Extreme rainfall climatology from weather radar

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Introduction

Extreme rainfall events have a large impact on society and can lead to loss of life and property. Weather radars give quantitative precipitation estimates over large areas with a high spatial and temporal resolution unmatched by conventional rain gauge networks. The current quality of quantitative precipitation estimation with radar and the length of the available time series make it feasible to derive a radar-based extreme rainfall climatology. KNMI has an archive of 11 years of radar rainfall depths for the entire land surface of the Netherlands. After adjustment using rain gauge data a high-quality rainfall climatology is obtained. Subsequently, a generalized extreme value (GEV) distribution is fitted to annual radar rainfall maxima and rainfall depth-duration-frequency (DDF) curves are derived, which describe the extreme rainfall depth as a function of duration for given return periods. It is shown that weather radar is suitable to derive the statistics of extreme rainfall, which can, for example, be used for design purposes in water management or the evaluation of the rarity of severe weather.

KNMI has an archive of 11 years of radar rainfall depths for the entire land surface of the Netherlands

Radar and rain gauge data

KNMI operates two C-band Doppler weather radars, from which rainfall intensities were obtained with a 2.4 km spatial resolution and a 5-min temporal resolution for the period 1998-2008 with a data availability of approximately 82%. The radars are located in the Netherlands in De Bilt and Den Helder, see Figure 1. From the rainfall intensities, accumulations were derived for durations of 15 min to 24 h. Accumulation images from both radars were combined into one composite covering the land surface of the Netherlands (35 500 km^2). Quantitative precipitation estimation with radar can become less accurate due to, for example, overshooting of precipitation by the radar beam, variability of the drop-size distribution and attenuation in the case of strong precipitation or a wet radome. Rain gauges are considered to produce accurate point measurements. Because of this, rain gauge networks (Figure 1) were utilized to adjust the radar-based accumulations: an automatic network with 1-h rainfall depths for each clock-hour (≈ 1 station per 1000 km^2) and a manual network with 24-h 08-08 UTC rainfall depths (≈ 1 station per 100 km^2). A daily spatial adjustment is applied to the 24-h 08 UTC rainfall depths using the manual gauge network. A mean-field bias (MFB) adjustment is applied to the 1-h unadjusted radar rainfall depths using the automatic gauge network. Both adjustment procedures were combined and are denoted by mean-field bias and spatial (MFBS) adjustment.

Verification

The radar data set of rainfall depths was verified using rain gauges for the period 1998-2007. The bias in unadjusted daily radar rainfall depths with respect to manual rain gauge depths is -0.88 mm, which is a considerable underestimation since the average daily manual rain gauge depth is 2.55 mm. The MFB and MFBS adjustment methods reduce the bias to respectively -0.15 and -0.03 mm. The residual standard deviation is reduced from 2.71 (unadjusted) to 2.14 mm (MFB) and 1.03 mm (MFBS). Rain gauges produce point measurements, whereas radar

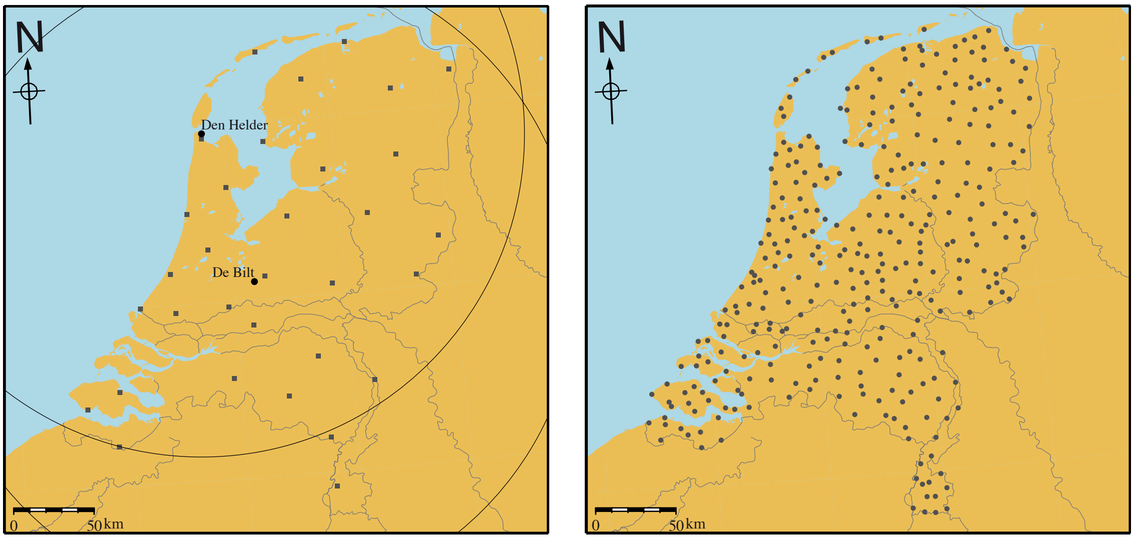

Figure 1. *Maps of the Netherlands with left the locations of the weather radars in De Bilt and Den Helder, their 200-km range (circles), and the 33 automatic rain gauges (squares) and right the locations of the 326 manual rain gauges.*

samples a volume with a horizontal surface of 5.7 km^2. The standard deviation of the differences in daily rainfall depths between manual and automatic rain gauges within a 2.4-km radius is 1.06 mm. This indicates that an important part in the differences between radar and rain gauge accumulations is caused by sub-pixel variation.

To investigate the spatial quality of rainfall depths, biases in the mean daily rainfall and the residual standard deviation are calculated for each radar-gauge pair for the MFB and MFBS adjustments. In the MFB adjustment method a constant factor is applied to the entire radar image, so that regional differences in the biases are not taken into account. Figure 2 shows that such an adjustment results in quite negative biases near the borders of the Netherlands and quite positive ones in the middle of the country. A constant adjustment factor only partly corrects the large negative biases in winter due to partial overshooting of precipitation from shallow stratiform clouds, and turns the smaller negative biases at short ranges into an overestimation. The MFBS adjustment clearly removes range dependencies in radar rainfall depths.
The 1-h radar rainfall depths are also verified against the depths obtained from the automatic rain gauges. Both adjustment methods are successful in removing the bias in the mean hourly rainfall depth and in reducing the residual standard deviation. If only radar and/or rain gauge depths larger than 5 mm in 1 h are considered, the bias in the unadjusted radar rainfall depths is -3.81 mm. This is reduced to -0.82 mm for the MFB-adjusted data and -0.51 mm for the MFBS-adjusted data. For these extreme events, the residual standard deviation decreases from 4.60 mm (unadjusted) to 3.96 mm (MFB) and 3.80 mm (MFBS). This implies that a daily adjustment using a dense gauge network, which improves the spatial quality of the rainfall depths, has added value if applied to already MFB-adjusted 1-h rainfall depths.

Fitting a GEV distribution

Data sets are usually too short to accurately estimate extreme rainfall depths for design purposes in water management. Often extrapolation is needed. A well-established method is to abstract annual rainfall maxima from a rain gauge record for a given duration and model these extremes with a GEV distribution. The quantile function of this distribution can be used to estimate rainfall depths for given average return periods T, and is given by:

$$x(T) = \mu \left\{ 1 + \frac{\gamma}{\kappa} \left[1 - \left(- \ln \left(1 - \frac{1}{T} \right) \right)^{\kappa} \right] \right\} \text{ for } \kappa \neq 0 \qquad (1)$$

$$x(T) = \mu \left\{ 1 - \gamma \ln \left[- \ln \left(1 - \frac{1}{T} \right) \right] \right\} \text{ for } \kappa = 0$$

with μ the location and κ the shape parameter of the distribution; γ is the dispersion coefficient. The value of κ determines the type of distribution, if $\kappa = 0$ the Gumbel distribution is obtained.

Rainfall depth-duration-frequency curves

A novel approach is to estimate extreme rainfall depths based on weather radar data, which is particularly

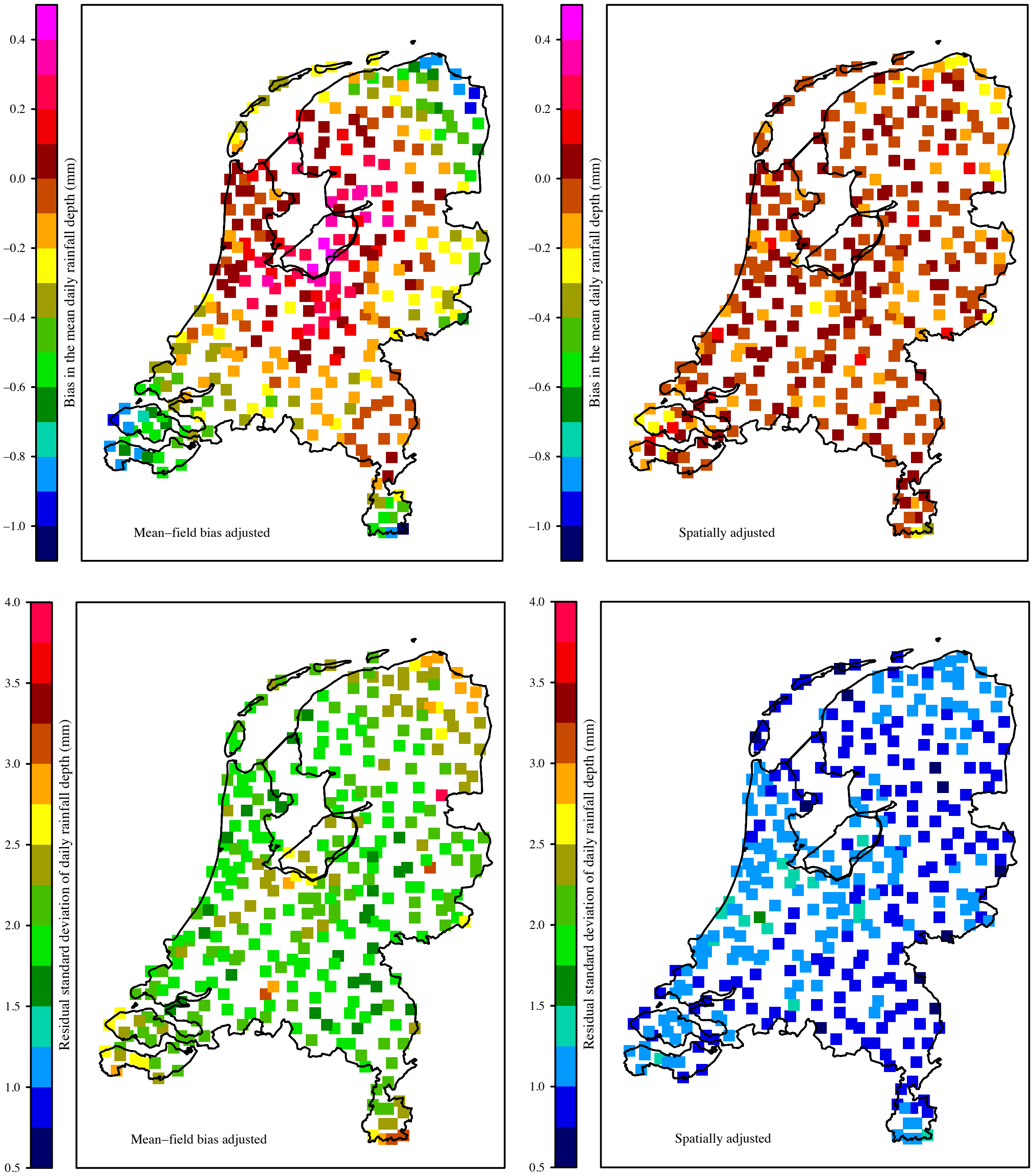

Figure 2. *Spatial verification of 24-hour 0800 UTC rainfall depths of radar composites against manual gauges for MFB- and MFBS-adjusted radar data: bias in the mean (upper panel) and residual standard deviation (lower panel).*

interesting for short durations for which few rain gauge data are available. For the 11-year period, each pixel contains 11 annual maxima, which are abstracted for durations *D* of 15 min to 24 h. For each individual duration, GEV distributions are fitted to the 6190 (pixels) × 11 (years) annual maxima assuming that the dispersion coefficient and shape parameter are constant over the Netherlands.

For longer durations the validity of this assumption is demonstrated by Buishand et al. in this Triennial Report. The location parameter is estimated for each radar pixel separately. In this paragraph, the estimated location parameters for the individual pixels are averaged to obtain one value of this parameter for each *D*. Relationships are found, which model the GEV parameters as function of *(in h)*:

$\ln \mu = 2.559 + 0.318D$ (2)

$\gamma = 0.312 - 0.025D$ (3)

$\kappa = -0.163$ (4)

These relationships are similar to those found using rain gauge data[1)]. Substituting them in Eq. (1) gives a general expression for the rainfall depth quantile *x(T)*, which can be used to obtain rainfall DDFs. An example of such a rainfall DDF curve is given in Figure 3 for *T* = 50 years based on radar data from this study (solid line) and based on 514 annual maxima from 12 rain gauges[1)] (dashed line). Most rain gauge data refer to the period 1977-2005. For instance, for a return period of 50 years the 60-min radar extreme rainfall is 35 mm. The underestimation of rainfall depths with respect to rain gauges for short durations may be related to remaining errors in the radar data.

It is important to estimate the uncertainty in DDF curves and to take this uncertainty into account in the design of hydraulic structures. The bootstrap method is employed to assess the uncertainty in the estimation of the GEV parameters, i.e. sampling errors. In the bootstrap method new samples (bootstrap samples) are generated by sampling with replacement from the original sample. The 95%-confidence intervals for the rainfall depth quantiles are shown as a light gray-shaded area (radar) or a dark gray-shaded area (rain gauge). The overlap region of the rain gauge and radar-based confidence intervals is shown in gray. For the radar data uncertainties become rather large for the longest durations. For example, the 95%-confidence interval ranges from 72 to 92 mm for *D* = 24 h and *T* = 50 years, which is due to the relatively small size of the radar data set for calculating the statistics of extreme rainfall. Nevertheless, the uncertainties for the radar data are small for short durations. This is because of the low spatial correlation of short-duration rainfall. The large number of observations in space then compensates for the small number of observations in time. The effective length of the 11-year radar data set ranges from approximately 80 years for *D* = 24 h to a few hundred years for *D* = 15 min.

Local rainfall depth-duration-frequency curves

Due to spatial variation of the value of the location parameter, the average DDF curve in Figure 3 cannot be used everywhere in the Netherlands. Figure 4 shows the location parameters for *D* = 60 min and 24 h and gives the rainfall depths for *D* = 24 h and *T* = 20 years. Most noticeable are the high values of the location parameter in the western part of the country, near the coast, for *D* = 24 h, which are considerably larger than those in the

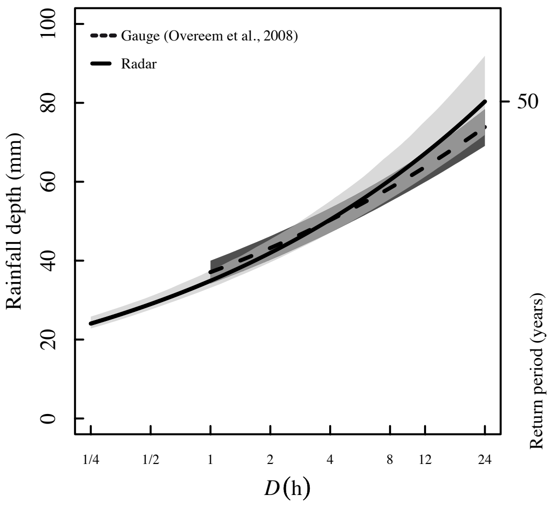

Figure 3. *Rainfall depth-duration-frequency curves for a return period of 50 years based on rain gauge data[1)] (dashed line) and based on radar data (solid line). Also shown are pointwise 95%-confidence intervals: dark gray for the rain gauge data, light gray for the radar data. The overlap region of these confidence intervals is shown as gray.*

rest of the country. This is in correspondence with results presented by Buishand et al. in this Triennial Report, where annual daily rainfall maxima were obtained from 55-year records of 141 manual rain gauges. However, in radar-based data larger spatial differences in the location parameter are found, resulting in rainfall depths ranging from 48 to 94 mm for *T* = 20 years and *D* = 24 h. For *D* = 60 min, several isolated areas with high values of the location parameter can be distinguished, but no clear spatial pattern is revealed. Although regional variability in the GEV location parameter in the Netherlands is statistically significant for most durations, an important part of the differences can be attributed to randomness, which will be relatively large for an 11-year data set.

If DDF curves are derived for each radar pixel, the uncertainties in the estimated quantiles of rainfall depths become rather large. As a compromise, local DDF curves are derived for the areas indicated by the white boxes in Figure 4b. For 24 h, area A is one of the 'driest' areas and area B one of the 'wettest' areas in the Netherlands. Local DDF curves for 50 years are shown in Figure 5, together with their 95%-confidence bands. For durations longer than approximately 4 hours, the 95%-confidence bands for the DDF curves of areas A and B do not overlap implying these DDF curves differ significantly. In general, the 95%-confidence bands are wider than those for the average DDF curve for the Netherlands, shown in Figure 3, due to the larger uncertainty of the location parameter.

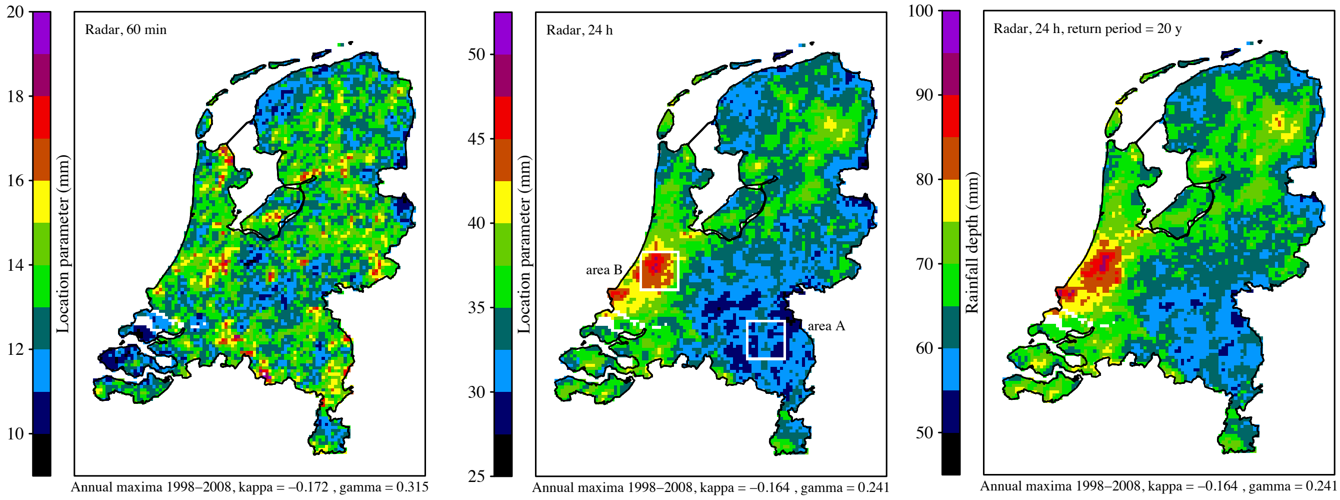

Figure 4. *The location parameter for 60 min (left) and 24 h (middle) and the 24-h rainfall depth for a return period of 20 years (right) for each pixel in the Netherlands.*

Weather radar is suitable to estimate extreme rainfall depths for chosen return periods

Conclusion

Using weather radar an 11-year rainfall climatology was constructed for the Netherlands for durations of 15 min to 24 h. The adjustment of radar rainfall depths employing rain gauges results in high-quality radar rainfall composites with a spatially homogeneous quality, which covers the land surface of the Netherlands. For an extensive description of the adjustment and verification, see [2,3]. It has been shown that weather radar is suitable to estimate extreme rainfall depths for chosen return periods[3]. The radar data set is potentially useful for rainfall parameterization in weather and climate models and for use in hydrological models. The climatological radar data set of 1-h rainfall depths for every clock-hour is available at the Climate Services division.

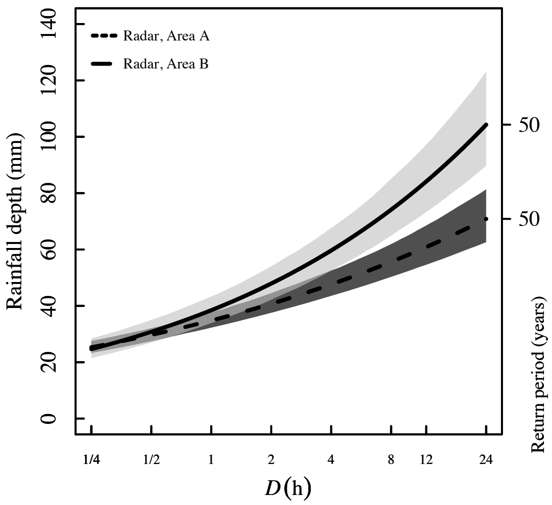

Figure 5. *Local rainfall depth-duration-frequency curves for the two areas indicated in Fig. 4b for a return period of 50 years based on radar data and their pointwise 95%-confidence bands.*

References

1) Overeem A., T.A. Buishand and I. Holleman, 2008. *Rainfall depth-duration-frequency curves and their uncertainties.* J. Hydrol., **348**, 124-134, doi:10.1016/j.jhydrol.2007.09.044
2) Overeem A., I. Holleman and A. Buishand, 2009. *Derivation of a 10-year radar-based climatology of rainfall.* J. Appl. Meteor. and Climatology, **48**, 1448-1463, doi:10.1175/2009JAMC1954.1
3) Overeem A., T.A. Buishand and I. Holleman, 2009.*Extreme rainfall analysis and estimation of depth-duration-frequency curves using weather radar.* Water Resour. Res., **45**, W10424, doi:10.1029/2009WR007869