rainfall information for the current climate consists of the following steps (Figure 4.1):
1. Determine which information is needed (point/area statistics, reference period, return times, rainfall durations, format)
2. Look what information is available on extreme rainfall (point/area statistics, reference period, return times, rainfall durations, format; look also at Table 2.1)
3. If what is needed and what is available matches, one can start using the data. If not, one has to adjust the data or generate new extreme rainfall statistics
4. If relevant, derived variables, such as run-off can be generated

The first steps may look redundant, but it is often not clear what climate the available data is representative for and for which “current” climate data is needed.

The protocol for extreme rainfall information for the future climate consists of the following steps (Figure 5.1):
1. What rainfall information needed for the future?
2. What rainfall information is already available for the future? (Tables 2.1 and 2.3)
3. Determine relation between daily and sub daily extreme rainfall and (dew point) temperature based on observations
4. Select relevant climate scenario(s) for the future
5. If not available, determine change of daily and sub daily rainfall extremes in relation to dew point temperature with climate model data for the relevant climate scenario(s) and time horizon
6. Determine the change in dew point temperature between the period used for the period of interest for the climate scenario(s) of interest
7. Synthesis of information on change in extreme rainfall statistics for the future climate
8. If relevant, calculate derived variables such as run-off for the future

The WATCH PROJECT

Many challenges exist in addressing intense rainfall events into proper design and maintenance of water management systems. These challenges exist both in the field of climate science itself, as well as in the translation of climate projections into proper design and maintenance of water management systems. The WATCH project addresses the most important high frequency causes of road flooding, caused by rainfall and run-off flooding in the area around the road, and heavy rain on the road itself. Objectives of the project are:

- Developing a manual to determine current and future resilience of the NRAs approach to water management, ensuring optimal maintenance planning and asset management.
- Providing easy access to climate data tailored to determining resilience and providing guidance on how to use these data, plus developing a simple tool to show climate analogues for rainfall extremes.
- Gaining insight in the application of SuDS (Sustainable Drainage Systems) for storage and cleaning of excess water.
- Gaining insight in the alternatives to the costly retrofitting of existing drainage systems.
- Enabling informed decision making on water management, supported by cost-benefit analysis.

1 Introduction to climate and climate change

Weather extremes affect the road infrastructure and its functioning. The weather is variable from day to day, year to year and from decade to decade. To deal with these extremes knowledge about the occurrence of extremes in the current climate is needed. The climate has changed already and it will change further in the future, but it is not known exactly how. To deal with this uncertainty various climate scenarios are used. This paragraph gives a short introduction to climate and climate change. This information is based largely on the ROADAPT guideline on the use of climate data (Bessembinder, 2015), however where possible information is updated and it focusses on rainfall extremes.

1.1 What is climate and climate change?

Climate is the average weather in a given area over a longer period of time. A description of a climate includes information on e.g. the average temperature in different seasons, rainfall, and sunshine. Also a description of the (probability of) extremes is often included. Climate change is any systematic and significant change in the long-term statistics (Figure 1.1) of climate variables such as temperature, rainfall, air pressure, or wind sustained over several decades or longer. Climate change can be due to natural forcings (changes in solar emission or changes in the earth's orbit, natural internal processes of the climate system) or it can be human induced.

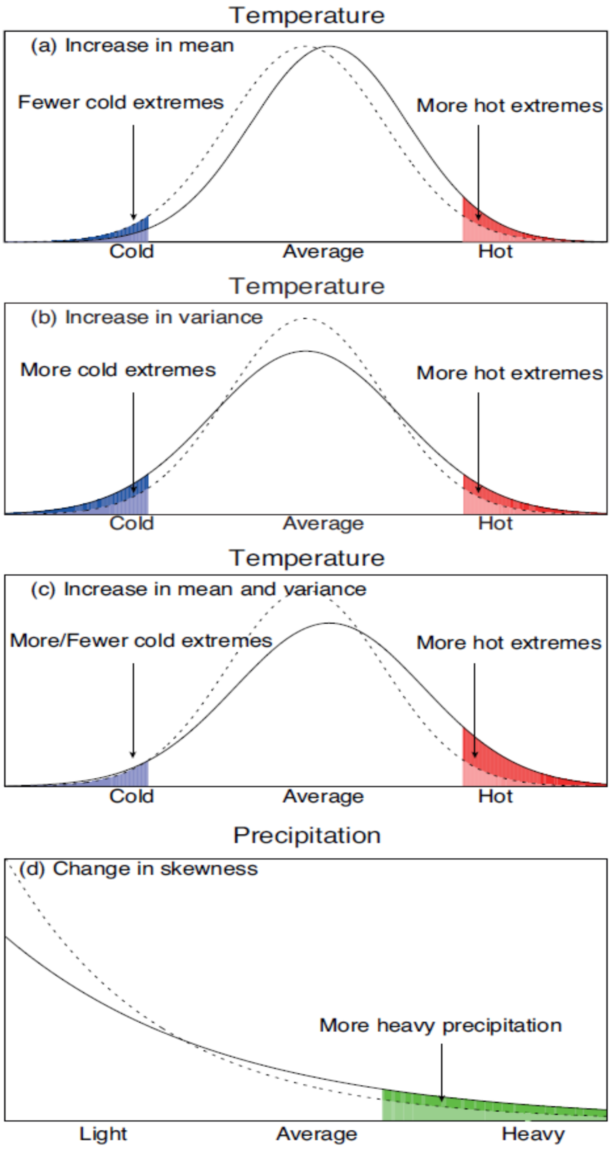

Figure 1.1 Schematic presentation of climate change (dashed line=current climate, solid line=future climate): the mean can change (a); the probability of extremes can change (b) or a combination of these changes can occur (c). Panel d shows an example for rainfall where the number of days with light rainfall decreases and the number of days with heavy rainfall increases (Source: IPCC, 2013).

1.2 How to describe a climate?

The classical period used for describing a climate is 30 years, as defined by the World Meteorological Organization (WMO). An overview of the periods that are used to describe the current climate in several European countries is given in Table 1.1. Only the larger scale spatial differences (spatial resolution > 10 km) are included generally in the climatologies.

Meteorological institutes are obliged by the WMO to make a new description of the climate of their country (and regions within the country) every 30 years. Currently the period 1961-1990 is used in several countries to describe the current climate, although many countries in Europe also make a new description every 10 years (after 1961-1990, the periods 1971-2000 and 1981-2010 were used).

Extremes of a climate are described with the help of statistics, or observed minimum and maximum values are reported. Even without climate change due to increased greenhouse gasses the climate would not be completely the same for each period of 30 years, due to internal variability and natural external forcings. To adequately describe the extremes that are rarer than e.g. once in 10 years ideally a period of more than 30 years is used.

Table 1.1 Some examples of descriptions of the current climate from European countries. Also indicated is which periods are used to describe the current climate (‘normals’; last update May 16, 2018).

Country	Web site	Current climate described with [A]
Austria	www.zamg.ac.at/cms/de/klima/klimauebersichten/klimamittel-1971-2000	1981-2010
Belgium	www.meteo.be/meteo/view/fr/16788784-Atlas+Climatique.html#navigate=1	1981-2010
Denmark	www.dmi.dk/vejr/arkiver/normaler-og-ekstremer/klimanormaler-dk/ www.dmi.dk/en/klima/climate-changes-over-time/denmark/	1961-1990
France	www.meteofrance.fr/climat-passe-et-futur/climat-en-france/le-climat-en-metropole#	1981-2010
Finland	en.ilmatieteenlaitos.fi/normal-period-1981-2010 ilmasto-opas.fi/en/ilmastonmuutos/suomen-muuttuva-ilmasto/-/artikkeli/1c8d317b-5e65-4146-acda-f7171a0304e1/nykyinen-ilmasto-30-vuoden-keskiarvot.html	1981-2010
Germany	www.dwd.de/DE/leistungen/klimadatendeutschland/langj_mittelwerte.html https://www.dwd.de/DE/leistungen/kvo/baden_wuerttemberg.html?nn=16102 [B] https://www.dwd.de/DE/klimaumwelt/klimaatlas/klimaatlas_node.html	1981-2010 1961-1990
Ireland	https://www.met.ie/climate/past-weather-statements [B]	1981-2010
Italy	www.isprambiente.gov.it/en/publications/state-of-the-environment/temperature-and-precipitation-climatic-normals-over-italy	1981-2010
Netherlands	www.klimaatatlas.nl/	1981-2010
Norway	www.senorge.no/index.html?p=klima	1971-2000
Portugal	www.ipma.pt/resources.www/docs_pontuais/ocorrencias/2011/atlas_clima_iberico.pdf https://www.ipma.pt/pt/oclima/normais.clima/	1971-2000 1981-2010 (provisional)
Spain	www.aemet.es/es/serviciosclimaticos/datosclimatologicos/valoresclimatologicos	1981-20100
Sweden	www.smhi.se/klimatdata www.smhi.se/klimatdata/meteorologi/nederbord/1.1628	1961-1990
Switzerland	www.meteoswiss.admin.ch/home/climate/the-climate-of-switzerland/climate-normals.html	1981-2010
United Kingdom	www.metoffice.gov.uk/public/weather/climate/gcpvn15h9	1981-2010

[A] Many countries also present the ‘normals’ for 1961-1990 and/or 1971-2000.
[B] In the graphs on this page the ‘normals’ for 1981-2010 are presented.

1.3 What are the observed and projected climate changes for Europe?

By definition, extremes relevant for road design and maintenance are rare and, therefore, it is also more difficult to detect significant changes in extremes. However, for maximum rainfall intensity in heavy showers (mm/day; Figure 2.2) and extreme rainfall events (long periods, mm/5 days; Figure 2.3) it is likely over most mid-latitude land that these have increased in the past.

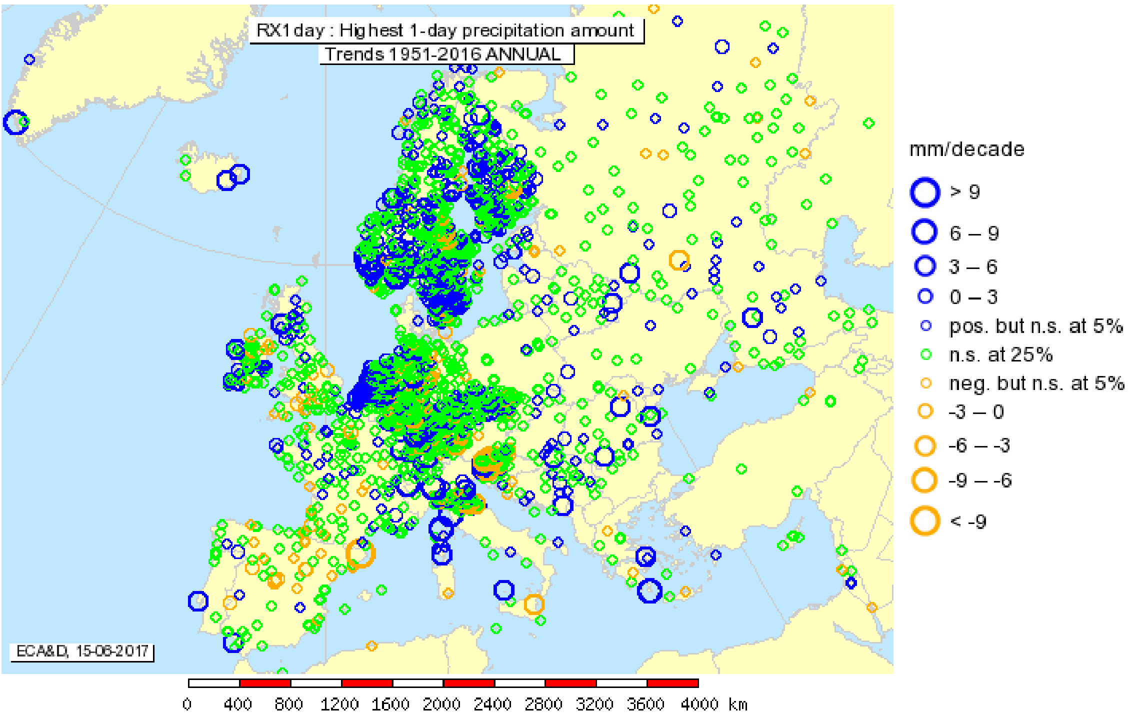

Figure 1.2 Trend in highest daily rainfall amount per year over the period 1951-2016 from the ECA&D website (generated June 2017).

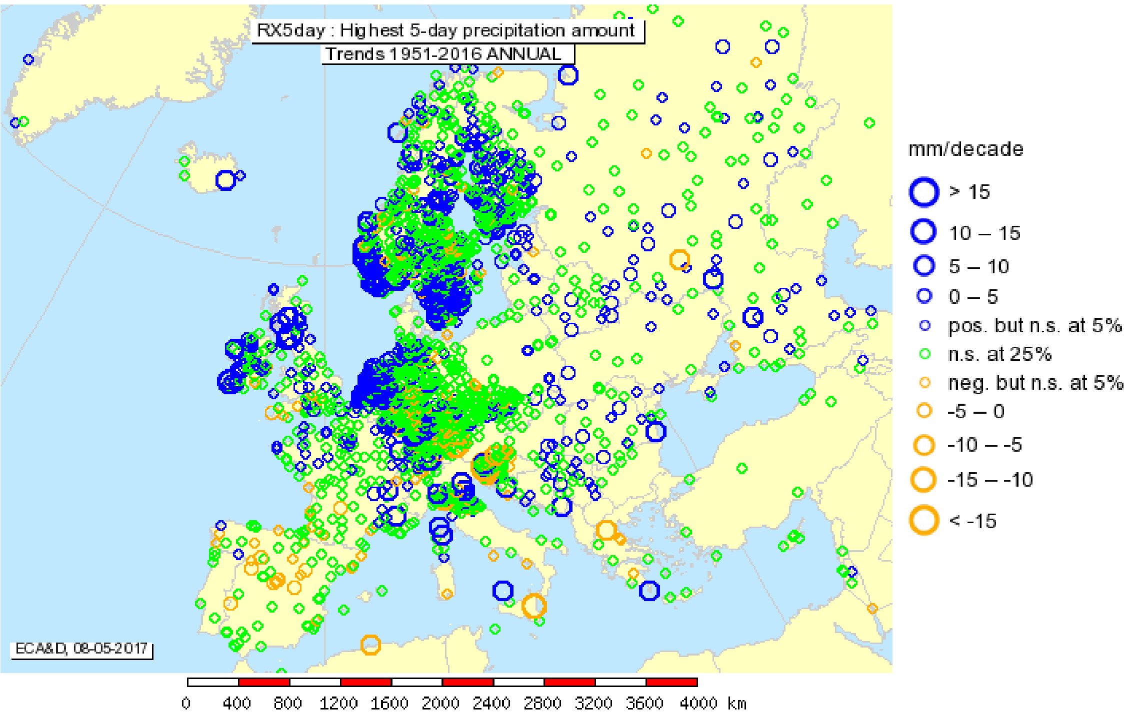

Figure 1.3 Trend in highest 5-day rainfall amount per year over the period 1951-2016 from the ECA&D website (generated May 2017).

Projections for the future are made with the help of climate models (and sometimes for the coming 10-20 years by extrapolating trends). For the IPCC reports Global Climate Models (or General Circulation Models; GCM's) are used. These climate models use greenhouse gas concentration scenarios as input. In many countries in Europe the IPCC climate change information is translated into more detailed *regional climate change scenarios* with the help of Regional Climate models (RCMs) since the IPCC information is often not detailed enough to estimate the effects of climate change in a particular region.

Although most countries are using the same basic information (GCM and RCM projections) from large European projects, they all have their own methods to construct climate scenarios. Table 1.2 gives an overview where information on the regional climate scenarios of various European countries can be found.

Table 1.2 Regional climate scenarios/projections in various European countries: links to the websites (source: among others Dalelane, 2014; links updated May 16, 2018).

Country	Website with regional climate scenarios[A]
Austria	https://www.bmlfuw.gv.at/umwelt/klimaschutz/klimapolitik_national/anpassungsstrategie/klimaszenarien.html (2015)
Belgium	www.kuleuven.be/hydr/cci/CCI-HYDR_rp.htm (2015)
Denmark	http://www.dmi.dk/fileadmin/user_upload/Rapporter/DKC/2014/Klimaforandringer_dmi.pdf (2014) http://www.dmi.dk/klima/fremtidens-klima/danmark/ekstrem-vejr/ (2014) www.dmi.dk/klima/fremtidens-klima/klimascenarier/nye-scenarier-fra-ipcc/
France	www.drias-climat.fr/decouverte www.meteofrance.fr/climat-passe-et-futur/le-climat-futur-en-france (2014)
Finland	ilmasto-opas.fi/en/ilmastonmuutos/suomen-muuttuva-ilmasto/-/artikkeli/74b167fc-384b-44ae-84aa-c585ec218b41/ennustettu-ilmastonmuutos-suomessa.html (2016) www.geophysica.fi/pdf/geophysica_2016_51_1-2_017_ruosteenoja.pdf
Germany[B]	DWD Klimaatlas: www.dwd.de/DE/klimaumwelt/klimaatlas/klimaatlas_node.html (2011) KLIWAS: www.kliwas.de/ (2015) GERICS: www.climate-service-center.de/products_and_publications/maps_visualisation/csm_regional/index.php.en (2015)
Ireland	www.epa.ie/pubs/reports/research/climate/Research_Report_244.pdf (2018) http://erc.epa.ie/safer/iso19115/displayISO19115.jsp?isoID=3050 (2018)
Netherlands	www.climatescenarios.nl/ (2014)
Norway	https://klimaservicesenter.no/faces/desktop/scenarios.xhtml https://www.klimaservicesenteret.no/faces/desktop/article.xhtml?uri=klimaservicesenteret/klima-i-norge-2100 (2015) http://www.miljodirektoratet.no/no/Publikasjoner/2017/Mai-2017/Climate-in-Norway-2100--a-knowledge-base-for-climate-adaptation/(English version, 2017)
Portugal	http://portaldoclima.pt/pt/ (2015?) www.ipma.pt/pt/oclima/servicos.clima/index.jsp?page=cenarios21.clima.xml siam.fc.ul.pt/
Spain	www.aemet.es/es/serviciosclimaticos/cambio_climat (2014?)
Sweden	https://www.smhi.se/en/climate/climate-scenarios (2014)
Switzerland	www.ch2011.ch/ (2011) (new scenarios to be released in 2018: CH2018)
United Kingdom	UKCP09: ukclimateprojections.defra.gov.uk/ (2011) (new scenarios to be released in 2018: UKCP18)

[A] Links to most recent scenarios for the various countries are shown (year indicated). Each country and organization uses its own methods to construct regional climate scenarios. Therefore, they cannot be easily combined or compared.
[B] More than one provider of climate scenarios or projections of climate change for this country.

2 Climate data and extreme rainfall statistics currently available and used

Ideally, in each country the same type of extreme rainfall statistics for the current and future climate would be available, based on the same or similar methods[2] and the same basic periods. However, the available information can differ largely from one country to another. In this paragraph first an overview is given of the available data (with links to the information) and the differences, and background information on the rainfall statistics and research on rainfall extremes.

2.1 Available data on current and future rainfall extremes

In this paragraph an overview of data on current and future rainfall extremes is given. The links and information in the WATCH Country Comparison Report are used as the basis (Bles et al., 2017) and additional information is collected on the available statistics[3] and available information on changes in extreme rainfall in the future.

The tables below give information as far as could be found through the links in the WATCH Country comparison report and by looking for information on "climate scenarios", "extreme rainfall (statistics)" and "climate normals" (in English and local languages). Table 2.1 presents the information on rainfall extremes for the current climate (the current period may be defined differently in each country). Table 2.2 gives links to climate data (mostly time series, observed or simulated), that could be useful for generating extreme rainfall statistics or for further research on the impact of rainfall extremes. In Table 2.3 an overview is given of which information on (short) duration rainfall extremes is presented in the climate scenarios for each country. Intensity duration frequency (IDF) curves or rainfall depth duration frequency (DDF) curves describe rainfall intensity or rainfall depth as a function of duration for given return periods. For rainfall statistics often first the relation between return periods and rainfall intensity or depth is determined for specific rainfall durations. The IDF/DDF curves are cross sections of these relations.

From the tables below and the efforts to collect the information, the following conclusions can be drawn:

- Different reference periods with historical data are used in the various countries, and it is often difficult to find which historical period was used as the basis for the rainfall statistics and IDF curves. With a changing climate it becomes more important to be clear about the basic or reference period.
- For the generation of rainfall statistics often long time series of rainfall are needed. These time series may contain trends[4]. In most statistics it is assumed that the past climate is static. In the Netherlands the statistics were corrected for the observed trend

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[2] However, different climatological regions often have their specific limitations and consequently also different methods may be most appropriate (e.g. in some regions certain parameters in a probability distribution can be considered constant, in other regions not).

[3] IDF-curves are used as a form of extreme rainfall statistics. Intensity duration frequency (IDF) curves or rainfall depth duration frequency (DDF) curves describe rainfall intensity or depth as a function of duration for given return periods. For rainfall statistics often first the relation between return periods and rainfall intensity or rainfall depth is determined for specific rainfall durations. The IDF/DDF curves are cross sections of these relations.

[4] Assume that one is using data from 1960-2010 for generating rainfall statistics and that this time series shows a linear increase in extremes. Than the rainfall statistics represent more or less the climate around 1985. Using these statistics may lead to underestimation of the rainfall extremes in the current climate (beginning this century).

in rainfall extremes. In Sweden and also in the Netherlands for the short rainfall durations (up to a few hours) only a relatively short and recent period is used where no trend can be detected. To get enough data for the statistics, data from a large number of stations is “pooled together”. This can only be done in regions with no clear regional differences in rainfall extremes. In some countries it is indicated that extremes increase, but that it was still assumed that there were no changes over the period used (methods for correcting for the trend only have been developed recently). E.g. this is done for Ireland, and it is indicated that therefore the statistics/IDF-curves may underestimate the rainfall extremes.

- Different methods/techniques to generate extreme rainfall statistics/IDF-curves are used. In principal the various methods can give the same IDF-curves, but they may also result in slightly different ones. For the very extreme return times (> 100 or 200 years) the method used may result in large differences (see par. 2.2)
- For most countries only point statistics[5] were found (including regional differences), whereas area statistics are needed for e.g. run-off estimation. Area statistics also often have to be determined for each location separately due to the regional differences in rainfall extremes and the orography: no general areal reduction factors (ARFs) can be used. The generation of area statistics also requires information on a very high spatial resolution, which is often not available.
- There is a large difference between countries in the availability of data on rainfall: observational data sets aren’t available freely in all countries, data sets on short durations (less than 1 hour) are rare, statistical information on rainfall extremes is available freely in some countries and in others a fee has to be paid, in some countries gridded products[6] are made from the stations data in others not. In some countries rainfall radar data at high resolution is available and/or high resolution (temporal and spatial) climate modelling results are available.
- When countries take into account climate change, they may use different methods. In most cases a percentage is added to take into account climate change. Regularly, it is not mentioned explicitly whether this percentage has to be added to the rainfall amounts for certain return times or whether this percentage is used for the derived impact (e.g. run-off), and often it is not possible to find how this percentage was determined and for what time horizon this should be used. It would be very useful to make this more explicit, since that makes the users aware of how up-to-date the percentages are. It would also make clear when these percentages should be adjusted or up-dated (when a different life cycle for the assets is used or when new scientific information or climate scenarios become available).
- Range of return times used (Table 2.4): differs considerably between countries (the return times used also differ between the various assets). In the Netherlands, Sweden and Norway the longest return times are used.
- Range of rainfall durations used: Also large differences between countries are observed here. In many countries a range of rainfall durations is used (dynamic calculations). However, the shortest and longest durations used may differ. The shortest durations mentioned are 2 min (Ireland and United Kingdom) and Austria mentions 15 min as the minimum duration.
- Hardly any of the climate change scenarios contain information on changes in short duration (less than one day) rainfall extremes. It is known from research that daily extremes and hourly rainfall extremes may change differently with temperature

[5] Point statistics describe the probability of extreme rainfall on one location or a small area (up to e.g. 5 km^2). Area statistics describe the probability of a certain average amount in larger areas (e.g. 100 km^2, 1000 km^2, etc.; see also par. 2.2). See also “Interpretation of point statistics” in par. 2.2.

[6] Gridded data: in the case of gridded data a region is divided in squares/rectangles (grid) with similar size and e.g. for each grid the (average) temperature is given. Station data can often be interpolated to get “gridded” data.

increase (see par. 2.3). However, climate models have difficulty simulating the small scale extreme rainfall events (short duration) that often happen in summer. Due to the limited availability of e.g. hourly rainfall data it is also more difficult to check the quality of the simulated short duration extremes. Where information on short duration rainfall extremes is given in climate scenarios it is (partly) based on observations.

Table 2.1 Overview of available **information on extreme rainfall statistics in the "current" climate**, for the countries in the WATCH country comparison report (Bles et al., 2017): for general use (also for road design) (latest check: March 2018).

Country	Reference period/ year*	Point/ area statistics	Rainfall durations	Return periods	Comments
Austria	? Before 2005, varying length: 1->50 years	Point Method described how area statistics can be obtained	For points: 5 min. to 6 days	1 to 100 years	• Link: ehyd.gv.at/ • Method: ehyd.gv.at/assets/ehyd/pdf/bemessungsniederschlag.pdf Based on modelled data and measured data; app.hydrographie.steiermark.at/berichte/seminargutachtennlv.pdf • Freely available, daily time series and statistics (look for "Bemessungsniederschlag" on the map with gridded data)
	?	?	?	?	• Link: www.zamg.ac.at/cms/de/klima/produkte-und-services/daten-und-statistiken/extremwertstatistik-1 • No detailed information on internet, not freely available
Denmark	1979-2012	Point	1 hour up to 24 hours Also > 24 hours?	2 years, 10 years, 100 years	• Link: https://universe.ida.dk/netvaerk/energi-miljoe-og-global-development/spildevandskomiteen/spildevandskomiteens-skrifter/ • Method: https://ida.dk/sites/default/files/svk_skrift30_0.pdf?_ga=2.138825715.1982837567.1497872368-1856766300.1497872368 • Excel file for calculating amounts and return times freely available
France	Varies per station	Point	6 min up to 48 (192) hours	1 week to 2 years and 5 to 100 years	• Link: http://services.meteofrance.com/e-boutique/climatologie/coefficient-montana-detail.html • Not freely available • More than 1000 rain gauges managed by Météo-France
Germany	1951-2010	Point	5 min up to 72 hours	1 to 100 years	• Link: http://www.dwd.de/DE/leistungen/starkniederschlagsgutachten/starkniederschlagsgutachten.html • Method: http://www.dwd.de/DE/leistungen/starkniederschlagsgutachten/download/kostra_dwd_2010_pdf.pdf?__blob=publicationFile&v=8 • Not freely available
Ireland	1941-2004	point	5 min to 25 days	Twice a year to 500 years	• Link: www.met.ie/climate/products03.asp • Methods: www.met.ie/climate/dataproducts/Estimation-of-Point-Rainfall-Frequencies_TN61.pdf • Freely available, but should be requested
Nether-lands	2014 (1906-2014 detrended to 2014)	Point/area	2 hours to 10 days	Twice a year to 1000 years	• Link: www.meteobase.nl/ • Method: 62.148.170.210/meteobase/downloads/fixed/literatuur/Beersma2015_STOWArapport_actualisatie_meteogegevens.pdf • Hourly data used as basis, freely available

					• For transfer to area statistics: bibliotheek.knmi.nl/knmipubTR/TR332.pdf. Updated extreme areal rainfall statistics available in the course of 2018 for durations 15 min-9 days and area sizes 6- 1700 km2. Will be updated in 2018 • Also similar statistics for future (KNMI'14 scenarios for 2050 and 2085)
	2003-2016	point	10 min – 12 hours		• Yearly maxima for 10 min -12 hours used, freely available • Method: Neerslagstatistieken voor korte duren, actualisatie 2018 (Beersma et al., 2018). http://www.stowa.nl/Upload/Publicaties%202018/STOWA%202018-12%20HR.pdf
Norway	Varying between stations, but at least 10 years between 1967-2014	Point	1 min to 24 hours	2 to 200 years	• Method: https://cms.met.no/site/2/klimaservicesenteret/rapporter-og-publikasjoner/_attachment/8171?_ts=1527e50a347 • Data: https://klimaservicesenter.no/faces/desktop/idf.xhtml • Tentative regional statistics for 7 regions • Trend detected in extremes on many stations • Freely available, also information on climate change
Sweden	1961-2011	point	1 to 30 days	1 to 100 years	• Data and method: http://www.smhi.se/publikationer/extrem-nederbord-i-sverige-under-1-till-30-dygn-1900-2011-1.24660 • Based on daily data • Freely available
	1995-2008	point	15 min to 96 hours	1 to 100 years	• Data and method: http://www.smhi.se/polopoly_fs/1.7847!/Meteorologi%20139.pdf • Based on 15 min data, freely available • Not clear whether also area statistics, but there is information about extreme rainfall over large areas: https://www.smhi.se/kunskapsbanken/klimat/extrem-arealnederbord-1.6153
United Kingdom	up to max of 2006	Point and catchment data?	1 to 192 hours	2 to 10,000 years	• https://fehweb.ceh.ac.uk/ (FEH 2013 rainfall model) • Data: https://www.ceh.ac.uk/services/rainfall-frequency-grids • Method: https://www.ceh.ac.uk/services/flood-estimation-handbook (annual maximum (AM) and peaks-over-threshold (POT), and fixed and sliding event durations.) In volume 2 of this handbook also info on the application of ARF's is given • Hourly data as basis

Table 2.2. Links to some **rainfall datasets per country** with observations (station data or gridded data) or simulated data (latest check December 2017; Norway July 2018).

Country	Name/Link(s)	Comments	Freely available?
Austria	http://www.zamg.ac.at/cms/de/produkte/klima/daten-und-statistiken/messdaten	Observations per station,	no
	http://www.zamg.ac.at/cms/de/produkte/klima/daten-und-statistiken/gitterdatensaetze	Gridded datasets, 15 min, 1 day or 1 month temporal resolution, spatial resolution often 1 km or 100 m, high resolution data starting in 1961 or later	no
Denmark	SVK http://svk28.env.dtu.dk/regnserier-kmd-7997.htm?	Point observations, at present 145 stations in Denmark, from 1979 on, 1 min resolution	?
	CGD: http://beta.dmi.dk/fileadmin/Rapporter/TR/tr12-10.pdf	Gridded data, 10 km resolution, 648 grid cells covering Denmark, 1980-2010, daily resolution	?
France	https://donneespubliques.meteofrance.fr/ https://publitheque.meteo.fr/okapi/accueil/okapiWebPubli/index.jsp	Daily and hourly station data, radar (high resolution) and satellite data, model data	no
	http://www.drias-climat.fr/commande	Bias-corrected daily gridded climate data for some models	yes?
Germany	http://www.dwd.de/DE/leistungen/klimadatendeutschland/klarchivtagmonat.html?nn=16102 http://www.dwd.de/DE/klimaumwelt/cdc/cdc_node.html	Hourly and daily station data Gridded datasets (current and future climate, KLIWAS)	yes
	http://www.dwd.de/DE/leistungen/fuenfminutenwerterr/fuenfminutenwerterr.html	5 min data	no?
	http://www.dwd.de/DE/leistungen/starkniederschlagsauswertung/starkniederschlagsauswertung.html	5 min radar data, Method: http://www.dwd.de/DE/leistungen/radolan/radolan_info/abschlussbericht_pdf.pdf?__blob=publicationFile&v=2	no
	HYRAS	high resolution gridded daily dataset, description: http://www.schweizerbart.de/papers/metz/detail/23/82855/Central_European_high_resolution_gridded_daily_dat?af=crossref	?
Ireland	http://www.met.ie/climate/climate-data-information.asp http://www.met.ie/climate-request/	Daily data and hourly data	yes
Nether-lands	http://www.knmi.nl/nederland-nu/klimatologie-metingen-en-waarnemingen	Daily and hourly station data	yes
	http://www.klimaatscenarios.nl/toekomstig_weer/transformatie/index.html	Daily station data for future (KNMI'14 scenarios)	yes
	https://data.knmi.nl/datasets	Gridded data (1 km) for current and future climate (KNMI'14 scenarios)	yes
	https://data.knmi.nl/datasets	Radar data	yes
Norway	http://eKlima.met.no https://thredds.met.no/thredds/projects/senorge.html https://klimaservicesenteret.no/faces/desktop/article.xhtml?uri=klimaservicesenteret%2Fklima-og-hydrologiske-	Main source of historical observations Gridded historical (1x1 km) Bias corrected climate data, 1971-2000 and projections, daily data (1x1 km)	yes

	data%2Fdatagrunnlag-klimafremskrivninger (https://www.met.no/frie-meteorologiske-data/frie-meteorologiske-data)	Access to more data	
Portugal	https://www.ipma.pt/pt/produtoseservicos/index.jsp?page=dataset.pt02.xml	Gridded data, daily resolution, 0.2 ˚resolution (about 20 km), 1950 a 2003	yes
	https://www.ipma.pt/pt/produtoseservicos/index.jsp?page=dados.xml	Station data, 10 min, hourly and daily	?
Sweden	http://opendata-download-metobs.smhi.se/explore/#	Station data, 15 min, hourly and daily data	yes
	https://esg-dn1.nsc.liu.se/projects/esgf-liu/	Climate model data	Yes?
United Kingdom	http://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0	Among others daily, hourly and sub-hourly rain data from Met Office station network	?
	https://www.europeandataportal.eu/data/en/dataset/gridded-estimates-of-daily-and-monthly-areal-rainfall-for-the-united-kingdom-1890-2012-ceh-gear	Gridded daily rainfall data to 1 km for period 1890-2012, based on station data from UK Metoffice	?
	http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/download/daily/gridded_quantities.html	Gridded data for period 1960-2011, large number of climate indices, also on daily and multi-day extremes	yes
General for Europe	www.ecad.eu/	Daily observed data per station and many derived climate indices.	Downloadable if freely available. If not, derived data and climatology of stations can be obtained
	https://climexp.knmi.nl/selectdailyseries.cgi?id=someone@somewhere	Daily observed data per station. Use station names or coordinates to find stations in the GCHN-D database	yes

Table 2.3 Overview of available information on **future changes in rainfall in the climate scenarios** in Table 1.2 for the countries included in the WATCH country comparison report (Bles et al., 2017) (latest check December 2017; Norway July 2018).

Coun-try	Reference pe-riod	Time hori-zons	Scenarios[7]	Averages		Extremes			Comments
				Per yr	Per sea-son	Multiple days	Daily	Sub-daily	
Austria	1971-2000	2021-2050 2071-2100	RCP4.5, RCP8.5	Yes	Yes	Per month	Wet days (rr1), Highest 1 day and 5 days rainfall per year (rx1day, rx5day), Rainfall amount wet days 30%-98% percentiles (rr1_30pct, rr1_60pct, rr1_90pct, rr1_95pct, rr1_98pct), Consecutive wet days per year (cwd_sum_days)	No	Info on temperature change, not on humidity
Den-mark	1986-2005	2081-2100	RCP2.6, rcp4.5, rcp6.0, RCP8.5	Yes	Yes	-	-	-	http://www.dmi.dk/klima/fremtidens-klima/danmark/ekstrem-vejr/
	1961-1990	2021-2050, 2071-2100	A1B (ensemble average)	-	-	-	Highest 1 day and 5 days rainfall per year, Avg. rainfall amount on wet days, Nr days with >10 mm and > 20 mm	-	http://www.dmi.dk/klima/fremtidens-klima/danmark/ekstrem-vejr/
	1979-2012	50 and 100 years ahead	RCP4.5, RCP8.5	Yes?	?	?	24 hours	1 hour and maybe shorter too	Method climate factors: https://ida.dk/sites/default/files/svk_skrift30_0.pdf?_ga=2.138825715.1982837567.1497872368-1856766300.1497872368
France	1976-2005	2021-2050 (Near) 2041-2070 (Mid-term) 2071-2100 (long-term	RCP 2.6 RCP4.5 RCP8.5 (A1B, A2, B1: model data available, but not presented)	Yes	Yes	Per month	Daily precipitation, Mean precipitation for wet days, Precipitation sum, Nr. wet days, Nr heavy precipitation days (>20 mm), Max. number consecutive wet days (>=1 mm), % of intense precipitation, drought period (consecutive days with <1 mm)	No	http://www.drias-climat.fr/

[7] Information on the scenarios mentioned here is given among other in the ROADAPT guide line on the use of climate data (2015): http://www.cedr.fr/home/fileadmin/user_upload/en/Thematic_Domains/Strat_plan_3_2013-2017/TD1_Innovation/I1_Research/TGR_TPM/Transnational_calls/CEDR_Call_2012/CEDR%20Call%202012%20Climate%20Change/ROADAPT/ROADAPT_Part_A1_-_Guideline_on_the_use_of_data_for_the_current_and_future_climate.pdf

Germa-ny	1971-2000	2031–2060 2041-2070 2051-2080 2061-2090	RCP2.6, RCP8.5 (A1b)	No	Yes winter summer	No	number of days exceeding the 95th percentile threshold of daily precipitation	No	Climate Signal maps: http://www.mdpi.com/2073-4433/6/5/677
	1951-2006	2021-2050 2071-2100	A1B (range based on ensemble)	Yes	Yes	No	No, but can be obtained from the datasets	No	KLIWAS: http://www.kliwas.de/KLIWAS/DE/Home/homepage_node.html
Ireland	1961-1980 and 1981-2000	2021-2040 2041-2060 2021-2060	Low-medium (RCP45, B2) and high (RCP85, A1B and A2)	Yes	Yes	No	Wet Days (> 20mm/day), Very Wet Days (> 30mm/day) Number of wet days	No	Method and more detailed info: http://www.epa.ie/pubs/reports/research/climate/research159ensembleofregionalclimatemodelprojectionsforireland.html#.VlwLUt_hCEJ
Nether-lands	1981-2010	Around 2030, 2050, 2085	4 scenarios based on change of 2 levels of global temperature + 2 levels of circulation	Yes	Yes	Monthly changes in transformation tool	Wet days Daily sum with return time 1/10 y, 10 day sum with return time 1/10 y 50%, 90% and 99% percentiles for wet days	Hourly sum that occurs 1/1 year.	Info on temperature change and on humidity change Transformation tool: http://www.klimaatscenarios.nl/toekomstig_weer/transformatie/Toelichting_TP.pdf
Norway	1971-2000	2031-2060 2071-2100	RCP4.5 RCP8.5 (and 10% and 90% percentiles)	Yes	Yes	No	Nr of days with heavy rainfall (exceeded twice per year), intensity on days with heavy rainfall	Analyses indicate: estimated 30% for 3-hour precipitation with 5 year return time for RCP8.5 (higher than increase daily extremes)	Report: http://www.miljodirektoratet.no/no/Publikasjoner/2017/Mai-2017/Climate-in-Norway-2100--a-knowledge-base-for-climate-adaptation
Sweden	1971-2000 (and 1961-1990?)	2011-2040 2041-2070 2071-2100	RCP2.6, RCP4.5, RCP8.5 (and 2C and A1b)	Yes	Yes	Max 7-day precipi-tation	Max. daily precipitation, nr. of days with heavy precipitation	No	Background: https://www.smhi.se/klimat/framtidens-klimat/klimatscenarier/haag_en.html
United King-dom	1961–1990	2010 to 2099 as overlap-ping 30-year time periods	Low, medium and high	Yes	Yes	Per month	Wettest day in summer/winter In weather generator: mean rainfall amount, the proportion of dry days, the variance and skewness of daily rainfall amounts and the lag-1 autocorrelation used for fitting	Hourly time series produced (besides daily), but change in hourly the same as for daily change (change in hourly rainfall not separately determined)	Reports and guidance: http://ukclimateprojections.metoffice.gov.uk/22530

Table 2.4. Used return times and rainfall duration in various countries and used approaches to take climate change into account for road design, based on the WATCH country comparison report (Bles et al, 2017).

	Rainfall durations	Return times	Climate change[8]
Austria	15 min up to 6 days	1 to 100 years	Not used for design
Denmark	?	10-25 years	Danish government dictates scenario A1B (IPCC, 2007) must be used for operations of infrastructure. Climate change adaptation strategy and action plan is currently set into effect
France	6 min to 24 hours (or 48 hours)	1 to 100 years	Not used for road drainage design, but often checked if asset can manage factor 1.5/1.8 of peak flow + safety margins
Germany	?	?	Recognized that climate change may have impact, but not taken into account explicitly due to difficulty to quantity impact
Ireland	2 min up to 6 hours	1 to 100 years	+ 20 % for design flows and rainfall intensities
Netherlands	10 to 120 min	10 to 250 years	% based on climate scenario with largest increase for around 2050 (+30%)
Norway	10 min to 24 hours	50 to 200 years	By multiplying the design water flow by a climate factor, factors up to 40% based on location and catchment size
Sweden	?	3 to 200 years	Currently not taken into account, but climate change strategy and action plan for future road management is currently being implemented
United Kingdom	2 min up to?	1 to 100 years (200 years for Scotland)	+ 20 % for design flows and rainfall intensities

? Could not be found with the information from the WATCH country comparison report, or complete document could not be found and read through internet.

2.2 *Methods for extreme rainfall statistics*

In the protocol for generating rainfall statistics in chapter 4 and 5 it is described how available rainfall statistics can be analysed and, if they are not available, how they can be generated. In this paragraph first some background information on rainfall statistics is given.

2.2.1 Methods for extreme rainfall statistics and IDF-curves (point statistics)

The most used methods for generating extreme rainfall statistics are Peak over Threshold (POT) and Block Maxima, often Annual Maxima (with resp. the GPD and GEV probability distributions)[9]. The first method uses all independent observations above a certain threshold to generate the statistics. The second method uses block maxima, and most often the maxima in blocks of one year are used. The GEV distribution (Gumbel, Fréchet, and reverse Weibull) has three parameters: the location parameter describes the amount with a return time of about once in 2 years, the scale parameter describes the steepness of the relation, and the shape parameter describes the curve of the line in the figure below. The POT method assumes a Generalized Pareto Distribution (GPD). This method uses also three parameters as for GEV distribution, but it has an additional parameter for the threshold.

[8] Hardly ever it is mentioned for which time horizon (or length of life cycles) the percentages increase in extreme rainfall for road design have to be applied.

[9] For more background information see e.g. Coles, S (2001): An Introduction to Statistical Modelling of Extreme Values. Springer Series in Statistics. Springer Verlag London. 208p or Beirlant, J; Y. Goegebeur; J. Segers; J. Teugels (2005): Statistics of Extremes. Theory and Applications. John Wiley & Sons Ltd. 490p

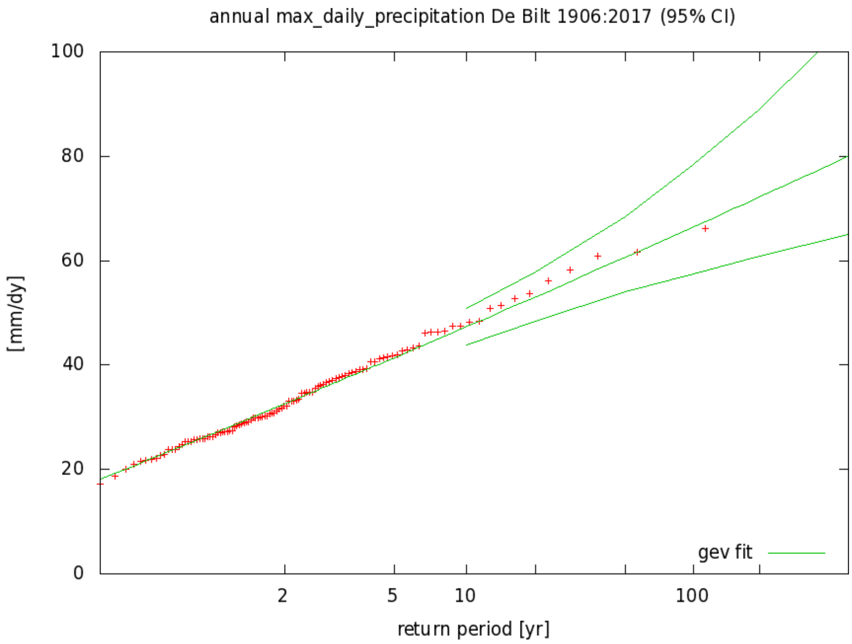

Figure 2.1 GEV plot for daily rainfall data from De Bilt over the period 1906-2016 (produced with the Climate Explorer on Oct 3, 2017). The middle green line gives the best fit with the data according to GEV, and the other green lines present the 95% probability range. The red crosses are the observed annual maxima.

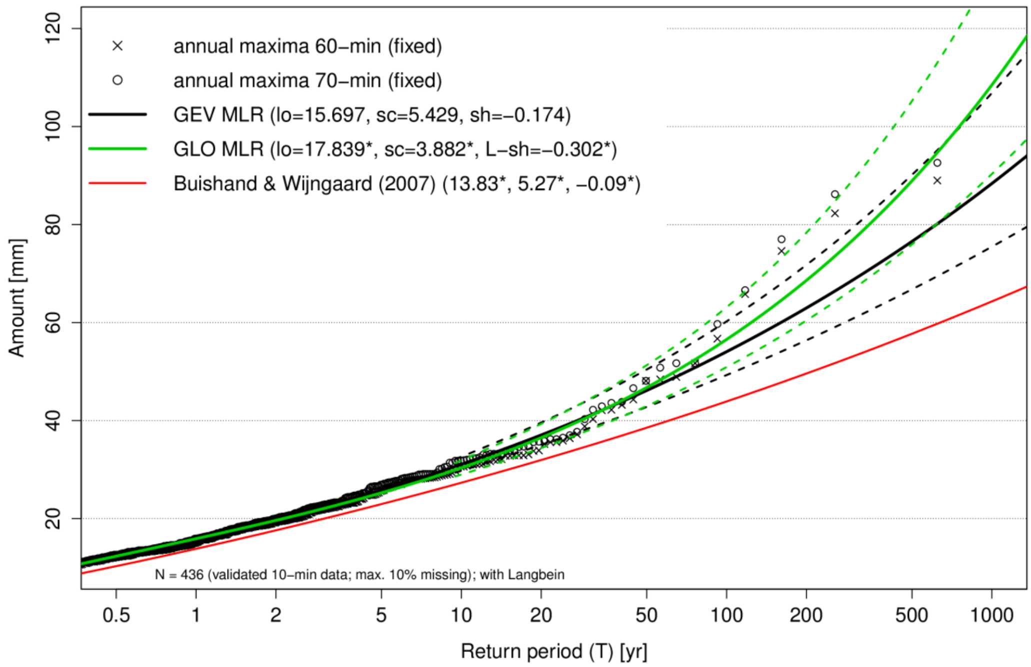

Figure 2.2 Comparison of the fit of a GLO and GEV distribution for 60 min duration annual rainfall maxima in the Netherlands for pooled stations for the period 2003-2016. The coloured dotted lines represent the 95% confidence bands for both fitted distributions (Beersma et al., 2018).

For short duration extremes (~ 10 minutes to 12 hours) the tail of the GEV distribution underestimates the amounts of rainfall in the Netherlands with high return times (larger than about 100 years. In such a situation the Generalised Logistic distribution (GLO) which has a thicker "tail" can be used. Figure 2.2 shows that the GLO distribution gives a better fit to the observations than the GEV distribution. The figure is for pooled 60-min data from a large number of stations from the Netherlands.

Table 2.5. Summary of main advantages and disadvantages of various probability distributions for rainfall statistics.

	GPD	GEV	GLO
Advantages	More observations can be used than just the “block” or annual maximum	Less parameters for the fit of the distribution, therefore less uncertainty	The long return times (> 1/100 or >1/200 years) are described more accurately (less underestimation than with GEV and GPD)
Disadvantages	Results are sensitive to the used threshold. This introduces an additional parameter and therefore an additional uncertainty Long time series needed to estimate the long return times[10]	Long time series needed to estimate the long return times (less values can be used than in GPD)	Long time series needed to estimate the long return times (less values can be used than in GPD)

As can be seen in Table 2.5 often long observation time series are needed, however, these time series can contain trends. Relatively recently (from about 2005 on) methods have been developed that can correct for trends in these time series (methods to correct for non-stationary data). In these methods the parameters become time-dependent (e.g. Beersma et al., 2015).

In regions with no clear regional differences in rainfall extremes also another approach can be used to avoid underestimating the rainfall statistics due to a changing climate. In these regions the observations of e.g. the last 10-20 years (where no trends can be observed) of various stations can be pooled together. This can be done especially for the short duration extremes, since these are generally caused by small scale events, and therefore the observations of the annual maxima for these stations are (in most cases) independent[11]. E.g. when you have 20 stations with 15 years of observations, you will have 300 independent annual maxima that can be used for GEV or GLO distributions. This approach is used e.g. by SMHI (Sweden) and KNMI (Netherlands) for the statistics for the short duration extreme rainfall.

> The most used probability distributions for generating extreme rainfall statistics are Generalized Pareto Distribution (GPD) and Generalized Extreme Value (GEV). They may give more or less the same statistics. For high return times (> about 100 years) these distributions may underestimate the extreme rainfall amounts.
>
> In many regions increases in extreme rainfall amounts are observed (or the frequency increases). In most countries included in this study, the available rainfall statistics are not corrected for these trends. This may result in underestimation of extreme rainfall amounts for the “current” climate.

2.2.2 Interpretation of point statistics

Point statistics give the probability to exceed a certain amount of rainfall for a certain point. If there are no regional differences in the extreme rainfall in a region or country each point has the same probability. In the case of extreme rainfall due to small scale events such as those that happen often in summer only one measuring station will measure the extreme event. E.g. in the Netherlands there are about 300 daily rainfall stations with an average horizontal

[10] Smaller uncertainties for short return times, but for return times longer than 5-10 years hardly any difference between GPD and GEV.

[11] For longer durations this is also possible, but fewer observations can be used since one has to take care of the spatial dependency.

distance of about 10 km, the small scale intense summer events often have a smaller diameter than 10 km. The regional differences in extreme rainfall in the Netherlands are limited. *This means that a once in 100 year*[12] *event will on average be measured 3 times a year in the Netherlands if one can assume that observations at all stations are independent!*

The temporal resolution of the basic data for the extreme rainfall statics influences the amounts obtained for the various return times. When using daily data[13], the estimated once in 10 years rainfall amount in 24 hours that will be exceeded, will be considerable lower than in the case of using hourly data as basic material. For extreme rainfall per 24 hours in the Netherlands Overeem et al. (2008) found a difference of 11 % between the statistics based on hourly data and those based on daily data. For extreme rainfall per hour they found 11-12 % lower values when the statistics were based on hourly data, compared to the use of data for 5-15 min, for extreme rainfall per 2 hours this difference had diminished to about 4 %. Førland (1992) found 13 % higher rainfall depths when based on hourly data instead of using daily data. In France the Weiss coefficient (1.14) is used. It describes the difference between the statistics based on daily data and those based on hourly data (pers. Comm. L. Foucher). In the case of hourly data the annual maximum in a window of 24 hours can be selected. Since rain showers don't always occur between e.g. 00:00 and 24:00 hours, this 24 hour maximum (based on moving window of 24 hours over the year) is generally higher than the daily maximum for a fixed definition of a day (when the maximum 24 hour amount is often split over two calendar days)[14].

The temporal resolution of the basic data used for deriving the extreme rainfall statistics determines the rainfall amounts that will be obtained for the various return levels.

Most extreme rainfall statistics found for the countries in this study are based on station data (point statistics). These give the probability to exceed a certain amount of rainfall for a certain point.

2.2.3 Techniques for generating areal statistics

For road inundation and runoff processes, it is important to estimate the total volume of rainfall over an area. One technique to generate such areal statistics is to use areal reduction factors that are applied to the station (point) data. In regions with hardly any regional differences in rainfall extremes, general Areal Reduction Factors can be derived from high spatial and temporal resolution data e.g. radar data, high density rainfall measuring network, gridded observations (if measured with sufficient high spatial resolution) or high resolution climate model simulations. These ARF's can then be applied to the whole region/country. Such ARF's have been derived from radar data for the Netherlands (Overeem & Buishand, 2012).

[12] Officially the return period in point statistics is the average time one has to wait after an event before such an event will happen again at the same location.

[13] There may be several rainfall measuring networks in a country. In the Netherlands and in France there is a network where once per day rainfall is measured and a network where rainfall is measured (almost) continuously. Information from this last network is often used to make e.g. hourly rainfall time series or time series with an even higher temporal resolution. The networks often have different measuring instruments, and therefore may have systematic differences in the rainfall amounts (e.g. in annual totals).

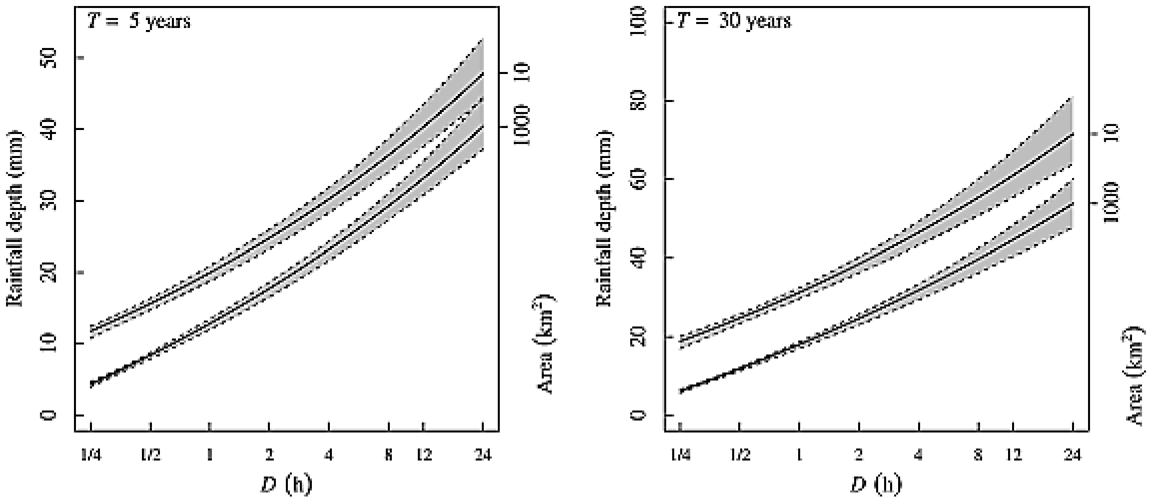

Figure 2.3 Example of near-point (10 km2) and area (1000 km2) statistics for extreme rainfall with a return time of once in 5 years (left) and once in 30 years (right) from the Netherlands (Overeem & Buishand, 2012).

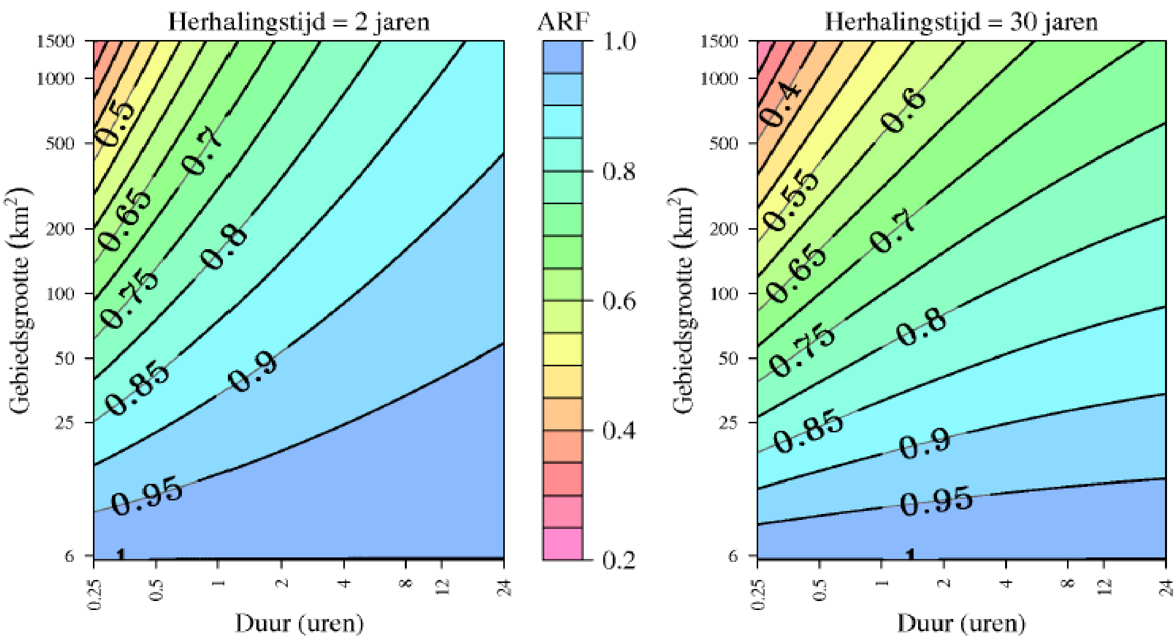

Figure 2.4 Example of Arial Reduction Factors (ARF) to get from point statistics to area statistics for the Netherlands for different rainfall durations ("duur", horizontal in hours) and different sizes of the area ("gebiedsgrootte", vertical in km^2) with a return time ("herhalingstijd") of once in 2 years (left) and once in 30 years (right) from the Netherlands (Overeem & Buishand, 2012).

However, in most countries there are clear regional differences due to the orography, but also the presence of large water surfaces could result in regional differences in rainfall statistics. In these cases the areal statistics have to be derived separately for each location (for Austria it is described how this can be done: http://ehyd.gv.at/assets/ehyd/pdf/bemessungsniederschlag.pdf). Radar data seem the best source to take into account spatial differences in rainfall extremes. However, radar data are in the best situation available only from the late '90 on. They should be calibrated with point observations and the correct estimation of the highest intensities may be a problem. Interpolation of observational point data is also possible, but very high resolution data sets over large areas are needed to capture all the spatial differences (such as those from the small scale high intensity summer rainfall events). However, the spatial resolution of the networks for measuring rainfall is generally not sufficient to get good estimates of area rainfall, especially not for the sub daily rainfall (Overeem & Buishand, 2012). In principle also high resolution climate model simulations can be used. These also have to be calibrated/bias-corrected with observational point data. Few data are available to check whether the effect of e.g. orography on rainfall is simulated correctly with the climate models. Also few data are available to check whether the climate model simulates the short duration rainfall (one hour or shorter) correctly (see also par. 2.3). Therefore, it is difficult to indicate the quality of the areal statistics based on these two later sources.

Overeem & Buishand (2012) mention a few studies that used rain gauge data for determining ARFs and also a few that used radar data. The ARFs derived for the Netherlands for return times of once in 2 years resemble those from the Flood Studies Report for the UK (NERC, 1975). However, the decrease in ARF with increasing return times for rainfall duration of 24 hours is stronger than the decline found by Bell (1976) for daily rainfall sums for the UK. This is probably due to the method used by Bell that does not take into account the changing form of the distribution for areal rainfall extremes. The ARFs from Overeem & Buishand are based on 10 years of radar data, which is relatively short. The ARF's may change somewhat if longer datasets are used. If the extensiveness of rain showers in the future will change substantially the ARF may have to be adjusted also.

In regions with hardly any regional differences in rainfall extremes Areal Reduction Factors can be derived from high spatial and temporal resolution data. However, in most countries there are clear regional differences in rainfall statistics. In these cases the areal statistics have to be derived separately for each location.

Only for a few countries included in this study, areal statistics on extreme rainfall for the current climate could be found.

2.3 Scientific research on extreme (short duration) rainfall in Europe

In this paragraph we present an overview of research on extreme rainfall in observations and in climate model simulations. This background information is used in chapter 4 and 5 to describe how one can generate information on extreme rainfall for the current and future climate. Since several aspects require further research, chapter 5 also describes how one can deal with uncertainties about future changes.

2.3.1 Changes in extreme rainfall with temperature increase: research with observations

The intensity of extreme rainfall is anticipated to increase by approximately 7% per 1 °C of warming. This expectation is based on the Clausius–Clapeyron relationship, which describes the change in atmospheric moisture holding capacity with temperature. On average, the actual rate of moisture increase is rather close to this value. As changes in rainfall extremes are, to first order, related to atmospheric moisture, the Clausius–Clapeyron relation provides an approximate guide to understanding future changes in heavy rainfall (Lenderink & Fowler, 2017).

However, research from Lenderink & van Meijgaard (2008), Lenderink et al. (2009), Romero et al. (2011) and Lenderink et al. (2011) showed that in observations, above a certain temperature, the extreme hourly rainfall can increase much faster with temperature than the extreme daily rainfall. Figures 2.5 and 2.6 show that the rainfall intensity increases with an increasing dew point temperature[15]. This applies to intensities that occur quite frequently, but also to very extreme situations. In figures 2.5 and 2.6 the dew point temperature is used and not the average daytime temperature. The dew point temperature is the temperature where the air becomes saturated and is therefore a precise measurement of the actual moisture in the air. The dew point temperature appears to show a better relationship with extreme rainfall, as the occurrence of severe showers is dependent on the amount of moisture in the air. With constant relative humidity a temperature rise of 1˚C will result in a dew point temperature rise of 1˚C.

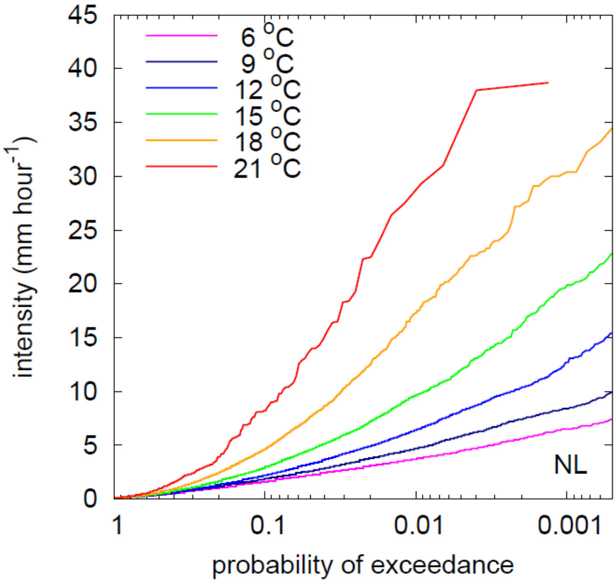

Figure 2.5. Probability of exceedance of rainfall extremes ('intensity' in mm per hour) at various average daily dew point temperatures at 27 stations in the Netherlands (Lenderink et al., 2011) in the period 1995-2010 (0.01 is once in 100 hours with rainfall within a certain temperature bin, etc.).

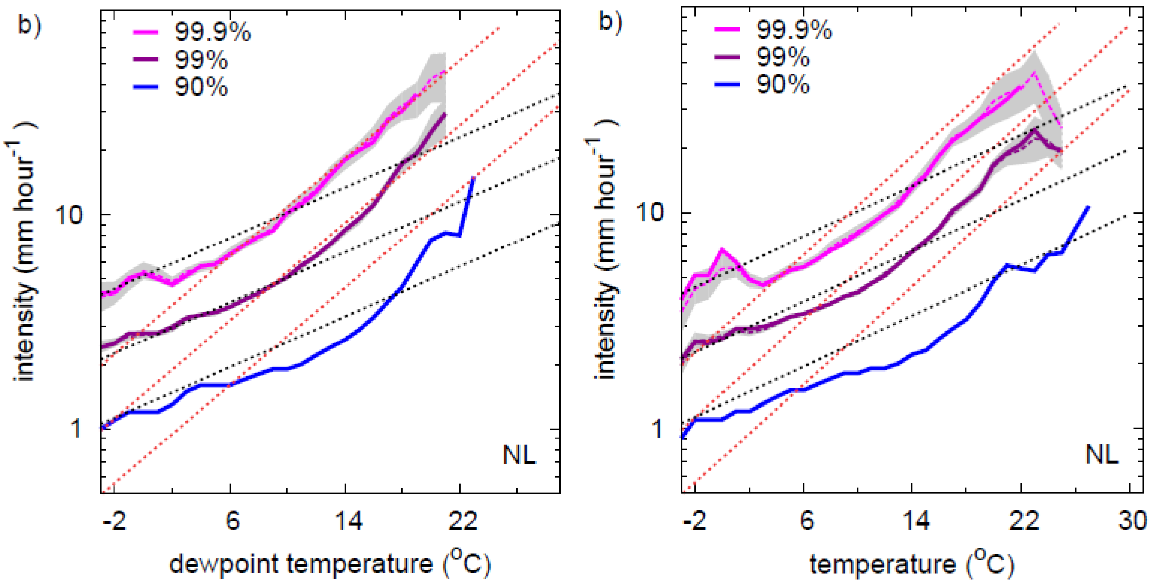

Figure 2.6. Relation between extreme rainfall intensities (for the 90, 99 and 99.9 percentiles; vertical axis) and the average daily dew point temperature (x-axis, left) and average day temperature (x-axis, right). Based on 15 years of data (1995-2011) for 27 stations in the Netherlands. The black dotted line gives an increase of 7% per °C, the red dotted line 14% per °C (Lenderink et al., 2011).

15 Dew point is the temperature to which air must be cooled to become saturated with water vapour.

Figure 2.6 also shows the relationship between temperature and rainfall intensity per hour. Up to a certain temperature, the relationship follows the Clausius–Clapeyron function. Lenderink & van Meijgaard (2008) found such a relationship for daily extremes. At higher temperatures, however, the increase in hourly rainfall intensity per ° C temperature rise is larger (up to about 14%). The turning point is approximately at a daily average temperature of 10-14 ˚C or an average dew point temperature of 6-10 ˚C (Figure 2.6). This applies especially to extreme percentiles. For the 75% percentile, the stronger increase with temperature seems to start only at significantly higher daily average temperature than 10-14 ˚C (Lenderink & van Meijgaard, 2008; Lenderink et al., 2011; Romero et al., 2011). Such rates of increase of up to double the Clausius–Clapeyron rate have been observed in multiple observational and modelling studies for sub daily extremes for temperature ranges between approximately 12°C and 22°C (e.g. fig 2.7). In some studies also decreases in rainfall intensities with temperature have been found above ~24°C. It is not clear yet whether this is due to the fact that the relation was determined with temperature and not with dew point temperature. Further research is needed on the extent to which these observed scaling relationships are valid for other regions and on the extent to which they can be applied to climate change projections (Westra et al., 2014). The lack of long, homogenous, high-quality extreme rainfall data at sub daily time scales is a clear limitation for this further research (Westra et al., 2014).

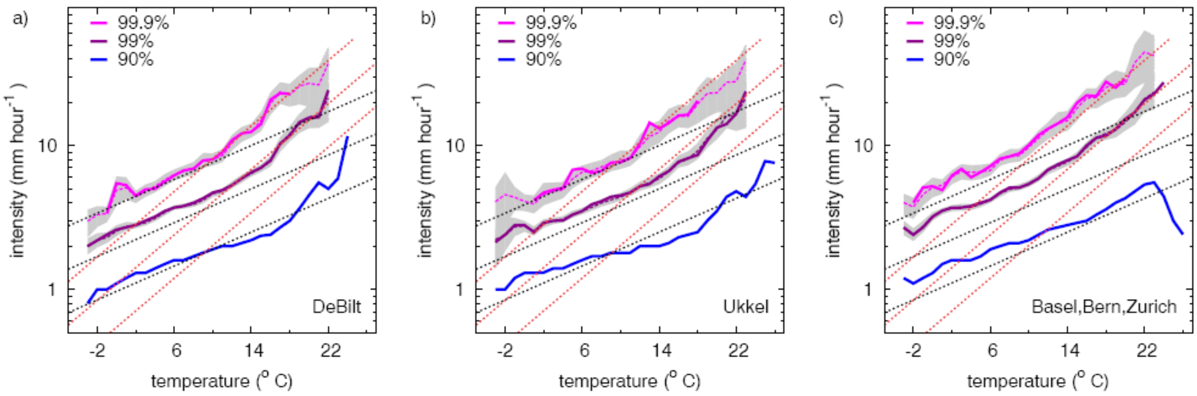

Figure 2.7 Relation between <u>observed</u> extreme rainfall intensities (for the 90, 99 and 99,9 percentiles; vertical axis) and the average daily temperature (x-axis) for 3 locations in Europe. Based on observed data. The black dotted line gives an increase of 7% per °C, the red dotted line 14% per °C (Lenderink et al., 2011).

Research on observations shows that in several countries the rainfall extremes on hourly basis increase stronger with temperature increase than the rainfall extremes on daily basis. For higher temperatures increases of up to 14% per ˚C for hourly extremes are observed. The turning point is approximately at a daily average temperature of 10-14 ˚C or an average dew point temperature of 6-10 ˚C.

Increases in rainfall extremes can be better explained when using dew point temperature than when using temperature, since dew point temperature directly measures moisture instead of the maximum water holding capacity (as with temperature).

2.3.2 Simulation of short duration rainfall extremes with climate models

Climate models are often used to provide information for the future. Therefore, it is relevant to check whether climate models can simulate the rainfall extremes reasonably good. This is done by comparing climate model simulations for the current climate with observations[16]. Lenderink & Van Meijgaard (2010) showed that the dependency of extreme hourly rainfall on increasing temperature for the Netherlands could be reasonably simulated with the climate models RACMO and CLM (spatial resolution 25 km) up to certain dew point temperatures (Figure 2.8). However, there are some differences with the observed relations, in particular at the highest (dew point) temperature range.

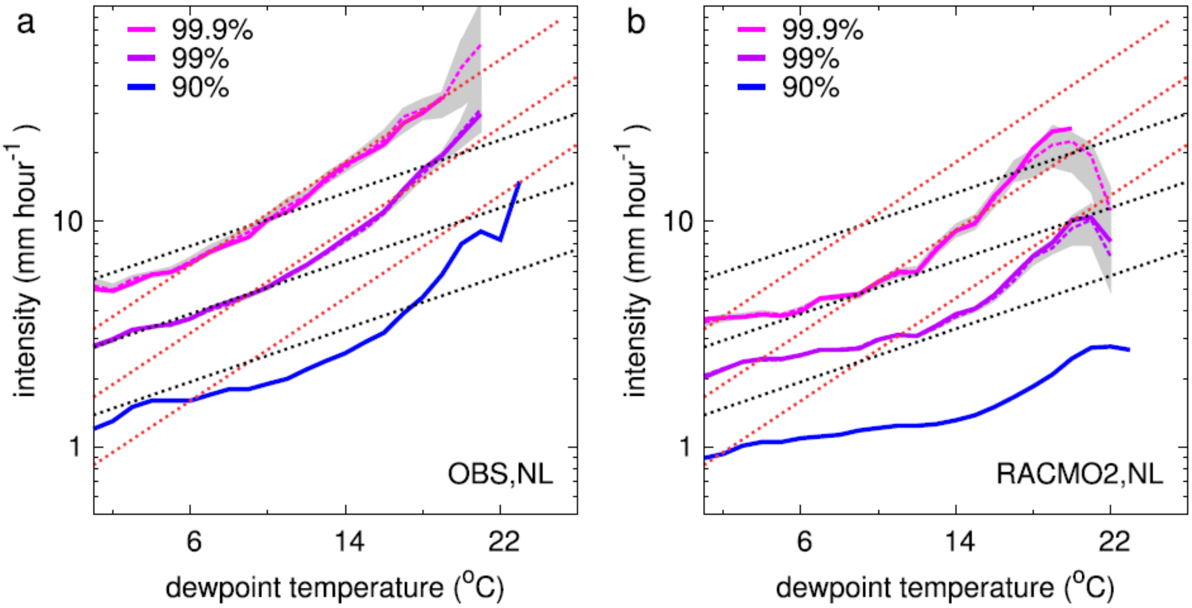

Figure 2.8 Dependency of hourly rainfall extremes on dew point temperature derived from 27 stations in the Netherlands over the period 2005-2009 on days with 0.25 mm rainfall or more; <u>right: observations, left: model output</u>[17] for a present-day climate simulation of HARMONIE for the same station locations. Dew point temperatures are taken 4 h before the event. Shown are results for the 90, 99 and 99.9th percentile of wet events. Solid line: raw data, stippled lines at end solid lines: estimated from a GPD fit, including uncertainty estimates (grey shading). Red and black linear lines show (exponential) dependencies of 7 and 14% per degree (Lenderink & Attema, 2015).

Climate models with spatial resolution of > 10-20 km cannot resolve local convective processes dynamically (they use convection parameterizations that strongly simplify the atmospheric dynamics at the cloud scale). These convective processes often cause the extreme and local rainfall events. Even a climate model with a 10 km grid cannot simulate convection dynamically and therefore does not represent sub daily rainfall intensity and the diurnal cycle adequately for the whole temperature range. However, numerous studies have found that characteristics of subfamily rainfall improve with increased resolution compared with coarser scale Regional Climate Models (RCMs) and Global Climate/Circulation Models (GCMs; Westra et al., 2014). Kendon et al. (2014) carried out continuous multiyear climate change experiments at a 1.5 km resolution over a region of the UK and showed a future intensification of hourly rainfall in summer not seen in a coarser 12 km resolution RCM. They suggest that the changes on (sub) daily rainfall extremes in regional climate change scenarios from coarser- resolution models should be reconsidered as the changes in convective events could have been underestimated. *Due to the limited number of climate studies undertaken at convection-permitting scales[18], it is still not possible to draw broader conclusions from these models on how sub daily rainfall will change under future climate*

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[16] If models can simulate the current climate reasonably, than there is more trust in what they produce for the future.

[17] The rainfall intensities in the model simulations are lower than the intensities based on the station observations, since model output always gives spatial/areal averages (see also par. 2.2.2)

[18] Because these simulations are computationally extremely expensive.

change, although this will likely improve as more high-resolution modelling studies become available (Westra et al., 2017). Evidence from these high-resolution climate models, in both real-world and idealized setups, suggests that the intensity of sub daily extreme rainfall is likely to increase in the future. Some of these studies show increases in rather close agreement with the Clausius Clapeyron relation (~7% per °C), whereas others show stronger dependencies (Westra et al., 2014). (We note that for some areas around the globe, mainly situated in the sub-tropics, extremes may even decrease). The number of very high resolution model simulations is too limited, and the typical length of these simulations too short, to draw definite conclusions.

Whether the above scaling relations of precipitation intensity on (dew point) temperature can be used as a proxy for the long term climate trends is still open to scientific debate. For the Netherlands (and Hong Kong outside the wet season) it has been shown that the relation is good predictor of the long term observed trends (Lenderink et al, 2011). However, in general results of linking local scaling to observed trends are less conclusive. Partly, this is because confounding factors (such as seasonality in circulation conditions) are influencing the scaling relations. For the Netherlands results indicate that the influence of these confounding factors is rather insignificant (Lenderink et al., 2017). However, this is generally not the case, which potentially leads to negative scaling rates e.g. in the Mediterranean. So locally derived scaling relations cannot be used straightforwardly to estimate climate change signals. But, there is reasonably support (also from modelling studies) that changes in sub-daily extremes could be as large as 14 % per degree as suggested by the scaling relations derived from the Netherlands data.

Most currently available climate models have too coarse spatial resolutions and are unable to represent local convective processes dynamically. Especially at higher temperatures they may underestimate the short duration rainfall extremes. Due to the limited number of climate studies undertaken at convection-permitting scales, it is still not possible to draw broader conclusions from these models on how sub daily rainfall will change under future climate change. But, there is reasonably support that changes in sub-daily extremes could be as large as 14 % per degree temperature increase.

2.3.3 Scaling changes in rainfall extremes with temperature

Various studies use a statistical (or scaling) approach to relate changes in rainfall extremes to air temperature, implicitly assuming that temperature is a reliable proxy for humidity, and that the intensity of rain responds directly to the humidity perturbation. However, several recent papers show that no reliable projections can be made based solely on temperature scaling (Lenderink & Fowler, 2017). Lenderink & Attema (2015) propose a scaling method whereby changes in rainfall extremes are set proportional to the change in dew point temperature, a combination of air temperature and relative humidity of the air. In chapter 5 it is described how one can estimate the range of changes in the future in rainfall extremes.

Information on changes in the future for the short duration rainfall extremes is often missing in countries. Therefore, scaling with available data such as temperature can be used. Based on the above information it seems most appropriate to use a scaling method whereby changes in rainfall extremes are set proportional to the change in dew point temperature.

3 Uncertainties in climate change and how to deal with them

In discussions on climate change inevitably the uncertainties on the future climate are discussed. Uncertainty is any departure from complete deterministic knowledge of the relevant system. The term uncertainty is often used differently in different sectors and disciplines, or other words are used for the same (e.g. range, variability, lack of knowledge). The word uncertainty often means something different to scientists than to others. Therefore in this section some more background information will be given on the types of uncertainties relevant for climate data.

3.1 Types of uncertainties in the current and future climate

Various types of uncertainties can be distinguished. Below we first give short description of these types of uncertainties and whether they are relevant for the description of the current or future climate.

Current climate

- Natural variability, day-to-day variation, year-to-year variation, and decade to decade: is the temporal variation of the atmosphere–ocean system around a mean state due to natural internal processes within the climate system (internal variability: e.g. the different position of high and low pressure areas, differences in air circulation) or to variations in natural forcings (e.g. solar intensity, volcanic eruptions). This uncertainty can be described with statistics, if enough data (observations or simulated) are available.
- Measuring "errors"[19]: difference in what is measured and the physical reality, can be caused by the quality of the instrument, its arrangement or the measurement of the measurement signal.
- Inhomogeneities: may occur when the conditions of measuring instruments change. In that case, changes in the observational time series do not reflect the change in the general climate, but, for example, the warmer (micro) climate around a measuring instrument due to increasing urban development, the change of measuring instrument, the movement of the measurement station.
- Uncertainties in rainfall statistics related to the length of the time series (sometimes called sampling uncertainty, regularly this is indicated with a 95% band).
- Uncertainties in rainfall statistics related to the used probability distribution (e.g. GPD or GEV).
- Biases: When observations are limited or not available for all regions, estimates of the missing observations can be obtained with the help of climate model simulations (re-analyses[20]). In these simulations for the current climate systematic deviations from the observed climate can be found.

[19] Met offices check for measuring errors (validation), but still there may be some measuring error that cannot be detected.
[20] Re-analysis: the climate in the past is simulated with a weather model integrating as much as possible observational data.

Future climate
For the future there are some additional uncertainties to the ones mentioned for the current climate[21]. Uncertainties about the future climate can be due to:

- Imperfect knowledge about the climate system, quantified with the help of a large number of climate models that simulated the future climate for the same emission scenario (often called "model uncertainty")
- Imperfect knowledge about the socio-economic future, causing the emission of greenhouse gasses, quantified by comparing the (average) impact of various emission scenarios or Representative Concentration Pathways on the future climate (often called "scenario uncertainty").

The relative importance of these uncertainties and the natural variability for different time horizons is indicated in fig. 3.1.

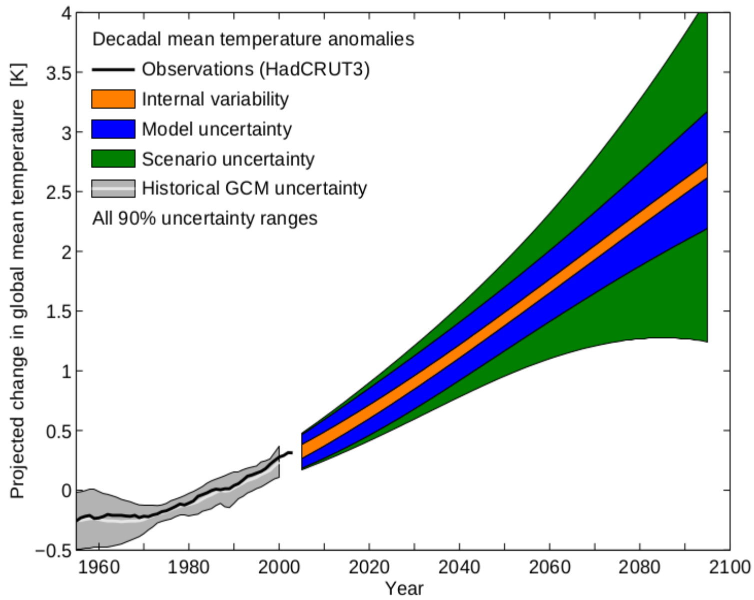

Figure 3.1 The total uncertainty in CMIP3 decadal mean projections of global mean temperature for the 21st century. The grey regions show the uncertainty in the 20th century integrations of the. same Global Climate Models (GCMs), with the mean in white. The black line before the year 2000 shows an estimate of the observed historical changes from HadCRUT3 (Brohan et al., 2006 in Hawkins and Sutton, 2011).

3.2 Dealing with uncertainties

3.2.1 Reducing uncertainties?

The sources of uncertainties give indications on how one can deal with them. Some uncertainties can be reduced, but others not:

- Natural variability itself cannot be reduced, but it can be quantified with the help of statistics. If not enough data are available, than monitoring is a way to get more information and reduce the uncertainty in the description of the natural variability;
- Measuring errors can be detected/avoided by quality control and validation of the observed data (standard practice at meteorological institutes)

[21] Also natural variability, measuring errors, inhomogeneities are important for the future climate, since climate model results for the current climate are calibrated and validated with the help of observed data. It is than assumed that the bias in the current climate is also present in the future projections.

- Inhomogeneities can be detected with statistical techniques and in case of changes of instruments, locations, etc. often 1 or 2 years of parallel measurements are done to be able to quantify the impact of the change.
- Biases in climate model output can be corrected for with the help of observations e.g. from stations (or gridded station data such as E-OBS) or from re-analysis.
- Uncertainty due to lack of knowledge of a system can be reduced by doing more research to better understand the system. In the meantime, scenarios can be used (no probability for the scenarios!) to study the effect of known uncertainties, and implications for impacts and adaptation options.

3.2.2 Strategies for dealing with weather extremes and uncertainties related to climate change

In the ROADAPT project (Bles et al., 2015) various strategies/approaches towards extreme weather events are presented (Fig. 3.2). In the phase of pro-action and prevention one takes measures that avoid or minimise the impact of extreme events. In the design phase information on the probability of relevant extreme events is taken into account. In the case of maintenance reconstruction/retrofitting can take place to adapt to new circumstances e.g. due to climate change or due to changes in the surroundings of the road that cause e.g. more run-off water.

PHASE		PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
FUNCTION	Adaptation strategy	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
TECHNIQUES / STRATEGIES	Planning for CCI&EWE	**Pro-active attitude**			**Extreme event management**			
	Robust construction		**Prevention**					
	Legislation , regulations							
	Resilient construction		**Upgrading**					
	Maintenance and management		**Maintenance and Replacement**					
	Traffic management for CCI&EWE		**Traffic management**					
	Capacity building			**Capacity building**				

Figure 3.2 Various strategies/approaches in dealing with extreme weather events from the ROADAPT project (Bles et al., 2015).

Attitudes towards risks vary across people, cultures, time and experience. Some people have a risk-seeking attitude whereas others have a risk adverse attitude. Availability of resources and the magnitude of the impact of extreme events may also influence whether a more pro-active or prevention approach is used or whether one focusses more on reducing the impact and repairing/recovering after extreme events.

Due to climate change the probability of many extreme weather events is expected to change. Some people only start adapting when there is almost 100% certainty that something will happen, whereas others already want to adapt when there is some suspicion or indication. There are also other factors that will influence whether climate change is included in the design and during maintenance: availability of resources, willingness and time needed to include it in legislation, the magnitude of the impact. Only in pro-action/prevention climate change is included explicitly. The uncertainty about future climate change is often considered an additional complication in how to deal with climate change. There are various approaches for dealing with this, e.g. using the average of the projections for the future[22], using a worst case scenario, using tipping points.

The Intergovernmental Panel on Climate Change (IPCC) does not indicate which of the underlying emission scenarios or representative concentration pathways (RCPs) is more likely than the others. This is also not possible, since it would require knowledge about which socio-economic developments are more probable than others. In most cases it is better to ask which climate scenario is most relevant for the user, and not which one is most probable. Most users are interested in extremes, which are by definition rare and therefore less likely. For some users, a different time horizon is relevant than for others. Below some examples are given to explain that what is relevant may differ considerably between users:

- In cities flooding mainly occurs after heavy showers (in North-western Europe especially in summer). In that case the climate scenario with the largest increase in extreme summer showers is probably most relevant;
- Agricultural production is influenced by the availability of water in the growing season. In that case the climate scenario with the largest decrease in summer rainfall is probably most relevant;
- Drainage tubes often go into the ground for 40-80 years. When one wants a sewerage system to function adequately at the end of its life cycle, it is relevant to look 40-80 years ahead;
- The economic depreciation period of many industrial installations is about 20 years. A time horizon of up to 2035-2040 is then relevant.

When deciding which climate projection/climate scenario to use, keep the following two aspects in mind:

- Which weather extreme is most relevant for your decision? What is the most probable is often not the most relevant.
- What is the life cycle of the asset one is working on? This will influence the time horizon that will be taken into account.

If one wants to be prepared for the worst case, often the scenario/projection with the highest change in rainfall extremes is used for estimating future risk. This approach is probably more often used for situations where the impact of weather extremes can be large. One could also make a selection from the climate scenarios based on the assumed socio-economic development (and the related emission scenario or RCP) by the stakeholder. Then one selects the climate scenario/projection that fits best this socio-economic development.

When deciding how to take climate change into account, keep the following aspects in mind:

- What is the life cycle of the asset one is working on? Determines the time horizon to take into account.
- Does one wants to be prepared for the worst case or a more average situation? Determines which projection or range of projections for the future to take into account.

[22] Implicitly this is often considered the most likely/probable, but this is not a correct assumption.

4 Generation of extreme rainfall statistics for the current climate

In this paragraph a procedure is described for checking or generating data on extreme rainfall for the current climate (fig. 4.1). Extreme rainfall statistics or IDF-curves for the "current" climate are generally available in a country (Table 2.1). However, it is useful to check what this "current" climate describes. If the data do not describe what is needed, the available data should be adjusted or new extreme rainfall statistics have to be generated. For adjusting or generating the required data often a lot of expertise is needed. Some publicly available tools exist for generating extreme rainfall statistics yourself (e.g. http://amir.eng.uci.edu/neva.php). However, probably the availability of good rainfall data for these statistics (observations or simulated data) is often the biggest problem. It is advised to check the results always with experts, e.g. from your national Meteorological Institute. In the figure below the procedure is described schematically for data for the current climate. In the sub-paragraphs the various aspects are further described.

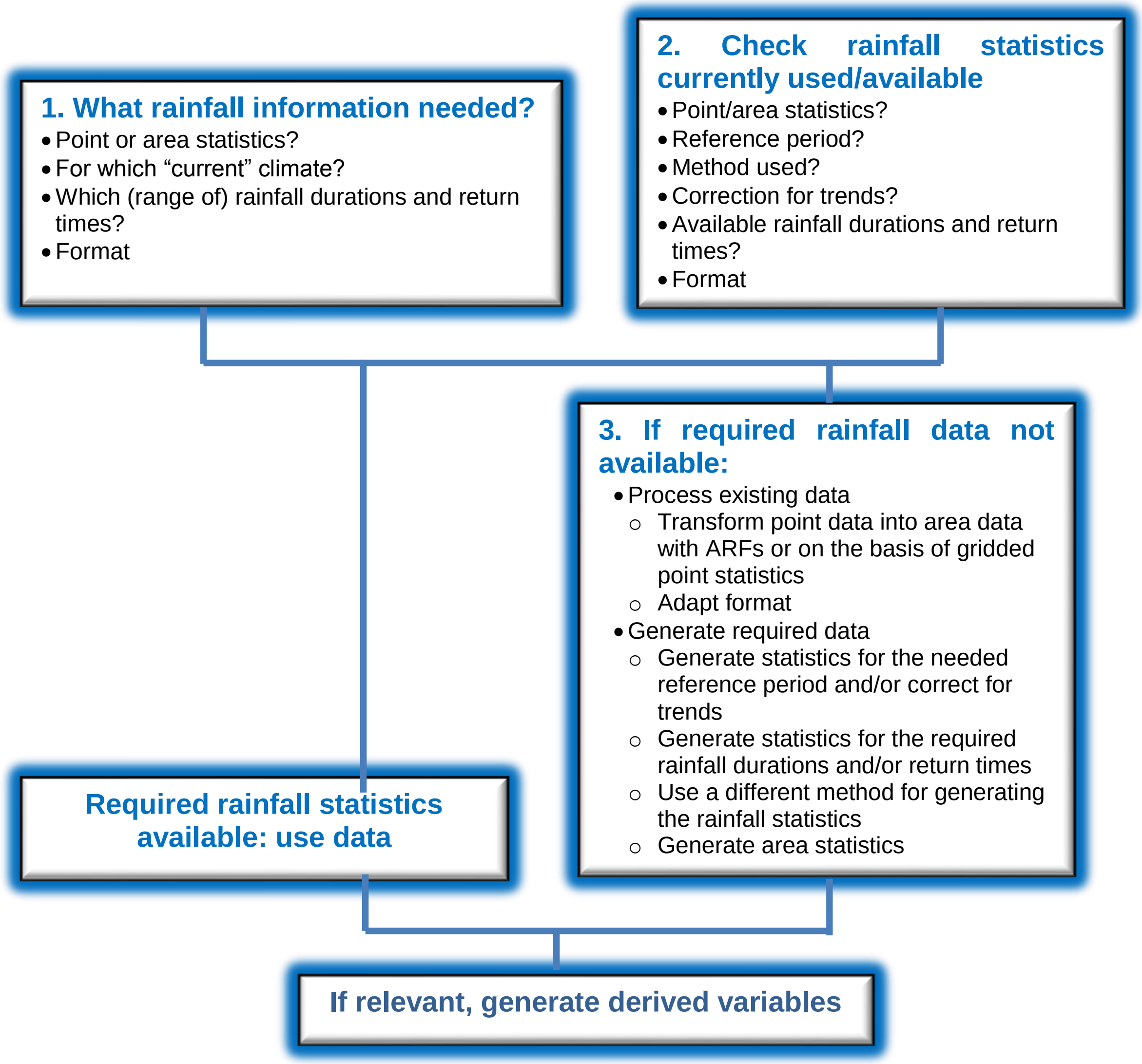

Figure 4.1 Procedure for data on extreme rainfall for the current climate.

The protocol for extreme rainfall information for the current climate consists of the following steps (Figure 4.1):

1. Determine which information is needed (point/area statistics, reference period, return times, rainfall durations, format)
2. Look what information is available on extreme rainfall (point/area statistics, reference period, return times, rainfall durations, format; look also at Table 2.1)
3. If what is needed and what is available matches, one can start using the data. If not, one has to adjust the data or generate new extreme rainfall statistics
4. If relevant, derived variables, such as run-off can be generated

The first steps may look redundant, but it is often not clear what climate the available data is representative for and for which "current" climate data is needed.

4.1 What extreme rainfall statistics do you need?

Before starting, look what information on extreme rainfall is needed **(step 1)**. Consider the following aspects:

- What is considered the current climate? This can be the climate described with the available extreme rainfall statistics/IDF/DDF-curves, but it can also be specified that the climate of e.g. the past 30 years should be used, or the climate around e.g. 2015. *Due to the trend in extreme rainfall observed in many regions, there is a risk that the available statistics underestimate the current climate that you may have in mind*.
- Are point or area statistics needed (par. 2.2)? Point statistics describe the probability of extreme rainfall at a certain location and are needed to estimate the risk of aquaplaning, or to check whether the drainage facilities at a certain location are sufficient to avoid water on the road (also for SuDS). In the case of culverts one wants to know whether they are big enough to let through the water that runs of from a certain area.
- What rainfall durations or range of rainfall durations are needed? For water on the road often short durations (<1 hour) are needed, but in the case of run off longer durations (> 1 hour) could be more relevant.
- What return times are needed? This depends on the norms for roads in the country one is working.
- Which format of the data is needed? Information on the probability of rainfall extremes can be presented in the form of tables, IDF-curves, DDF-curves, formulas where one has to fill in the desired rainfall duration and return time to get the corresponding rainfall, etc. Often they can be transformed into each other.

***Example from Denmark** (case study WATCH): As a general standard, water management systems, e.g. drainage systems, are dimensioned to be able to cope with a 1 in 25 year precipitation event. More specifically, water systems on motorways are designed to manage and drain surface water up to 260L/sec/hectare, corresponding to a 1 in 25 year precipitation event over 10min in Denmark.*

4.2 Check and adjust extreme rainfall statistics currently used or available

It is often difficult to find all the information mentioned in Figure 4.1 if one is not an expert. Therefore, for the countries in the WATCH country comparison report, most information is summarized in Table 2.1. When you cannot find all relevant information, contact an expert (the producer of the statistics/IDF-curves or someone at your national met office, or a specialised meteorological or engineering consultant). Below the various points that should be checked (**step 2**) are mentioned. In the case the required information is not available, it has to be generated or available data has to be adjusted (**step 3**). Some information on this is given below the points that have to be checked.

4.2.1 Is the information for points or for areas?

Most statistics are calculated for points/locations ("point" statistics: chance that a certain amount of rainfall in a certain duration is exceeded at one location; par. 2.2). In the case of water excess due to short duration/high intensity rainfall in most cases this type of information is needed. However, e.g. for culverts that have to let through water from a larger area, one needs area statistics (chance that a certain average amount of rainfall in a certain duration is exceeded in an area of a certain size).

Sometimes point statistics can be transformed into area statistics with the help of general Areal Reduction Factors. Otherwise area statistics have to be derived from gridded point data/statistics derived from radar observations or from a high density rainfall observation network (par. 2.2).

> ***Example from Ireland*** *(http://www.met.ie/climate/dataproducts/Estimation-of-Point-Rainfall-Frequencies_TN61.pdf): In this case it is mentioned explicitly that this document gives point-rainfall-frequencies*
> ***Example from France*** *(http://services.meteofrance.com/images/stories/virtuemart/product/durees_retour_infra_horaire5.png): This does not mention explicitly different sizes of areas. Often this means that it is point-statistics, as it is in this case.*
> ***Example from Denmark*** *(case study WATCH): the statistics mentioned in Table 2.1 for Denmark are point statistics*

4.2.2 What is the reference period on which the available data are based?

The reference period is the period used for calculating the extreme rainfall statistics/IDF/DDF-curves. If there is a trend in the extreme rainfall, it is important to know the reference period, since this indicates how representative the extreme rainfall statistics are for the current climate. Sometimes a combination of observed and simulated data is used, since not enough observed data are available to describe all regional differences with the observed data only. Then it may not be very clear what the reference period of the simulated data was.

If the available extreme rainfall statistics do not describe the required period, than new extreme rainfall statistics have to be generated. For the longer return times sufficiently long time series are needed (or in some situations data from various stations can be pooled) and possibly the statistics have to be corrected for trends in the observed data (see also par. 2.2 and below). It is advised to check the results always with experts, e.g. from your national Meteorological Institute.

When the reference period is 1961-2010 with a significant linear upward trend in this period, the statistics would be representative for the climate around 1985! If there is an upward trend, one makes an underestimation of the rainfall extremes in the "current" climate.

> ***Example from France*** *(http://services.meteofrance.com/images/stories/virtuemart/product/durees_retour_infra_horaire5.png): the period 1961-2014 is used as the reference*
> ***Example from Ireland*** *(http://www.met.ie/climate/dataproducts/Estimation-of-Point-Rainfall-Frequencies_TN61.pdf):* Here rainfall data from 1*941-2004 are used to produce the rainfall statistics shown in the example of what can be obtained from the Irish Metoffice*

Example from Austria: *modelled extreme rainfall at very high spatial resolution and extreme rainfall based on interpolated station data is calculated (*[*http://ehyd.gv.at/assets/ehyd/pdf/bemessungsniederschlag.pdf*](http://ehyd.gv.at/assets/ehyd/pdf/bemessungsniederschlag.pdf)*). The "bemessungsniederslagh" is the average of these two. From the document it is not clear what was the reference period for the station data nor for the modelled data.*

Example from Denmark (case study WATCH): *The statistics mentioned in Table 2.1 for Denmark are based on data for the period 1979-2012. The figure below shows that in this period no significant trend in the maximum daily precipitation is found in the ECA&D database for almost all stations around Copenhagen. There is one station with a significant change, but others do not show a significant change over the period 1979-2017. This makes it unclear whether there is a trend over the period 1979-2012.*

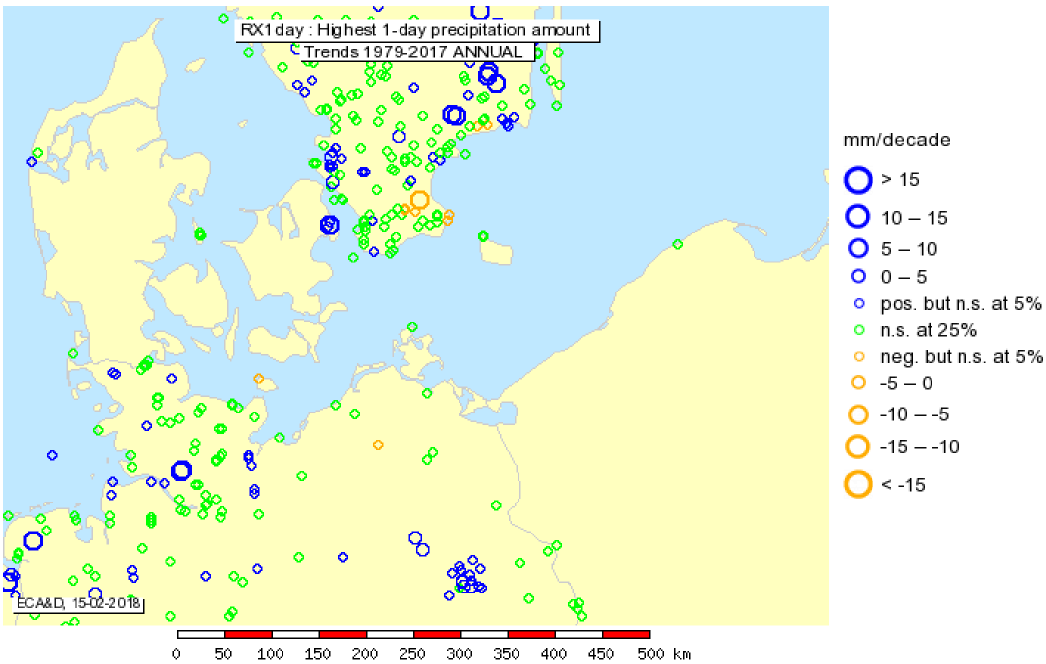

Figure 4.2 Trend in the annual maximum daily rainfall over the period 1979-2017 in Denmark (derived from www.ecad.eu/ on February 15, 2018)

4.2.3 What method is used to generate the extreme rainfall statistics (step 2)?

Statistical methods: In par. 2.2 various methods are described to generate extreme rainfall statistics. Especially in the case of long return times (> about 100 years), check which method was used. When using GPD or GEV distributions the rainfall amounts for the long return times may potentially be underestimated.

Temporal resolution of basic data: It is also important to know what the temporal resolution of the basic data for the extreme rainfall statistics was. Using daily rainfall data for estimating e.g. the once in 10 years rainfall amount for 24 hours will give a lower amount than using hourly rainfall data (par. 2.2).

From point to area statistics: When area statistics are available, check whether they were derived from point statistics with the help of Areal Reduction Factors (ARFs) or whether they are derived directly from available data. The use of general ARFs is not possible in each country when there are large spatial differences in extreme rainfall.

Observations or simulated data: When simulated data are used to determine the extreme rainfall statistics, it is important to know the quality of the simulation. Many climate models still have difficulties simulating well the short duration extreme rainfall events. They often underestimate these rainfall amounts. Climate model data give area average rainfall amounts. Unless the spatial resolution is very high (e.g. 1 km) they cannot be compared directly with point statistics.

4.2.4 How to adjust extreme rainfall statistics (step 3)?

Statistical methods: If the available extreme rainfall statistics do not describe the rainfall amounts for the long return times well, than new extreme rainfall statistics have to be generated with another method (e.g. GLO distribution, see par. 2.2).
Temporal resolution of basic data: If the available extreme rainfall statistics do not describe the rainfall amounts well, because too coarse temporal resolutions have been used, than new extreme rainfall statistics have to be generated with higher temporal resolution data. In some situations the percentage difference between e.g. 24 hour statistics based on daily or hourly data is known. In these cases the statistics can be adjusted easily.
Observations or simulated data: The quality of extreme rainfall statistics based on simulated data of high resolution can be checked by comparing it with extreme rainfall statistics for points or areas based on observed data. These are often not available for the whole area/country, but if the statistics are more or less the same for points and areas distributed over the area/country, the statistics based on the simulated data can probably also be trusted. If this is not the case, than the used climate model has to be improved (iterative process), run again, and rainfall statistics have to be derived again. This will take a lot of time, therefore it may also be an option to use other sources of basic data.

> ***Example from INTACT (for step 2):*** *The website from the INTACT-project shows information on rainfall statistics all over Europe for the near and far future (http://scm.ulster.ac.uk/~scmresearch/intact/index.php/Extreme_weather_maps). The reference period is clearly indicated. The information is based on climate model output without correction for biases.*
> ***Example from ECA&D website and WATCH analogues tool (for step 2)****: the information on return times and related rainfall amounts are based on daily data:* http://www.ecad.eu/Watch/index.php. *Various reference periods in the past can be selected. The base periods used are relatively short (20 years). If in such a period a very high rainfall occurred, this may influence the statistics generated: than higher rainfall depths will be shown for a certain return time than expected on the basis of a longer period.*
> ***Example from the Netherlands (for step 3)****: Based on research of Overeem et al. (2008) we know that the GEV location parameter is about 11-12 % lower for the hourly rainfall in the Netherlands if based on hourly data, compared to the one based on 5 min. data. For the statistics for precipitation per 120 min the difference is about 4 %.This information can be used to adjust existing statistics that are based on relatively coarse temporal data.*

4.2.5 Was there a correction for the trend in the underlying data?

New techniques have become available to correct for trends in observational data. It is difficult to distinguish between natural variability and anthropogenic climate change (e.g. due to change in greenhouse gasses). Therefore, it was difficult to remove the trend due to climate change and at the same time keep the natural variability. With new techniques this can now be done, but it is not yet widely used for the available extreme rainfall statistics/IDF/DDF curves.

First indications about trends in extreme rainfall can be obtained from the following sources:

- Often there are reports on the current climate from the Meteorological institute in your country. They may contain information on trends in average rainfall and maybe also on extreme rainfall. Reports on climate change and climate scenarios per country may also contain information on trends in average and extreme rainfall. For extreme rainfall it is more difficult to determine whether there is a significant change, since by definition, less data are available on extreme rainfall.
- Look at the ECA&D website under “indices of extremes” (http://www.ecad.eu/indicesextremes/index.php). The figures 1.2 and 1.3 show some

examples from this website. It is possible to zoom in on specific countries and locations, to check trends in certain seasons, over different historical periods.

If the available extreme rainfall statistics do not describe the required “current” climate, because there is a clear trend in the observed data, than the statistics should be generated again, but with a non-stationary method (does not assume that the climate is stable). Methods and tools are available for this (e.g. http://amir.eng.uci.edu/neva.php). It is advised to check the results always with experts, e.g. from your national Meteorological Institute.

Example from the Netherlands*: the extreme rainfall statistics for 2 hours up to 8 days were updated in 2015. A correction for the trend was applied to get the statistics for the climate around 2014 (Fig. 4.3).*

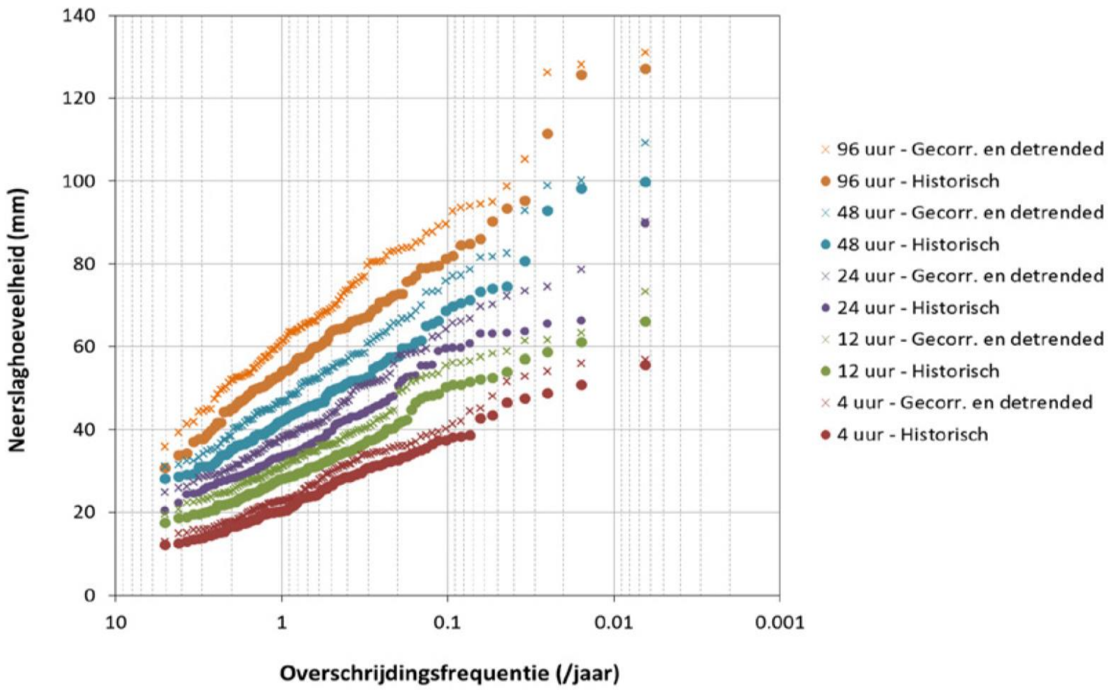

Fig 4.3 *Example from the Netherlands: effect of detrending the period 1906-2014 (“historisch”) to 2014 (“gecorr. en detrended”) on the relation between extreme rainfall amounts (vertical) and return times (horizontal, 1/return time). On average about 10% increase in rainfall amount per return time compared to the situation without detrending and on average a halving of the return times for rainfall extremes.*

Example from Ireland *(http://www.met.ie/climate/dataproducts/Estimation-of-Point-Rainfall-Frequencies_TN61.pdf): This document states explicitly that it is assumed that the “underlying assumption is that the 1941-2004 data used in this study will reasonably represent the upcoming rainfall regime”. However, it is also mentioned that “Given the consensus view that we are in a period of global warming this is not a safe assumption even in the medium term.” “Appropriate adjustments are not included in the estimates of the return period rainfalls as it appears that for quite a number of years into the future the indications of the effects of global warming on rainfall regime will change from assessment to assessment.” This means that no correction for trends was applied.*

Example from Denmark *(Case study WATCH): The statistics for the current climate mentioned in Table 2.1 are for the period 1979-2012. Figure 4.2 shows that based on the ECA&D website there were no significant trends in this period for the annual maximum daily rainfall. Although no information is available on trends in the shorter duration rainfall extremes, the first impression is that there is no direct need to adjust these statistics for trends.*

4.2.6 For which rainfall duration and return times are extreme rainfall statistics available?

Check for which rainfall durations and return times information on rainfall depth is available. Since the temporal resolution of the basic data for the very short durations and for the longer durations may be different, not always the same type of information may be available for all rainfall durations.

Sometimes estimates for missing rainfall durations or return times can be made by simple extrapolation of existing statistics. However, be careful with too much extrapolation. As described in par. 2.2 for very long return times it may be better to use different statistical distributions. Be also careful with extrapolation to the very short rainfall durations! As explained in par. 2.2 the temporal resolution of the basic data for the statistics is important: statistics about the extreme rainfall per hour (moving 60 min window) should be based on e.g. 5-15 min time series.

> ***Example from the Netherlands (for step 2)***: *information for durations of 2 hours and longer is available through www.meteobase.nl/. For these statistics hourly rainfall data were used. For the shorter duration a much higher temporal resolution of the rainfall data is needed (e.g. 10 min). Therefore, the statistics for these durations were generated in a separate project (Beersma et al., 2018).*

4.2.7 What is the format in which the extreme rainfall statistics are available?

The required information on extreme rainfall is often available in the form of tables or IDF curves. Information in tables can be presented per rainfall duration or return time.

In principle, IDF-curves can be derived from the tables with the extreme rainfall statistics. In some cases formulas are available with which the return times for certain rainfall extremes can be calculated, or with which the rainfall amounts for certain return times can be calculated.

> ***Example from France:*** *formulas are available for which the rainfall corresponding to a certain rainfall duration and return time is produced, the Montana-formula: $h(t) = a \times t^{(1-b)}$, in which t is the rainfall duration in minutes, h is the rainfall amount in mm, and a and b are the Montana-coefficients. The coefficients for this “Montana” formula are derived for the reference period of the station (variable according to the station and the required return periods) for rainfall durations between 6 min to 48 hours (variable ranges according to the user demand and with a tipping point / pivot point if needed) for return times weekly to once per 100 years (usually : 1 and 2 weeks, 1, 2, 3 and 6 months, 1, 2, 5, 10, 20, 30, 50 and 100 years). The “Montana”-coefficients are derived for each location separately.*
>
> ***Example for UK and Ireland****:* Volume 2 of the Flood Estimation Handbook presents the methods for estimating rainfall frequency in the UK. The user obtains results from a model of rainfall depth-duration-frequency. The procedure is built on rainfall growth factors, which relate the rainfall depth of a given return period to an index variable. Growth factors derive from the Focused Rainfall Growth Extension (FORGEX) method, which gives precedence to rainfall extremes observed locally and takes account of inter-site dependence in rainfall extremes to get estimates for long return periods.

4.3 Calculate derived information

On the basis of the rainfall statistics, extreme runoff can be estimated with the purpose of determining the required design (**Step 4**, optional). Within the context of this project for road design and maintenance, we are concerned only with runoff alongside the roads (related to road ditches), as well as culverts under the roads. Bridges are not considered as part of the drainage of roads and drainage of runoff directly around the road, but rather for larger streams and rivers.

There are two main approaches for estimating extreme runoff in drainage design and maintenance:

- When runoff data based on a water level gauge is available, estimates can be made based on recorded discharge extremes (volumes). This is done using the correlation between stage level (h) and discharge (Q); so-called Q-h relationship. This approach is most precise, and is preferred. Typically, these data are available for larger drainage areas and in more urban locations. The approaches used here are commonly referred to as extreme value analyis, to estimate the required design dimensions. These methods are standard practice, and are not further discussed here.
- When no runoff records are available, methods are available to estimate runoff. This is typical for smaller catchments, and rural locations. Runoff can be estimated using the IDF curves (see previous sections), as well as information on chatment characteristics, and evaporation.

Runoff estimation methods for this second purpose, commonly applied in different European countries, are listed in Table 4.1 below. These methods were found and reported in the country comparison analysis.

Table 4.1 Methods for extreme runoff estimation, and commonly applied design standards (source: Bles et al., 2017).

Country	Asset	Design standard	Runoff calculation methods
Austria	Culverts	100 year return period (duration depends on catchment area)	**Prandtl-Colebrook**
United Kingdom	Ditches	75 year return period	**IH 124 Method** for catchments > 0.4 km^2 **ADAS Method** for catchments < 0.4 km^2
	Culverts	For catchment areas >50ha and 100 year return period in England and Wales, and 200 year return period in Scotland	**Rainfall transformation methods based on runoff coefficients** Method from the Flood estimation handbook (Institute of Hydrology, 1999) for drained areas > 50 ha
France	Ditches	Ditches are sized for those implemented at crest of cut embankments (return period 100 yr)	**Rational method** based on IDF curves. Hydraulic calculation: **Manning-Strickler equation**
	Culverts	Return period 100 years (plus check 1.5*Q100). There is no prevailing duration of precipitation in design as the time of concentration is calculated for each watershed.	Hydrology: **rational method** and **Crupedix method** and IDF curves for non-gauged catchments; Hydraulics: **Manning-Strickler equation** (preliminary design); Bernoulli and energy equations (detailed design)
Ireland	Ditches	Mean annual runoff for 75 year return period.	**IH 124 Method** for catchments > 0.4km2 **ADAS Method** for catchments < 0.4km2
	Culverts	Annual peak runoff for 100 year return period, plus (typically 300mm) freeboard (UK CIRIA C689 culvert design guide).	**Rainfall transformation methods based on runoff coefficients**
Nether-lands	Ditches	Roads in fill and bridges 10 years; roads in cut 50 years; tunnels 250 years	No information
	Culverts	Requirements for culverts are given by the water boards.	Requirements for culverts are given by the water boards.
Norway	Ditches	For existing structures often no information available about the design method or design capacity 200 year return period (highways)	Rational method and IDF curves. Revised guidelines (coming up soon) include several other methods, distinguish between catchment

Country	Asset	Design standard	Runoff calculation methods
		50-100 year return period (other roads).	characteristics.
	Culverts	Annual peak runoff for 100 year return period, plus (typically 300 mm) freeboard (UK CIRIA C689 culvert design guide).	IDF curves No further information
Sweden	Culverts	50 year return period, in some cases 200 year return period.	No information
Denmark	Culverts	25 year return period (highways); 10 to 25 years return period for other roads.	No information

What is clear from this table is that many countries have adopted their own methods for runoff estimation when no runoff gauge data is available for estimation of extreme runoff. However, most use very similar approaches, based on observed rainfall (extremes), and catchment characteristics (see table). Most methods also use IDF curves as key input, to determine design storms, or at least rainfall values based on IDF curves for the relevant return periods and rainfall durations, required for the design.

Regarding design standars, for culverts the 100-year return period runoff (the 'design runoff', related to a particular storm event) is most often used. For ditches, not all countries have standards, but countries with standards for ditches use ranges of some 50 to 100 years.

As discussed in par. 2.2, point statistics may overstate the amout of rainfall over large areas, and area reduction factors can be applied to account for this. For draigane design of culverts, point statistics are most often sufficient, and no area reduction factors are required, as these play only a role in catchment sizes of 6 km^2 and larger.

The basic steps involved in an analysis for culvert design are listed here below. Typically, for culverts draining small catchments, a calculation will be made using empirically derived functions, to calculate design runoff that need to be accommodated. These steps include:

- Derive the IDF curve using methods described in par. 4.2.
- Determine the required return period and corresponding rainfall intensity; for most culverts this is the 50, 100 or 200 year runoff).
- Calculate the design runoff using the empirical formula. Most methods use several parameters, which can include:
    - Catchment surface area;
    - Parameter for soil characteristics (infiltration);
    - Time of concentration, which is derived empirically from catchment length and slope.
- Freeboards and other factors are added for safety.

5 Generation of extreme rainfall statistics for the future climate

It is generally anticipated that rainfall extremes will increase with global warming - a statement which was assigned high confidence in the latest IPCC report (IPCC, 2013). The theory behind the intensification of rainfall is that as the climate warms more moisture will be available to a rainstorm, and this will cause more extreme precipitation. In the absence of substantial changes in relative humidity, the moisture content of the air will rise by 6–7% per degree temperature rise following the Clausius–Clapeyron relation. However, as shown in paragraph 2.3 for sub-daily rainfall extremes (mainly convective situations) several studies have shown larger increases than expected based on the Clausius–Clapeyron relation.

The protocol for extreme rainfall information for the **future** climate consists of the following steps (Figure 5.1):

1. What rainfall information needed for the future?
2. What rainfall information is already available for the future? (Tables 2.1 and 2.3)
3. Determine relation between daily and sub daily extreme rainfall and (dew point) temperature based on observations
4. Select relevant climate scenario(s) for the future
5. If not available, determine change of daily and sub daily rainfall extremes in relation to dew point temperature with climate model data for the relevant climate scenario(s) and time horizon
6. Determine the change in dew point temperature between the period used for the period of interest for the climate scenario(s) of interest
7. Synthesis of information on change in extreme rainfall statistics for the future climate
8. If relevant, calculate derived variables such as run-off for the future

You may not be able to perform all steps (step 3 and 5). In the description per step below, suggestions are given what you can do in these cases.

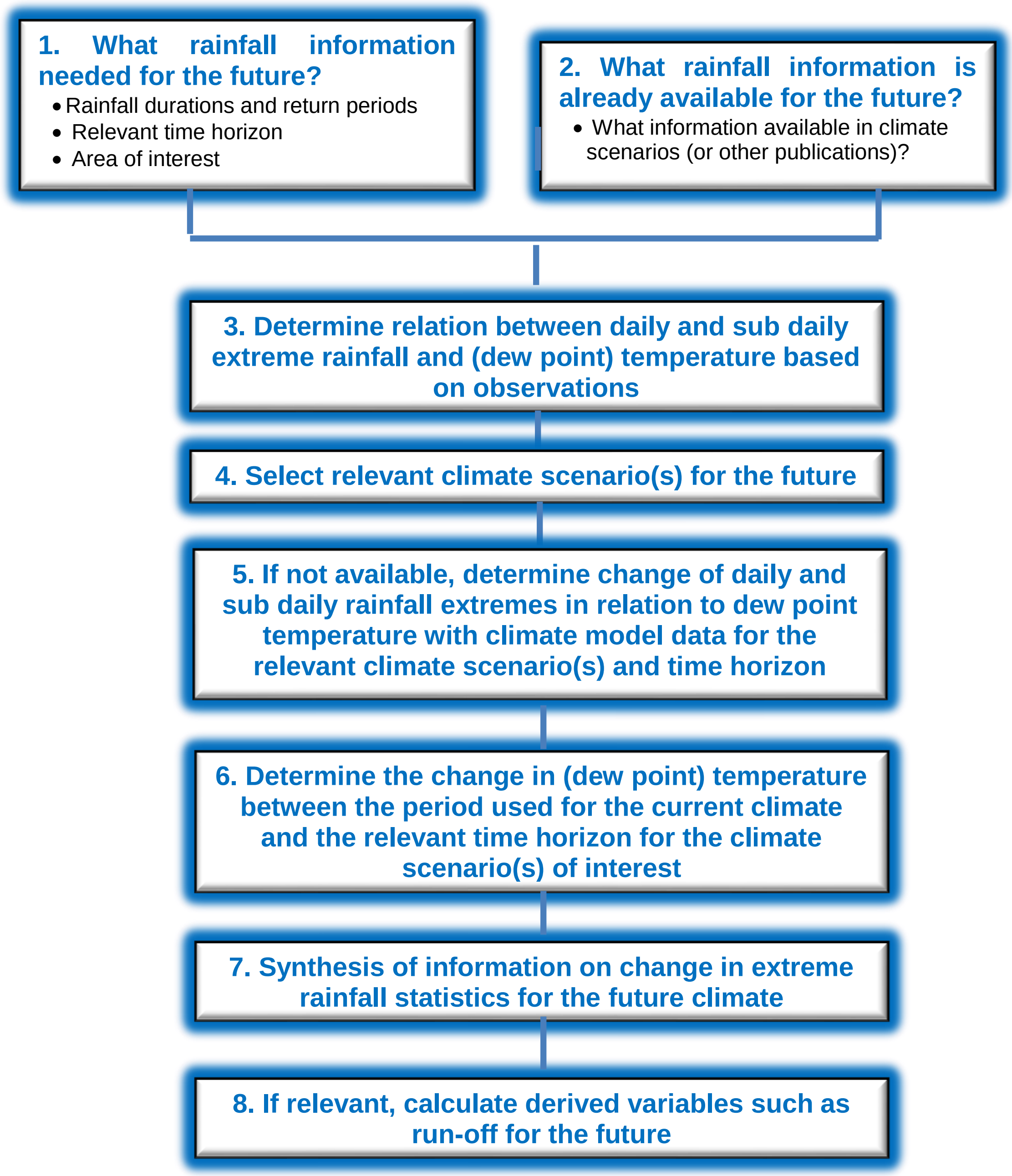

Figure 5.1. Schematized approach to estimate possible changes in sub daily and daily rainfall extremes in the future.

Most available climate models have a spatial resolution that is too coarse to simulate convective rainfall well. Climate scenarios are based on climate model projections for the future. Most climate scenarios mentioned in Table 2.1 do not contain information on changes in sub daily rainfall extremes or they assume implicitly that these sub daily extremes change in the same way as the daily extremes. Below we describe a procedure to estimate the (range of) possible changes in sub daily and daily rainfall extremes in the future and how to process this information into a usable format. Figure 5.1 shows the schematized approach. In the next subparagraphs the various steps are explained in more detail. This approach is based partly on the approach described by Lenderink & Attema (2015). They set the changes in precipitation extremes proportional to the change in water vapour amount near the surface as measured by the 2m dew point temperature (see par. 2.3). This simple scaling framework allows the integration of information derived from observations and climate models and thus combines the advantages of both observations and climate models, but avoiding the disadvantages.

It is advised to check the results always with experts, e.g. from your national Meteorological Institute.

5.1 What information on rainfall extremes is needed for the future and what is available already?

5.1.1 What rainfall information needed for the future?

In most cases the same or very similar information is needed for the future as was used for the current climate. Therefore, most information for this **step 1** is already collected during step 1 in the protocol for the current climate

Rainfall durations and return periods: probably the same is used as for the current climate (see chapter 4)
Relevant time horizon: the relevant time horizon can be determined on the basis of the design life, expected life cycle or standards set by the NRA.

> ***Example:*** *When designing a culvert (expected life cycle for concrete structures around 50 years), the relevant time horizon is somewhere around 2070 (current year + 50 including also the time needed to design and built the culvert.*

Area of interest: the current climate and climate change may not be the same everywhere in a country, therefore it is good to determine the area/region of interest. Differences in climate and climate change are gradual over a country and Europe. Therefore, look at the region that is comparable with the location that you are interested in.

5.1.2 What rainfall information is already available for the future?

For **step 2** table 2.3 gives an overview of what information is available on rainfall extremes in the climate scenarios currently available in a number of European countries. Also information is given on the reference periods and time horizons in these climate scenarios. In general, limited information is available on daily extremes in the form used for road design, and for sub daily rainfall extremes hardly any information is available. Check also on which data information on rainfall extremes is based. Most climate models cannot simulate correctly the small scale (convective) extreme rainfall events. Therefore, climate scenarios often do not contain information on short duration rainfall extremes. Scaling with available data such as temperature can be used. This will be explained in later steps.
If the climate scenarios do not contain information on rainfall extremes, sometimes in other sources estimates on changes of the extreme rainfall amounts per return time are available.

> ***Example from Denmark (for step 2)*** *(case study WATCH): In the document on https://ida.dk/sites/default/files/svk_skrift30_0.pdf?_ga=2.138825715.1982837567.1497872368-1856766300.1497872368 the table with factors for generating future rainfall extremes are presented, compared to the rainfall statistics for the current climate (1979-2012). Tables are given for 50 and 100 years ahead. Standard factors and high (høj) factors are presented.*

Table 5.1. Recommended climate factors for Denmark based on three scaling methods, 17 climate model runs and five emission scenarios, time horizon 100 years ahead (100 års horisont). Vertical: return times (hændelse). See also text for link and explanation.

	50 års horisont		100 års horisont	
	Standard	høj	Standard	høj
2-års hændelse	1.1	1.23	1.2	1.45
10-års hændelse	1.15	1.35	1.3	1.7
100-års hændelse	1.2	1.50	1.4	2

Example from the Netherlands (for step 2): *After the publication of the KMI'14 climate scenarios, the limited information on the rainfall extremes was translated into rainfall statistics for the future (around 2050 and 2085, besides an update of the statistics for the current climate). The information can be found among others through www.meteobase.nl/.*

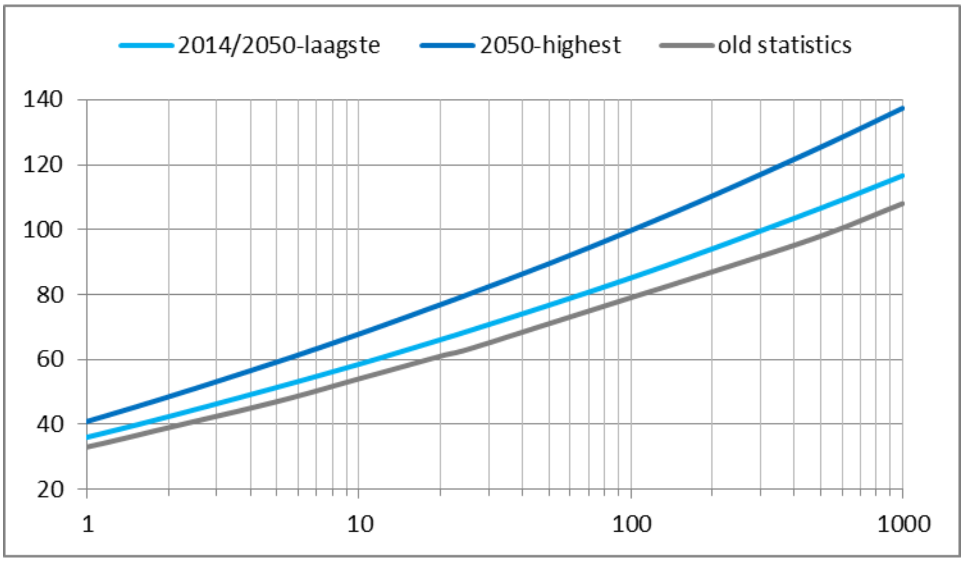

Figure 5.2. Rainfall statistics for the Netherlands: rainfall amounts for various return times for a duration of 24 hours. Vertical: rainfall amounts in mm; horizontal: return time in years. Grey line: old statistics from 2004, light blue: updated statistics for around 2014 (almost the same as the lowest scenario for around 2050), dark blue: extremes in the scenario with the highest changes in rainfall extremes around 2050.

Sometimes information on sub-daily extreme rainfall events in the future may be available for a country, but not included in the climate scenarios. Check with your local provider or national meteorological institute if such information is available.

5.2 Determine relation between rainfall extremes and (dew point) temperature in observations

If the required information on rainfall extremes is found directly in projections in your country (step 2), you can use these extremes and skip this step 3.

If not available, information from climate models and observations can be used to estimate the range of possible changes in the future (largely based on the approach of Lenderink & Attema (2015) par. 2.3). In this **step 3** first the relation between rainfall extremes and (dew point) temperature in observations is determined.

Research on observations shows that in several countries the rainfall extremes on hourly basis increase stronger with (dew point) temperature increase than the rainfall extremes on daily basis. For higher temperatures increases of up to 14% per ˚C for hourly extremes are observed. The turning point is approximately at a daily average temperature of 10-14 ˚C or an average dew point temperature of 6-10 ˚C (par 2.3). Increases in rainfall extremes can be better explained when using dew point temperature than when using temperature, since dew point temperature directly measures moisture instead of the maximum water holding capacity (as with temperature).

If possible, check what is the local/regional relation in observations between daily extreme rainfall (on wet days) and (dew point) temperature and do the same for sub daily extreme rainfall (in many cases hourly data are available). E.g. Lenderink & van Meijgaard (2010) decribe how this can be done to get figures such as in Figures 2.6 up to 2.8. As mentioned in par. 2.3 in several countries the 2 times Clausius–Clapeyron relation (2*7=14% increase) is found for the sub daily extreme rainfall above certain (dew point) temperatures. However, there may be confounding factors (such as seasonality in circulation conditions) influencing the scaling relations that will be found in observational data.

The information needed for this analysis:

- Time series on temperature (daily and sub daily values)
- Time series on dew point temperature (or relative humidity[23]; daily and sub daily values)
- Time series on rainfall (daily values and sub daily values)

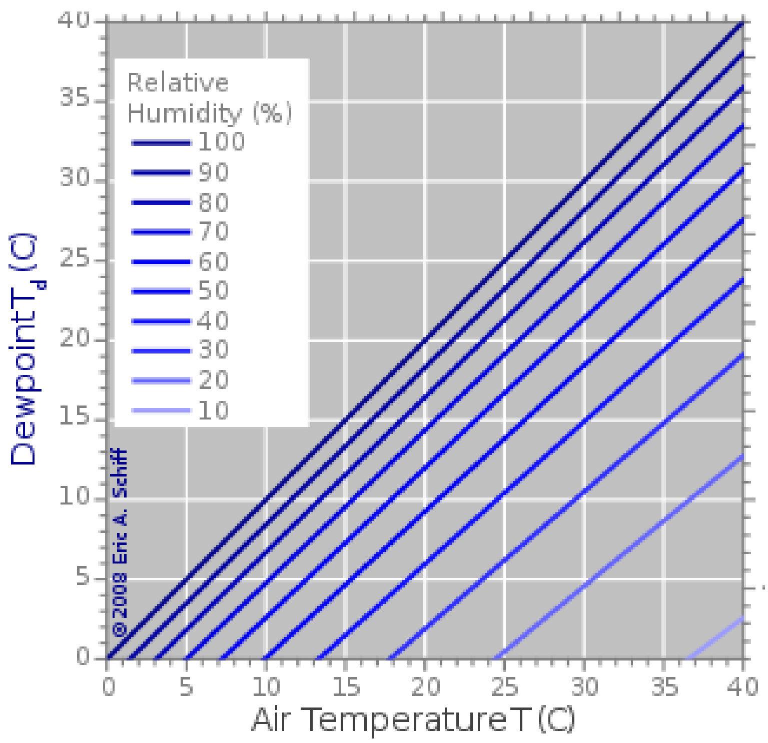

Figure 5.3 Dew point temperature as a relation of air temperature and relative humidity.

If information on relative humidity is not available, the analysis can also be performed with air temperature, although the relation between temperature and extreme rainfall is probably not as clear (see figure 2.6). This may not be a problem if one can assume that the relative humidity has hardly changed (< a few %).

If the time series on extreme rainfall are not available, one can assume as a *first estimate* for the north-western and northern part of Europe that the relations found by e.g. Lenderink & Attema (2015) also apply for your region of interest. The increase of about 14 % increase per

[23] Dew point temperatures can be calculated from temperature and relative humidity data.

°C (dew point) temperature increase can then be used as the upper limit of the change in short duration extreme rainfall above certain temperatures. For the southern and south eastern part of Europe the relations may apply, although especially when summers become dryer the air may not contain enough moisture. If it is expected that relative air humidity will decrease more than a few percent, than the dew point temperature may increase less than the air temperature. In case of decreases in relative humidity the changes found by Lenderink & Attema may not apply.

5.3 Select the relevant climate scenario(s) for the future

The potential changes in extreme rainfall do not have to be determined for all available climate scenarios or projections in your country, but only for the one or ones relevant for you (**step 4**). Which scenario(s) are relevant, depends on the approach/strategy you use (see chapter 3). When you want to take into account the worst case, select the climate scenario or projection in which the highest change in extreme rainfall on daily or sub-daily level can be expected. If the scenarios do not contain explicit information on this, it is the scenario with the highest change in dew point temperature in the period of the year where you experience now already the highest extremes. A scenario with the strongest increase in air temperature, but with a clear decrease in relative humidity, may not be the scenario with the strongest increase in dew point temperature.

> ***Example from Denmark*** *(case study WATCH)***:** *suppose you want to take into account the worst case situation for a road, since it is an important road and you would like to minimize the risk of problems due to local flooding. In that case it would be logical to select the factors under "høj" (high) in Table 5.1 above. If the expected life time of the drainage system for the road is about 50 years, take the factors under the time horizon of 50 years.*

5.4 Determine relation between rainfall extremes and (dew point) temperature in climate models

If the required information on rainfall extremes is found directly in projections in your country (step 2), you can use these extremes and skip this **step 5**.

If not, use the correlation with (dew point) temperature as described in the approach of Lenderink & Attema (2015; par. 2.3). For this, if possible check what is the regional relation in the climate model data used as basis for the climate scenarios between daily extreme rainfall (on wet days) and dew point temperature and do the same for sub daily extreme precipitation, as for the observations described in par. 5.2 (see also figures 2.6-2.8).

If information on relative humidity is not available or not easy to get, the analysis can also be performed with air temperature, although the relation between temperature and extreme rainfall is probably not as clear (see figure 2.6).
If one has no possibility or limited possibility to analyse the climate model data, one can also assume for this step that the change in daily extremes (see table 2.3) also applies to sub-daily extremes (see also Lenderink & Attema (2015) for relations in climate models). This is only possible when information on daily extremes is available in the climate scenarios.

Realize that the average rainfall can decrease in a season in the future, but at the same time extreme rainfall may increase in that season.

5.5 Determine the change in (dew point) temperature over the relevant period

If the required information on rainfall extremes (with correct time horizon and reference period!) is found directly in projections in your country (step 2), you can use these extremes and skip this step.

If not, in this **step 6** the change in (dew point) temperature over the period of interest will be determined. The period used for the description of the extreme rainfall statistics for the "current" climate (Chapter 4) may not be the same as the reference period used in the climate scenarios for your country or region. This difference should be taken into account to determine the change in (dew point) temperature between your "current" climate and the relevant time horizon in the future (step 4).

> ***Example:*** *When the information for the "current" climate that you use is representative for e.g. the climate around 1970 and the reference period for the climate scenarios is 1981-2010 (representative for climate around 1995), the approximate change in (dew point) temperature between 1970-1995 should be added to the change in (dew point) temperature that the climate scenarios give until the relevant time horizon (e.g. 2 °C up to 2050). A first indication of the change in temperature for the period 1970-1995 can be obtained with the help of the ECA&D website by determining the trend in temperature for your region from about 1951 until now. From this the approximate change in temperature for the shorter period can be determined. Check also whether rainfall or humidity has decreased significantly, in order to get an idea whether the change in dew point temperature may be clearly less than the change in temperature.*

Climate scenarios often give the changes for specific time horizons or periods[24] in the future. When you are interested in a time horizon in between these given time horizons in the climate scenarios, linear interpolation gives you a reasonable estimate of the temperature change until your time horizon of interest (even though the climate will not change linearly).

> ***Example for the Netherlands****: In the KNMI'14 climate scenarios information on changes is given for the time horizons 2050 and 2085 compared to the reference period 1981-2010. If you are interested in the time horizon 2070 and the scenario with the highest increase in rainfall extremes in summer (W_L scenario), the local temperature change for 2050 and 2085 is respectively +1.7 °C and +3.2 °C. The estimated temperature change for 2070 is than +1.7 + (2070-2050)*(3.2-1.7)/(2085-2050) = 2.6 °C. In this scenario the relative humidity will hardly change in summer (*http://www.klimaatscenarios.nl/toekomstig_weer/transformatie/Toelichting_TP.pdf*: about 0.2 % in summer months June-August), therefore it can be assumed that the change in dew point temperature is more or less the same as the change in air temperature.*

5.6 Synthesis of information for extreme rainfall statistics for the future climate

In this **step 7** the information from steps 3 to 6 is combined to get the (range of) potential change in the rainfall extremes, similar to the approach described by Lenderink & Attema (2015). Observations do have the advantage that they do not have to rely on assumptions, but they are often difficult to interpret (e.g. due to trends) and they cannot always be

[24] E.g. if the period 2041-2070 is given for the future, this can be considered representative for the climate around 2055).

extrapolated far into the future. Regional climate models do take into account many aspects of climate change that may influence the changes in (extreme) rainfall (e.g. temperature, humidity, circulation). Since they simulate long periods they also allow us to look at the changes in rare events. However, they do not all represent the small scale short duration extreme rainfall very well. By combining the information from observations and climate models the advantages of both sources are used, while avoiding the disadvantages. Lenderink & Attema (2015)[25] use the range in extreme rainfall presented by models and observations. Often, climate model projections of the extreme rainfall changes per °C dew point temperature change show the lowest changes, and the extreme rainfall changes per °C dew point temperature change in the observations show the highest changes.

To get the range of possible change in extreme rainfall compared to the rainfall statistics that is used now for the "current" climate (point statistics):

- Lower limit: multiply the lowest % change per °C change in (dew point) temperature with the expected change in (dew point) temperature over the period of interest (step 6), but take into account the (dew point) temperatures throughout the year). The lowest percentage is often obtained from step 5, from the climate models, but not always;
- Upper limit: multiply the highest % change per °C change in (dew point) temperature with the expected change in (dew point) temperature over the period of interest (step 6), but take into account the (dew point) temperatures throughout the year). For the short duration extreme rainfall the highest percentage is often obtained from step 3, from the observations, but not always.

The figure below shows the ranges used by Lenderink & Attema (2015) for the 99% on wet days[26]. For other countries the ranges may be different, since the temperatures may be higher or lower (see par. 2.3 for thresholds above which the stronger temperatures can occur, but also look at the results form step 3 for your own region). In the Scandinavian countries winter temperatures are lower than in the Netherlands. Therefore, it can be assumed that in winter the chance of crossing threshold dew point temperatures of 6-10 °C is clearly lower than in the Netherlands. It is therefore logical to have lower upper values for the changes in winter. For countries with higher temperatures than the Netherlands this can be the other way around.

As can be seen in the figure below, Lenderink & Attema (2015) did not always use the exact lower or highest changes from observations and models. They also used expert judgement to determine the ranges. It always may be useful to discuss the range that you want to you with an climate expert.

[25] The method used by them is more complicated and also includes the use of high resolution climate model simulations.

[26] The 99-percentile on wet days may coincide with different return times in different countries and seasons. In the Netherlands on average 50% of the days has some rainfall. When looking at 30 years of observations for the summer season, there will be approximately 1350 wet days (0.5 * 30 years * 90 days). The 99-percentile will be described by the 13-14 highest rainfall amounts. For the summer season (June-August) this will be an event that happens approximately once in 3 years (13-14 times in 30 years). Consequently, the 99.9-percentile will be an event that happens approximately once in 30 years. The 90-percentile will be an event that happens approximately 4.5 times a year.

Table 1. Scaling constants used for daily and hourly precipitation extremes (P99w) in % per degree dew point for summer and winter (first column), in comparison with results from RACMO, Harmonie, and observations. The last column provides additional information, provided when the α range does not correspond to the range given by RACMO2 and Harmonie (indicated by bold, italic numbers in second column).

	Scenario range α (% °C^{-1})	RACMO2 (% °C^{-1})	Harmonie (% °C^{-1})	Obs. (% °C^{-1})	Additional information/expert judgment
DJF daily	4–8	5–7	—	~7	Possible influence North Sea, increases in CAPE
DJF hourly	5–9	5–7	—	~7	increases in CAPE
JJA daily	2–12	3–5	7–12	~7	
JJA hourly	7–14	6–8	7–14	10–14	RACMO2 limitations

Figure 5.4. The table from Lenderink & Attema (2015) with the ranges of changes in extreme rainfall events in the Netherlands. The changes under "RACMO2" and "Harmonie" are changes from climate models, "Obs" stands for observations.

The information from the former sub paragraphs gives information on changes in specific percentiles, although often return values are used for far more extreme rainfall events (much higher percentiles). These return values can often not be determined directly from the available model data (and also often not very accurately from the available observations). In general, it is assumed that the higher percentiles change in the same way as the 99 percentiles. By analysing also the 90 and 99.9- percentiles in the analyses in par. 5.2 and 5.4 one can get an idea on how good this assumption is.

> ***Example:*** *If the change in dew point temperature is 2.6 °C between the "current" climate used now and the time horizon of interest (e.g. 2070) in the climate scenario of interest, the range of change in the extreme daily and sub daily rainfall in summer using the information from Lenderink & Attema (2015) would be:*
>
> - *Daily rainfall extremes: 2*2.6 – 12*2.6 = 5 – 31 %*
> - *Hourly extremes: 7*2.6 – 14*2.6 = 18 – 36 %*

Information on changes in rainfall durations shorter than 1 hour is generally not available from climate models, and often limited information is available from observations. Therefore it is assumed that the range of change for hourly rainfall extremes can also be applied to sub hourly rainfall durations. If observational data for sub-hourly rainfall durations are available it can be checked with the approach described in par. 5.2 if this assumption is correct.

In the case there is information available on rainfall statistics for the future or on factors to use for the future, one can also check whether this information is in line with expected temperature changes.

> ***Example:*** *Assume one expects a temperature change of 4 °C during the life time of an asset, and it is advised to use and additional 30 % above the hourly rainfall amounts for specific return times to take into account climate change. If the climate in the region under study is comparable with the Dutch climate, this would probably result in an underestimation of the extreme hourly rainfall at the end of the life time of the asset. In the Netherlands the observed increase in hourly rainfall with 1 °C temperature increase is about 10-14%. With 4 °C temperature increase, the increase in extreme hourly rainfall could be about 40-56%.*
>
> ***Example for Denmark*** *(case study WATCH)**:** in the most recent document on climate change in Denmark (http://www.dmi.dk/fileadmin/user_upload/Rapporter/DKC/2014/Klimaforandringer_dmi.pdf) the estimated increase in temperature is 1-2 °C for around 2045-2065 compared to 1986-2005 and 1-3.7 °C for 2081-2100. The available rainfall statistics for the current climate are based on the period 1979-2012, which does not differ too much from the reference period of the climate scenarios. The climate of Denmark resembles a lot the climate in the Netherlands. If we use the observed changes in the Netherlands to make*

a first check on the factors in Denmark (assuming no clear change in humidity), we would expect a 10-28 % change for around 2045-2065 for extreme hourly rainfall, or factors ranging from 1.1 to about 1.28. The highest factors used in Denmark are higher (1.23-1.5), and for the period 2081-2100 the factors recommended for Denmark (1.2-2.0) are also higher than based on the estimate with the observed changes in the Netherlands (10 – 52 %).

5.7 Calculate derived variables for the future

In this optional **step 8** the run-off can be calculated from the information in step 7. As explained in Section 4.3, two alternative methods exist to estimate runoff extremes. These were based either on actual observed discharge records, or estimation methods based on rainfall and catchment characteristics.

For estimating future runoff extremes, the estimates from these two methods can be transformed.

To get an idea how people deal with the estimated future rainfall extremes that you expect for your region, one can use the Climate analogues tool to find regions where your estimated rainfall extremes occur already. The tool and how to use it is described in Chapter 6.

5.7.1 Empirical runoff estimation

With the estimation methods that are using rainfall data as input, use can be made of the projected change in extreme rainfall, as explained previously in par. 5.6 and corresponding revised IDF curves. Table 2.6 indicates which countries include climate change in their guidelines, according to the country comparison report. The basic steps involved in such an analysis are provided in par. 4.3.

5.7.2 Estimation using runoff observations

The method using observed runoff data to estimate runoff extremes needs to make assumptions about the relation between rainfall change and runoff change. In many European countries, such assumptions about changes in extreme runoff are made. For instance, in the UK and Ireland, a fixed 20% increase in design runoff conditions is applied to observed (or estimated) discharges. This is an assumption, rather than based on estimated changes in rainfall and actual runoff. Also, such changes are dependant not only on rainfall intensity changes, but also changes in rainfall regimes, changes in soil moisture conditions and evaporation that may alter catchment response, especially in larger gauged catchments.

As a general rule, it is advised to apply a percentage increase in design rainfall, per degree centigrade projected warming. If no information is available on the change of daily or hourly rainfall the protocol can be used to make an estimate of this based on observations and climate model results (chapter 5). The protocol mentions up to 14% increase per degree centigrade warming for hourly extreme rainfall. This additional rainfall, derived from an IDF curve, can be translated to additional runoff for the known catchment size.

This is a maximum estimate that will result in a conservative design, assuming that all additional rainfall is translated to runoff. This rule is a first order approach only, and should be applied with caution, as local conditions may require alternative changes to be taken into account. For instance, in larger catchments where time of concentration is long, soil conditions allow infiltration, and in larger catchments (larger than ~0.5 km^2), applying an analysis using empirical functions (see above) is worthwhile, to avoid an overly conservative design.

6 Climate analogues tool

6.1 Introduction

Aim/objective: find stations that show analogue values in the current climate for extreme rainfall indices that you may expect in the future for your region of interest. This may help in finding locations where you can look how others deal with the extreme precipitation amounts that you expect in the future.

Source of data: This tool is based on daily station data available for the ECA&D website. This analogue tool is developed for statistics on extreme rainfall, but it can be used also to get analogue stations for the other available climate indices in the ECA&D database[27].

Type of analogues: Analogues can be found for two types of climate indices:

- Return values: extremes that are surpassed once in 1, 2, 5, 10 or 20 years, based on daily time series. As default rain related climate indices are shown. The most relevant indices for the WATCH project are probably the “1-day and 5-day precipitation amounts”, but also other rain related indices are available.
- Climatology values: average values over longer periods (e.g. 30 years) for various climate indices (e.g. average annual rainfall), also based on daily time series.

Where to find it? The WATCH climate analogues tool can be found through the following link: http://www.ecad.eu/Watch/index.php.

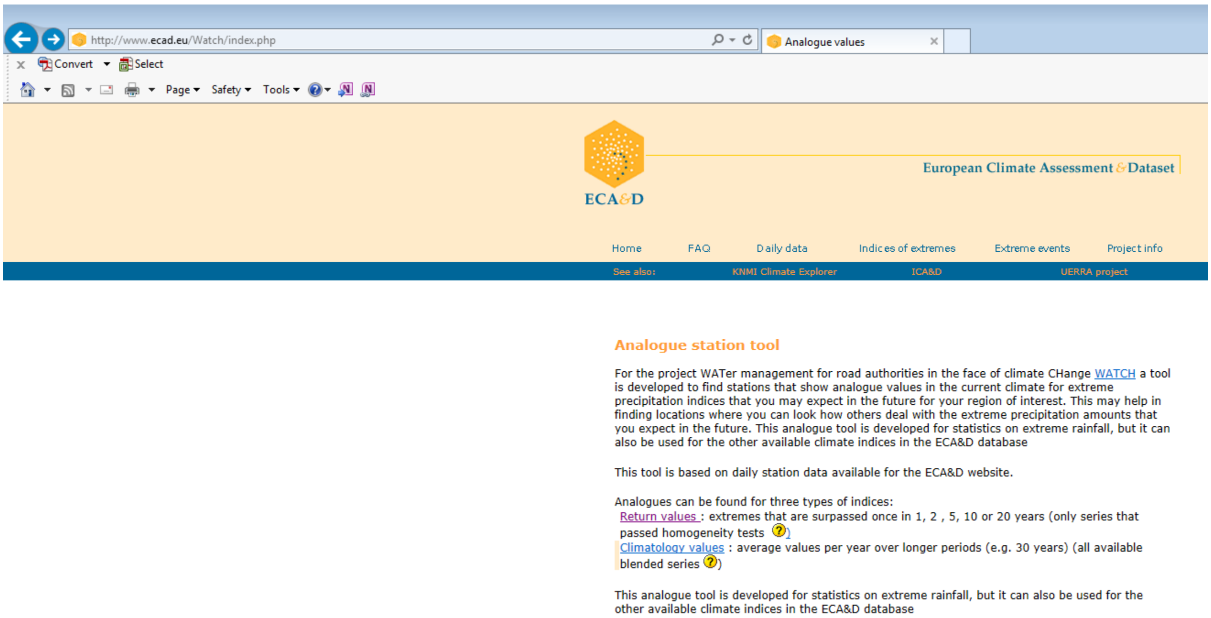

Figure 6.1. First page of the WATCH analogues tool

Below more information is given on the background of the data and the tool, a more detailed guidance is given and information on the interpretation of the maps is presented.

[27] Since the WATCH climate analogues tool is based on the ECA&D website, the data and methods behind it are automatically updated. This assures the continuity of the product.

6.2 Sub daily and daily rainfall extremes and the importance of the basic data for the statistics

6.2.1 Daily and sub daily rainfall extremes

In the ECA&D data base only daily data are available. Daily observational data are available in all European countries, although not always freely available. Hourly observational data are much scarcer, and there is no database with observed hourly precipitation data for a large number of European countries. Therefore, in this analogues tool we can only show daily extremes. The extremes (rainfall depths) for sub daily periods are, of course, lower than the extremes for daily extremes. However, the form of the distributions is very similar for the daily and sub daily extremes (see figures below), but the difference between e.g. the hourly amounts and the 24 hour amounts may differ per region or country. This may be due partly to the main type of rainfall that causes the extreme rainfall events.

Rainfall always occurs from clouds. The cooling of the air necessary for cloud formation takes place in the atmosphere by the upward movement of air. The main causes for this upward movement are convection and fronts:

- For convection it is usually necessary for air to warm up at the earth's surface. Air expands when it warms. The density of the air decreases and locally warm air bubbles will move upward. When moving upward, the air will cool again. When the air is moist enough clouds are formed. When the conditions in the atmosphere are favourable, then the air can rise up to high altitudes. This way strongly developed vertical clouds can develop from which intense rain can fall down. These kinds of systems are called "showers" or convective precipitation systems. Often the rainfall is of short duration and intense and sometimes the rainfall is combined with hail or thunder.
- A front is the separation between two air types with a different temperature. The fronts move under the influence of the air circulation. When the warmer air type expels the colder air type, we speak of a heat front. In the opposite situation we speak of a cold front. Due to the lower air density of warm air, it will move over the cold air, causing clouds and rainfall. The upward movements in a front are much slower and less local than with showers. When a rain front passes a region it often rains for several hours from a completely cloudy sky. The rainfall intensity is usually much lower for fronts than for showers.

The difference between the daily and hourly rainfall amounts for the various return times may differ also between the seasons. When most rainfall occurs as convective rainfall (often relatively local, short duration and regularly intense rainfall), the amounts for the hourly and daily rainfall amounts for the same return time may be closer to each other than when rainfall is more distributed over the day. When the occurrence of the various rainfall types changes in the future, the difference between the hourly and 24 hour rainfall extremes may change also. Figures 6.2 and 6.3 show that the factor between the 24 hours and 60 min once per year rainfall is not the same for various locations.

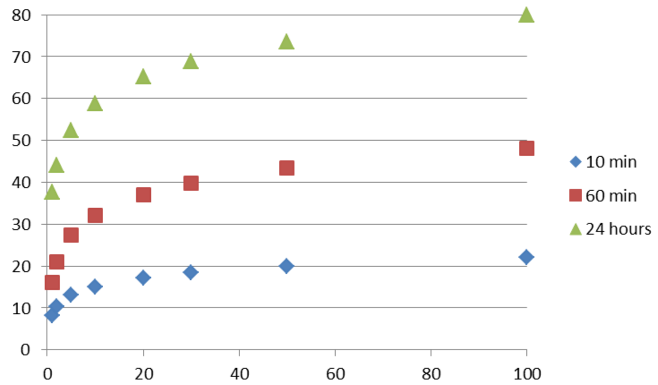

Figure 6.2. Annual rainfall statistics for 10 min, 60 min and 24 hours for Musterort, Germany over the period 1951-2010. Vertical axis: rainfall amounts in mm, Horizontal axis: return times in years. (http://www.dwd.de/DE/leistungen/starkniederschlagsgutachten/download/mustertabelle_gutachten_pdf.pdf;jsessionid=E652D9F23739B44ECD64354EB1D391AA.live21072?__blob=publicationFile&v=5).

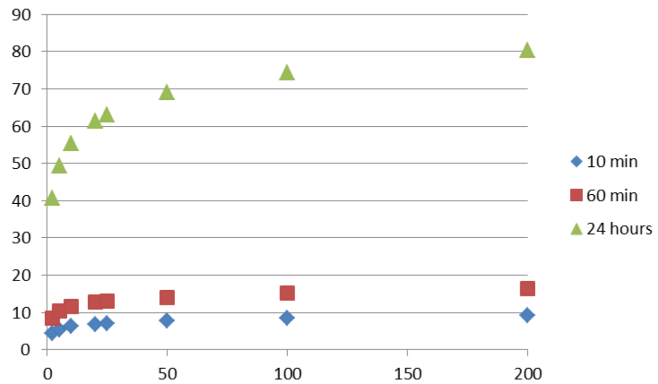

Figure 6.3. Annual rainfall statistics for 10 min, 60 min and 24 hours for Bodo-Skivika, Norway over the period 1997-2012. Vertical axis: rainfall amounts in mm, Horizontal axis: return times in years. (https://cms.met.no/site/2/klimaservicesenteret/dimensjonerende-nedb%C3%B8r/ivf-verdier-fra-et-utvalg-m%C3%A5lestasjoner/_attachment/6404?_ts=14fcabfaf39)

6.3 Effect of daily and sub daily data on extreme rainfall statistics

Using daily rainfall data as the basis for determining the 1-day statistics or using hourly rainfall data as the basis for determining the 1 day or 24-hour statistics will not result in the same rainfall statistics. Rain showers may not always fall between e.g. 0:00 and 24:00 hours (fixed definition of days as often used for daily data). Therefore, when using a moving 24 hour window and hourly rainfall data as basic material, you will find higher rainfall amounts for the moving 24 hour window than for the fixed definition of days. This will result in higher rainfall amounts for 24 hours for the statistics based on the hourly rainfall data. The difference can be considerable as shown in the examples below:

- For extreme rainfall per 24 hours in the Netherlands Overeem et al. (2008, Rainfall depth-duration-frequency curves and their uncertainties. J. Hydrol., 348, 1, 124-134, doi:10.1016/j.jhydrol.2007.09.044) found a difference of 11 % between the statistics based on hourly data and those based on daily data. For extreme rainfall per hour they found 13-15% lower values when the statistics were based on hourly data, compared to the use of data for 5-15 min; for extreme rainfall per 2 hours this difference had diminished to about 4 %.
- Førland (1992: Manual for beregning av påregnelige ekstreme nedbørverdier. Report 21/92 Norwegian Meteorological institute, Oslo, Norway. http://www.met.no/Forskning/Publikasjoner/) found 13 % higher rainfall amounts when based on hourly data in stead of using daily data.

- In France the Weiss coefficient (1.14) is used. It describes the difference between the statistics based on daily data and those based on hourly data (pers. Comm. L. Foucher).

For infrastructure it is relevant how much rainfall falls in a certain time period (e.g. sequence of hours). Therefore, statistics based on time series with daily values will give too low values. Rainfall statistics for use for infrastructure design preferably should be based on "moving windows" for the relevant rainfall durations (the same is true for hourly data: statistics for hourly extreme rainfall should be based on sub hourly data, e.g. 5-15 min data).

To learn more about extreme value analysis, see the WMO-guide on Extreme value analysis in a changing climate (http://www.wmo.int/pages/prog/wcp/wcdmp/wcdmp_series/documents/WCDMP_72_TD_1500_en_1.pdf).

6.4 *Guidance on how to use the climate analogues tool for rainfall extremes*

Below the various steps to get analogue stations for extreme rainfall are described.

Step 1: Determine the extreme of interest:

1. Choose the base period. This can be either the base period that can be best compared to the rainfall statistics that you use now for the current climate (see chapter 4; if the statistics is based on the period 1960-2010, you could select the base period 1981-2000[28]), or you could select a recent period you use now).
2. Choose season of interest (most often annual).
3. Choose the return time of interest: extremes that are surpassed once in 1, 2, 5, 10 or 20 years.
4. Select category of climate variable (default is "rain").
5. Select type of extreme, e.g. highest 1-day or highest 5-day precipitation amount. Sub-daily extremes are not available. To get some information on the relation between daily and sub daily extremes, look at the box on daily and sub daily rainfall extremes.
6. (Do not fill in anything yet for "range")

Subsequently, the tool will generate the corresponding map (may take a while). It will show the minimum and maximum values as well (after "range").

[28] Currently only base periods of 20 years are available in the analogues tool, but later some periods of 40 years will probably be added.

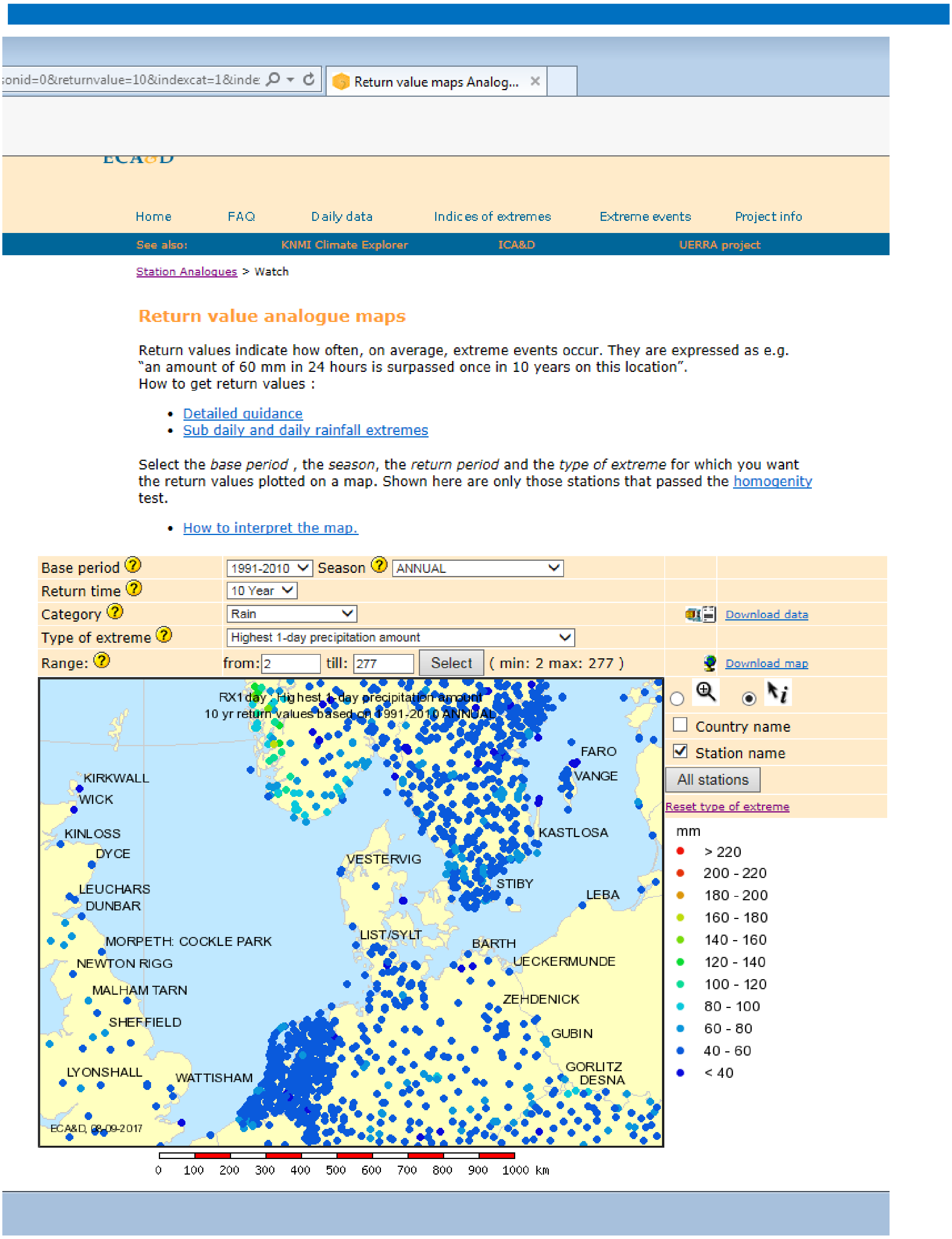

Figure 6.4. Screen shot of what you can see after step 1 and part of step 2 (adding station names and zooming in).

Step 2: Select your reference station and determine the value for your station.

1. Optional: Click 'Station name' to show some station names in the map (the names may only appear after zooming in due to the limited space on the map). This may make it easier later on to select the station of interest.

2. You can zoom in to your location, by clicking on the icon and then by clicking in the map, up to 6 times.

3. Click the icon.
4. Click the dot corresponding with your reference station of interest in the map.

A box pops up with information on the chosen station, including the extreme rainfall amount corresponding to the selected return time and reference period. This value may be lower than the one you use, due to the fact that here daily values are used (see box on this).

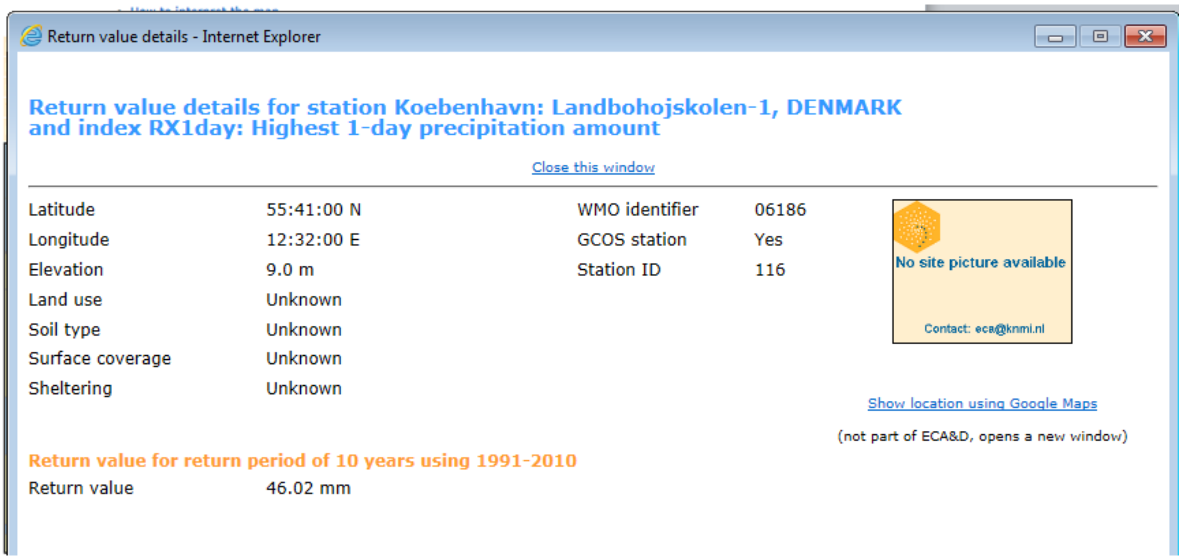

Figure 6.5. Screen shot of what you can see after step 2: the pop-up box with the information for your selected reference station, base period and return time.

Step 3: Determine the future values for the extreme.

This value can be based on estimates of changes in various climate scenarios for the relevant time horizons for your study, as described in the WATCH protocol, or it can be based on the percentages used currently to take climate change into account (e.g. often 20-30% for rainfall; link to report WATCH with overview of current approached per country). Multiply the value found for your own region in step two with (1+percentage/100) to get the amount of rainfall with a certain return time that you expect in your own region in the future or that is currently taken into account.

> ***Example***: *When you assume a 2 degree Celsius increase in temperature, than the maximum increase could be about 2 times 14 % = 28%. This would result in a future amount of 58,9 mm for the station presented in figure 3. Looking for analogues with +/- 0.5 mm than the range should be 58.5-59.5 mm*

Step 4: Get locations with analogues.

1. Fill in a range around the projected value that you determined in step three in the" [from]" and "[till]" boxes after "Range" (e.g. plus and minus 1 mm: or less than 1 mm; the larger the range the more stations will be given). Then click on "Select". A map pops up that only shows the stations that have values within the range you filled in (again the map for the whole of Europe is shown).
2. Click 'Station name' to show station names in the map.
3. Optional: you can zoom in by clicking on the icon and then by clicking in the map, up to 6 times.
4. If there are many stations, you can reduce the number by narrowing the range and following the points from 1 on again (under this step).
5. Click the icon.
6. Click on a dot that could represent a suitable analogue station for you. A box pops up with information on the chosen station, including the extreme rainfall amount

corresponding to the selected return time and reference period. If your reference station lies in a flat area, it is better to select an analogue station that also is located in a flat area. The information on elevation in the pop-up box may help with this, but regularly you can also click on “Show location using google maps” in the pop-up box to get more information on the surrounding area of the potential analogue station.

7. If the selected analogue station is not suitable, close the pop-up box and select another potential analogue station. You can select various stations.

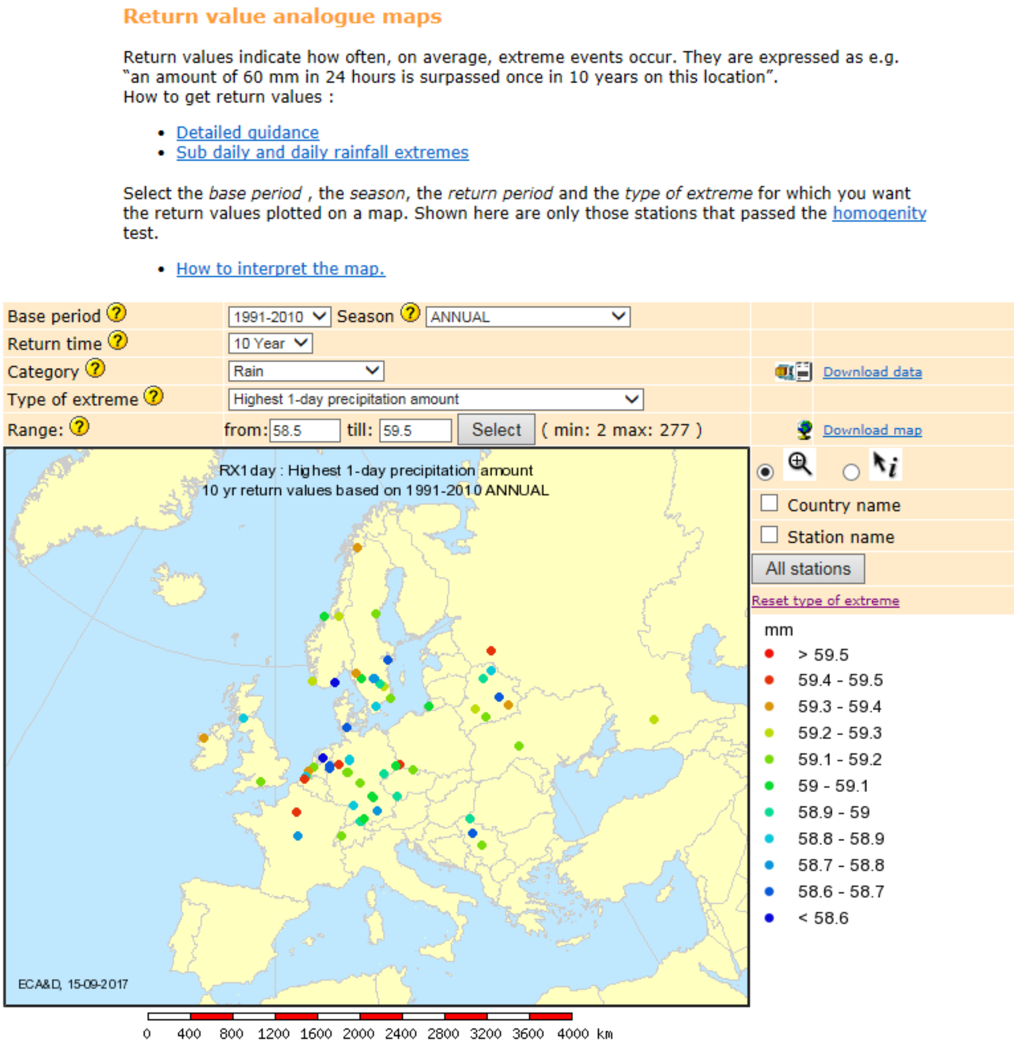

Figure 6.6. Screen shot of what you can see after step 4 (filling in a range and clicking on Select). In this case stations put up as analogues for the future that have currently more or less the same rainfall statistics (e.g.in the Netherlands) as in Denmark (reference station near Copenhagen).These stations probably had some relatively extreme events in the base period 1991-2010. When using the base period 1971-1990 no station in the Netherlands will pop-up.

The base periods in the analogues tool are relatively short (20 years at the moment). If in such a period a very high rainfall occurred, this may influence the statistics generated: than higher rainfall depths will be shown for a certain return time than expected on the basis of a longer period. This may be a problem especially for the once in 10 and once in 20 years return times. To avoid this, it is advised to redo the procedure for a base period before or after the first selected base period (if you first selected 1991-2010, select in a second round the period 1971-1990; 1981-2000 is also an option, but it may contain the same observed extreme that caused the bias in the statistics). If you get the same suitable analogue stations, the chance is high that these are indeed suitable analogue stations. <u>If a station does not appear for the other base period, than this may be due to an extreme observation (or due to climate change).</u>

This climate analogue tool is developed for rain statistics retrieval, but also other available indices under the return values analogues tool.

6.5 Guidance on how to use the tool to get climatology analogues

It is also possible to look for climatology analogues. In that case you should select “climatology values” on the starting page of the WATCH analogues tool. The guidance for this part is very similar to the one for extreme rainfall, but on some points it is slightly different.

Step 1: Determine the climate index of interest

1. Choose the “Normal period”. This is the period that is used for the description of the current climate. In most countries currently the period 1981-2010 is used (see chapter 4))
2. Choose the season of interest or choose annual.
3. Choose the climate index by choosing
    - Select the category (main climate variable e.g. temperature, rain, etc.).
    - Select the index (e.g. for rain “precipitation sum”)
4. ((Do not fill in anything yet for "range".)

Subsequently, the tool will generate the corresponding map (may take a while). It will show the minimum and maximum values as well.

Step 2: Select your reference station and determine the value for your station.

1. Optional: Click 'Station name' to show some station names in the map (the names may only appear after zooming in due to the limited space on the map). This may make it easier later on to select the station of interest.
2. You may zoom in to your location, clicking on the  icon and clicking in the map up to 6 times.
3. Click the  icon.
4. Clicks the dot corresponding to the station of interest in the map.

A box pops up with information on the chosen station, including the value of the climate index you selected.

Step 3: Estimate the future value for the index.

This projected value change can be based on estimates of changes in various climate scenarios as described in the WATCH protocol (see chapter 5). Climate scenarios often contain information about changes in average temperatures and precipitation per year and per season, but not necessarily for other climate indices presented under “climatology”. You can also look for analogues by just adding a percentage that is not necessarily based on a climate scenario/projection.

Step 4: Get locations with analogues.:

1. Fill in a range around the projected value that you determined in step three in the” [from]” and “[till]” boxes after “Range” (e.g. plus and minus 5 mm for the precipitation sum per year; the larger the range the more stations will be given). Then click on “Select”. A map pops up that only shows the stations that have values within the range you filled in (again the map for the whole of Europe is shown).
2. Click 'Station name' to show station names in the map.
3. Optional: you can zoom in by clicking on the  icon and then by clicking in the map, up to 6 times.
4. If there are many stations, you can reduce the number by narrowing the range and following the points from 1 on again (under this step).

5. Click the icon.
6. Click on a dot that could represent a suitable analogue station for you. A box pops up with information on the chosen station, including the value for the selected climate variable. The information on elevation in the pop-up box may help in determining whether this is a suitable analogue (preferably look for stations that have a more or less similar environment), but regularly you can also click on “Show location using google maps” in the pop-up box to get more information on the surrounding area of the potential analogue station.
7. If the selected analogue station is not suitable, close the pop-up box and select another potential analogue station. You can select various stations.

You may zoom out by clicking [Select] again. You may reset the chosen range and zooming by clicking [All stations].

6.6 How to interpret the analogues maps

Below are a few points that will help to interpret the analogue maps on the website:

- Each circle or dot on the map represents a station.
- The legend on the right of the map indicates what the colours mean. For the analogues retrieval the colours adapt to the chosen range of values.
- For an analogues tool, such as for the WATCH project it is desirable to show only those stations with values near a chosen value. This tool can be used to filter the stations where the projected value of a chosen station are already realised. Stations with values outside the chosen range are left out.
- Using the -button and clicking on a station dot on the map will give a pop-up with details of that station, depending on the chosen index.
- The station density varies over Europe. This indicates that stations with data series available for the requested time period are not equally distributed over Europe. In some areas there are fewer stations or fewer stations with long observation records. In other areas the ECA&D team does not have access to all available station series (often due to data policy differences between countries). Zooming in will make it possible to distinguish between different stations.
- The base periods in the analogues tool are relatively short (20 years). If in such a period a very high rainfall occurred, this may influence the statistics generated: than higher rainfall depths will be shown for a certain return time than expected on the basis of a longer period. This may be a problem especially for the once in 10 and once in 20 years return times. Under the detailed guidelines, it is described how you can find out if this is the case.

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