

Reply to the review of:

Areal Reduction Factors from High-Resolution Rain Gauges in Austria

Golbarg Goshtasbpour¹, Jannick Alpers¹, Kai Schroter¹, and Hannes Müller-Thomy^{1,i}

¹Leichtweis-Institute for Hydraulic Engineering and Water Resources, Dept. Hydrology and River Basin Management,

Technische Universität Braunschweig, Braunschweig, 38106, Germany

ⁱpreviously published under the name Hannes Müller

Correspondence: Hannes Müller-Thomy (h.mueller-thomy@tu-braunschweig.de)

We thank referee #1 (R1) for his positive evaluation, and referee #2 (R2) for the more critical, but very constructive comments. Please find here out detailed [point-to-point response \(blue\)](#) to the comments (black) by both, R1 and R2. A [possible modification within the manuscript \(green\)](#) is suggested as well, with line numbers referring to the original submission.

Referee #1 (R1)

The paper presents an estimation of areal reduction factors using high-resolution rain gauges in Austria. The study utilizes a dense network of station data from which point extremes were estimated. A raster product was then employed for areal rainfall extremes prediction. Subsequently, ARFs were estimated empirically from the estimated quantiles. The authors then explored the behavior of the ARFs as a function of duration, area, season, and topography. Overall, the paper is well-written, and I recommend publication, subject to some minor corrections.

[We thank R1 for the very positive evaluation.](#)

Minor comments:

While the literature review and state of the art on ARF have been extensively presented in the introduction, I think the novelty of the present study needs to be elaborated.

[The main novelty of this study is the estimation of ARFs from such a dense network for sub-hourly durations. This enables for the first time comparisons with findings from other references, which were based on less dense networks or from different data types \(radar\). We will highlight this novelty in the introduction and in the conclusion section.](#)

What is the size of the study area?

[The size of the study area is defined by the spatial extension of the regionalized raster data of the WegenerNet. A total area of 330 km² is covered by 75 x 110 raster cells, each with a raster width of 200 m x 200 m \(see L127\).](#)

More information should be provided on the raster product. How long is the series in years? Is it a reanalysis or simply an interpolation of the station data?

[The raster data is a “simply” a regionalization raster product, directly provided by the WegenerNet \(see L126\). The time series of the raster product are 15 yrs in total \(2007-2022\) with 5 min resolution \(see L125-126\).](#)

What is the role of the Data Product Generator?

The Data Product Generator is part of the WegenerNet Processing System, which consists of four steps:

1. Command Receive Archiving System: collection of measurements in a central database
2. Quality Control System: Automatic quality check of the collected data (eight levels) and subsequent flagging of the measured data (passed / not passed). All passed measurements are stored as Level-1 data.
3. Data Product Generator: Regionalization of the Level-1 data in space and time to fill gaps and to generate raster data and other data products, all considered as Level-2 data.
4. Visualization and Information System: Visualization of the Level-2 data along with supporting information.

We would add the following text in a revised manuscript at L129:

The Data Product Generator regionalizes the gauge-based time series with an inverse distance-squared method (IDSW, Fuchsberger et al., 2021). Inverse distance-based methods lead to similar results as Ordinary Kriging for a high station network density (Berndt and Haberlandt, 2018). Also, additional improvements from e.g., external drifts, can be questioned for such a dense network. IDSW is able to represent the spatial variance of the precipitation field, by simultaneously representing the extreme values well due to favouring the immediate stations by squaring the distance. Using the regionalized data product also enables comparisons with other studies.

Is there any specific reason to relate the choice of the POT to the Euler number?

The choice of the Euler number for the identification of POT threshold follows the recommendation of the DWA (2012). The Euler number is chosen as compromise between i) taking too few extreme values into account (as it would be the case with an annual maximum series for a short time series), and ii) taking too many extreme values into account (since the smallest values could represent a more moderate behaviour than an extreme behaviour). In previous studies we analysed the impact of using $x=\{2, e, 3\}$ as input for Eq. 3 of the original submission (shown below). However, since only neglectable differences could be identified, we prefer to follow the recommended value of $x=e$ by DWA (2012).

$$\text{POT}(p, t) = P_{p,t}(D) | P_{p,t}(D) \geq x \times n_{\text{yr}} \quad (3)$$

What are the u and w parameters of the exponential distribution? I think the equation should be given, since the usual case is a one-parameter distribution.

We thank R1 for the hint. We used this form of the exponential distribution:

$$P(T) = u_p + w_p \cdot \ln(T)$$

with precipitation amount P , return period T and shape parameters u_p and w_p . In a semi-logarithmic plot with P on the y -axis and T on the x -axis the distribution function will be a straight line, characterized by u_p as zero point shift and w_p as slope. We would add the function at L159 in the revised manuscript.

In the result section, the goodness-of-fit of the fitted models on the point and areal rainfall should be illustrated, at least for a few stations. Otherwise, it would be difficult to ascertain the quality of the model fits. Additionally, the claim of the agreement with the reference values from eHYD should be supported by a figure at least in the appendix.

We thank R1 for this suggestion, which is align with comments from R2. In a revised version of the manuscript we would add a supplement S1, containing information about the goodness-of-fit for point and areal rainfall as well as an comparison with ÖKOSTRA values from eHYD. Since both reviewers raised this comment in a similar way, we have added a draft of the supplement S1 at the end of our reviewer reply.

In line 211, the statement “The ARF increases with duration, and so does its range” does not seem to correspond to the figure.

R1 is right, in a revised version the sentence will be corrected to “The ARF increases with increasing area, and so does its range.”

Figures 6 and 7 are interchanged both in the text and their labels.

We are very thankful for spotting this mix-up, it will be corrected in a revised version.

The ARF plots in Figure 6 should be elaborated. How were the values obtained? Are they for a given station? Which one? Or are they for the entire study area? How then were they obtained? Mean? Median?

R1 points out missing information in caption of Fig. 6 (same for Fig. 7). We will add the missing information in a revised version, so the caption for Fig. 6 and Fig. 7 would be: “Mean ARF values over all raster cells of seasonal time series, multiple durations and $T = 10$ yr.” and “Mean ARF values over all raster cells of whole year time series, multiple durations and $T = 1$ and 10 yr.”, respectively.

Could the deviation observed in Figures 6 and 7 regarding the 18 and 24 h be related to the estimation step? Probably the underlying EVT model didn't correctly fit the data, thereby giving wrong quantiles?

We thank R1 for that hint, we double-checked the results shown in Fig. 6 and 7 and found no irregularities. Daily extreme values origin from events (often) larger than the study area, so the spatial extent and spatial pattern are not fully captured. This could be a reason, which will be added to the discussion about the influence of the duration on the ARF.

Additionally, the authors should highlight the key findings of their study that advance the state of the art. It seems most of the conclusions are already established by earlier studies. Or is the work meant to be a case study?

No, the work is not meant to be a case study. One highlight of this study is that ARFs are estimated for the first time from such a dense network for sub-hourly durations. This enabled comparisons with findings from other references, which were based on less dense networks or from different data types (radar). The majority of existing findings is confirmed in our study, but it is important to proof them. We would emphasize this highlight more in the conclusion section and in the motivation part of the introduction of a revised manuscript.

Referee #2 (R2)

This manuscript presents an extensive empirical analysis of areal reduction factors (ARFs) based on a dense high-resolution rain gauge network in southeastern Austria. The dataset offers valuable opportunities to investigate sub-hourly spatial rainfall variability. The methodological framework is generally sound, and the paper is adequately structured and well written.

However, several aspects related to data selection, climatological context, spatial representativeness, and interpretation require further clarification and, in some cases, additional analyses. In its current form, some conclusions appear too general given the limited spatial extent and specific climatic setting of the study area.

We thank R2 for the constructive and detailed comments.

Major comments

Reference Data and use of design precipitation values

The manuscript uses official Austrian design precipitation values from eHYD for validation. However, eHYD provides different products (observational ÖKOSTRA values, hybrid design values ("Bemessungsniederschlag"), and model-based products). Only the observational ÖKOSTRA values represent an independent reference suitable for validation in this context. The authors should clearly specify which eHYD products were used and justify their choice. Hybrid design values should not be used for validation, as they already incorporate modelling assumptions.

R2 points at the need for clarification regarding the applied eHYD data used. From the three eHYD data sets the interpolated observational data set ÖKOSTRA was used, as recommended by R2. However, an error was spotted regarding the number of the raster field: for this study we used raster field 5433 instead of 5432 (which was mentioned in the manuscript). We would add the information "(ÖKOSTRA values from the eHYD catalogue)" and change the raster field to "5433" in a revised manuscript version (both at L189).

Climatological context and precipitation regimes

The interpretation of seasonal and return-period dependencies would benefit from a stronger climatological and synoptic context. The study area is located in a transition zone influenced by convective summer storms, frontal systems, and Mediterranean inflow.

A more explicit discussion of dominant precipitation regimes and seasonal weather types would help to interpret the observed ARF patterns and assess their broader relevance.

We agree with R2, the reader would benefit from an extended climatological description of the study area (additional to L116-119). The following text would be added in a revised manuscript at L119 of the submitted manuscript:

On a fine scale, the Feldbach region is dominated in summer by heavy rainfall from thunderstorms (Breinl et al., 2020). This is endorsed by lightning information accessible from the Austrian Lightning Detection and Information System (ALDIS, Schulz et al., 2005), indicating the federal states Styria (including the Feldbach region) and Carinthia as regions with highest frequency of thunderstorms (see Breinl et al., 2020). Furthermore, large hail events and severe wind gusts are typical for the Feldbach region according to the European Severe Weather Database (ESWD, Dotzek et al., 2009). The mean wet spell duration in summer is approx. three hours, the overall mean dry spell duration ranges between 30 and 32 hours (Breinl et al., 2021). Matulla et al. (2003) points out historical region-dependent differences in precipitation-generating processes on a monthly basis for Austria, but concludes that precipitation events in winter result from large-scale advective processes. Seibert et al. (2007) identified the strongest precipitation events on a daily basis in the period July-October. Although Matulla et al. (2003) and Seibert et al. (2007) use data sets with different temporal resolution and station density, their findings were combined by Breinl et al. (2021) with their own findings, classifying the Feldbach region as Eastern mixed region and thus highlighting its transition characteristic.

Spatial representativeness and generalizability

The study area covers only a few hundred square kilometres and exhibits relatively homogeneous climatic and orographic conditions. Nevertheless, several conclusions are formulated in a rather general manner, particularly regarding return-period effects at sub-hourly scales.

Given the limited spatial extent, it remains unclear whether these findings reflect general methodological effects or region-specific climatic characteristics. An extension to a larger surrounding region with lower station density, including additional available gauges from local meteorological and hydrological services, would help to disentangle these effects.

Such an extended analysis would also strengthen the assessment of the scientific novelty of the study, as it would clarify whether the reported patterns represent transferable insights or primarily reflect local climatic peculiarities.

This issue is closely related to the interpretation of elevation effects (see below).

R2 is critical about the spatial extension of the study area and recommends an extension, taking into account a less dense network for the extended study area. Indeed, the spatial limitation is unfortunate, but in our opinion the network density is more important than its extent.

Lengfeld et al. (2020) analysed for Germany the probability to ‘miss’ precipitation extreme values by a comparison of extreme values derived from station data and radar data. While on the daily scale only 18.1 % of all extreme values were not captured by the rain gauge network, on the hourly scale 82.7 % of extreme values were not detected by the rain gauge network. It can be assumed, that on an even finer scale the probability to miss extreme values increases even more. The hourly station network density in their study (roughly one station per 150 km²) is higher than the sub-hourly network density in Austria (271 rain gauges with sub-hourly resolution [TAWES data set, GeoSphere Austria, 2026], so roughly one station per 300 km²), which increases the probability of undetected extreme values even more. However, for a representative estimation of ARFs capturing the extreme values is essential.

Since the aim of the study is to provide a deep insight into ARF behaviour on the sub-hourly scale, we prefer to keep the high network density of the Wegener net and take into account the limited spatial extent. To keep in mind, there are only a few network with such high density, and the derived insights and findings are valuable, even if spatial extension is limited.

Although we will not extend the study area as suggested by R2, we agree with R2 regarding the annoyance of the spatial limitation. To overcome this limitation, a follow-up study was carried out using radar data in Germany (Goshtasbpour et al., submitted). While for the new study the focus has moved on comparisons of ARFs derived from radar data and rain gauge data, the majority of findings regarding return periods (and others) for sub-hourly ARFs from this study were confirmed. Nevertheless, in a revised manuscript we will rephrase the ‘general statements’ and emphasize that the transferability of the findings is limited to the climatic conditions of the study area (which will be described more in detail, please see our reply to the previous comment).

Elevation dependence

The elevation range within the study area is small (approximately 250–600 m), which strongly limits the interpretability of the reported weak ARF–elevation relationships. Additional analyses including higher-elevation stations from neighbouring regions would be required to draw more robust conclusions on topographic effects.

We agree with R2 regarding the limited insight into ARF-elevation relationship caused by the spatial limitation of the study area. However, we will not extend the study area due to methodological reasons (please see our reply to the previous comment).

Regionalized precipitation product

The estimation of areal precipitation relies on a regionalized raster product derived from station data. Given its central role in ARF estimation, the derivation of this product should be described in more detail, including the interpolation method, smoothing effects, and associated uncertainties. Although limitations are briefly mentioned in the discussion, they should be addressed earlier and more explicitly in the methodology section.

We agree with R2, the regionalization should be described more in detail in the manuscript. Based on the description in Fuchsberger et al. (2021), the regionalized precipitation product is obtained via an inverse distance-squared weighting (IDSW), which is similar to the inverse distance method an averaging of surrounding stations with higher weight given to closer stations. Squaring the distance favours immediate neighbours. Based on the systematic comparisons of regionalization methods of Berndt and Haberlandt (2018), IDW outperforms Nearest Neighbour and leads to similar results as Ordinary Kriging, but is outperformed by Kriging with External Drift (drift: elevation; radar; elevation and radar), all results evaluated on an hourly basis. Given the very high station density of the network, the additional improvement by an external drift can be questioned. Indeed, IDSW enables to represent the spatial variance within the precipitation field, by simultaneously conserving extreme values by amplifying the importance of the immediate stations by the squared distance. Thus, we did not see any reason to regionalize the point data again. Moreover, using the existing data set enables comparisons with other studies and is favoured by the authors.

We would add the following text in a revised manuscript at L129:

The Data Product Generator regionalizes the gauge-based time series with an inverse distance-squared method (IDSW, Fuchsberger et al., 2021). Inverse distance-based methods lead to similar results as Ordinary Kriging for a high station network density (Berndt and Haberlandt, 2018). Also, additional improvements from e.g., external drifts, can be questioned for such a dense network. IDSW is able to represent the spatial variance of the precipitation field, by simultaneously representing the extreme values well due to favouring the immediate stations by squaring the distance. Using the regionalized data product also enables comparisons with other studies.

Methodological framework and model performance

The study relies strongly on national guidelines (DWA, 2012) for extreme value analysis and IDF estimation. While this is appropriate in an applied context, the methodological implications and limitations should be more critically discussed and embedded in a broader international framework.

R1 is correct, for the application of the distribution function we followed a national guideline. However, this application is based on the exponential distribution, which is not a national-specific distribution function. The exponential distribution can be derived from the Weibull-distribution function (with $\lambda=1$). Both, Weibull- and exponential distribution function are applied internationally for sub-daily precipitation extreme value analysis (e.g., Alexopolous et al., 2023, Ebers et al., 2024, and the TENAX model by Marra et al., 2024 with all subsequent applications).

We would add the following text at L154 in a revised manuscript:

The exponential distribution can be derived from the Weibull-distribution function (with $\lambda=1$). Both, Weibull- and exponential distribution function are applied internationally for sub-daily precipitation extreme value analysis (e.g., Alexopolous et al., 2023, Ebers et al., 2024, and the TENAX model by Marra et al., 2024 with all subsequent applications).

However, the application of another (or additional) distribution function would probably change the resulting precipitation quantiles. Since the relative change will be ‘similar’ for all durations and areas, the ARFs as ratio of two precipitation quantiles will change only slightly. So most likely the choice of distribution function will have a smaller impact on ARFs than the

already considered characteristics area, duration, seasons, return period and topography. This could also be the reason why the impact of the choice of the distribution function was not studied before by other authors (to the authors knowledge).

In addition, the goodness-of-fit of the applied extreme value models should be illustrated and discussed more explicitly, both for point and areal precipitation.

We agree with R2, a similar comment was formulated by R1. In a revised version of the manuscript we would add a supplement S1, containing information about the goodness-of-fit for point and areal rainfall as well as an comparison with ÖKOSTRA values from eHYD. Since both reviewers raised this comment in a similar way, we have added the supplement S1 at the end of our reviewer reply.

Length of record and uncertainty

The analysed time series covers only 15 years. For POT-based extreme value analysis at sub-hourly scales and return periods up to 10 years, this is relatively short. A more explicit assessment of sampling uncertainty and parameter uncertainty would strengthen the robustness of the conclusions.

R2 is right, the estimation of a precipitation quantiles with $T=10$ yrs from a time series with 15 yrs length can be questioned. For a revised version of the manuscript the new supplement S1 will be complemented by a bootstrapping approach to quantify the uncertainty resulting from the observation length. Therefore, a sampling from the 40 extreme values with replacement will be carried out, and the distribution function will be fitted to the so derived sample. The bootstrapping will be done station-based (different durations) and areal-based, consistent with the distribution function validation already included in S1. If the uncertainty for $T=10$ yrs differs strongly from lower return periods, it will be implemented in the discussion of the results.

Interpretation and framing of results

Several interpretative aspects require further discussion and probably also analysis:

- Statements suggesting that the WegenerNet dataset is the first capable of revealing certain ARF behaviours should be moderated or more carefully justified, as comparable high-resolution datasets may exist internationally.

We agree with R2, who relates probably to L26 “The high-resolution data from WegenerNet appear to be the first data set capable of revealing this behavior.” (at other txt locations the phrasing is different/less absolute). We would rephrase the sentence in a revised manuscript, for example:

However, since the spatial and temporal high-resolution data from WegenerNet appear to be one of only a few data sets existing globally, and is the first station-based data set data set of this kind used to estimate ARFs.

- The reported weak increase of ARF with return period at sub-hourly durations contradicts many previous studies. While this may be related to the exceptional data density, alternative explanations (e.g. local climatic effects, sampling variability, and interpolation effects) should be discussed more thoroughly. A complementary analysis on a larger regional scale within the same climatic setting would help to disentangle observational-scale effects from genuine regional climatic signals. If the observed behaviour persists beyond the dense core network, this would indicate a robust regional meteorological characteristic. If the effect weakens at larger scales, this would suggest that high station density is required to resolve sub-hourly spatial variability that remains obscured in conventional raingauge networks.

R2 questions the (weak) increase of ARFs with increasing return period, which is contradicting previous studies. As in our reply to previous comments from R2, we can not extend the study area. However, we compared this finding with the results from the

follow-up study in Germany mentioned before. Indeed, for Germany the sub-hourly ARFs decrease with increasing return periods. So the ARF increase in this study can either be caused by an observational-scale effect or be related to the regional climate. We would modify the discussion of the results (L292-294) in a revised manuscript as follows:

Also in the study for Germany from Goshtasbpour et al. (submitted) with a very similar setup the increase of ARFs with increasing return period is not confirmed. So it seems this finding represents rather a general behaviour than an observational-scale effect, or it is related to the regional climate. In both cases, the spatial variability of the short-duration precipitation events decreases with increasing return periods.

- The literature review is comprehensive but largely organized chronologically. A clearer thematic structure (e.g. by methodological approach, data source, climatic regime, and scale dependency) would improve readability and better position the present study within the existing literature.

We partly agree with R2. Indeed, after the definition of ARF and some classification possibilities (L1-L32), we provide a brief history of ARFs (L33-46). However, the following paragraphs (L47-90) provide references for studied factors as duration, area, return period, event type, location, topography, calculation method, and rain gauge density. Afterwards, most recent studies are cited in this context (L90-96). Since a thematic structure as suggested by R2 is used in the discussion section (5.1 Area, 5.2 Duration, 5.3 Return Period, 5.4 Seasons, 5.5 Topography, all including references), we prefer to not modify the structure of the introduction section.

References

- Alexopoulos, M. J., Müller-Thomy, H., Nistahl, P., Šraj, M., Bezak, N.: Validation of precipitation reanalysis products for rainfall-runoff modelling in Slovenia, *Hydrol. Earth Syst. Sci.*, 27, 2559–2578, 2023. <https://doi.org/10.5194/hess-27-2559-2023>
- Berndt, C., Haberlandt, U.: Spatial interpolation of climate variables in Northern Germany- Influence of temporal resolution and network density, *Journal of Hydrology: Regional Studies* 15, 184-202, 2018.
- Breinl, K., Müller-Thomy, H., Blöschl, G.: Space-time characteristics of areal reduction factors and rainfall processes, *Journal of Hydrometeorology*, 21, 671-689, 2020.
- Breinl, K., Lun, D., Müller-Thomy, H., Blöschl, G.: Understanding the relationship between rainfall and flood probabilities through combined intensity-duration-frequency analysis, *Journal of Hydrology*, 602, 126759, 2021.
- Dotzek, N., Groenemeijer, P., Feuerstein, B., Holzer, A.M.: Overview of ESSL’s severe convective storms research using the European Severe Weather Database ESWD. *Atmos. Res.* 93 (1–3), 575–586, 2009. <https://doi.org/10.1016/j.atmosres.2008.10.020>
- DWA: Starkregen in Abhängigkeit von Wiederkehrzeit und Dauer, DWA-M 531, Dt. Vereinigung für Wasserwirtschaft, Abwasser u. Abfall e.V, Hennef, sept. 2012 edn., ISBN 978-3-942964-28-9, 2012.
- Ebers, N., Schröter, K., Müller-Thomy, H.: Estimation of future rainfall extreme values by temperature-dependent disaggregation of climate model data, *Nat. Hazards Earth Syst. Sci.*, 24, 2025–2043, 2024. <https://doi.org/10.5194/nhess-24-2025-2024>
- Fuchsberger, J., Kirchengast, G., Kabas, T.: WegenerNet high-resolution weather and climate data from 2007 to 2020, *Earth System Science Data*, 13, 1307–1334, 2021. <https://doi.org/10.5194/essd-13-1307-2021>
- GeoSphere Austria: TAWES Messstationen (Rohdaten) Zehnminutendaten v1, 2026. <https://doi.org/10.60669/5ebv-gm29>
- Goshtasbpour, G., Meyer, F., Schröter, K., Müller-Thomy, H.: Areal-Reduction-Factors from high-resolution radar-based dataset for whole Germany, submitted.
- Lengfeld, K., Kirstetter, P.-E., Fowler, H. J., Yu, J., Becker, A., Flamig, Z., Gourley, J.: Use of radar data for characterizing extreme precipitation at fine scales and short durations, *Environmental Research Letters* 15, 085003, 2020. *doi:* 10.1088/1748-9326/ab98b4
- Marra, F., Koukoulou, M., Canale, A., Peleg, N.: Predicting extreme sub-hourly precipitation intensification based on temperature shifts, *Hydrol. Earth Syst. Sci.*, 28, 375–389, 2024. <https://doi.org/10.5194/hess-28-375-2024>
- Matulla, C., Penlap, E.K., Haas, P., Formayer, H.: Comparative analysis of spatial and seasonal variability: Austrian precipitation during the 20th century. *Int. J. Climatol.* 23 (13), 1577–1588, 2003. [https://doi.org/10.1002/\(ISSN\)1097-008810.1002/joc.v23:1310.1002/joc.960](https://doi.org/10.1002/(ISSN)1097-008810.1002/joc.v23:1310.1002/joc.960)
- Seibert, P., Frank, A., Formayer, H.: Synoptic and regional patterns of heavy precipitation in Austria. *Theor. Appl. Climatol.* 87 (1–4), 139–153, 2007. <https://doi.org/10.1007/s00704-006-0198-8>.
- Schulz, W., K. Cummins, G. Diendorfer, M. Dorninger: Cloud-to-ground lightning in Austria: A 10-year study using data from a lightning location system. *J. Geophys. Res.*, 110, D09101, 2005. <https://doi.org/10.1029/2004JD005332>

Supplement S1 – Validation of the fitted exponential distribution function

For the DAF estimation precipitation quantiles of different return periods are required. An exponential distribution is fitted to the peak-over-threshold series (POT), consisting of the highest 40 extreme events of each time series for each duration (see Section 3.1.1).

In Fig. S1, for the two rain gauges closest to the raster centre of the Feldbach raster field, the observed extreme values of the POT are shown together with the fitted distribution function and the ÖKOSTRA design values. While for $D=5\text{min}$ an overall good fit is visible, for $D=1\text{h}$ a slight underestimation for return periods $2\text{yrs} < T < 5\text{yrs}$ can be identified. However, the fitted distribution function represent the observed extreme values better than the ÖKOSTRA values for $D=1\text{h}$, which underestimate the precipitation quantiles. This indicates the need of spatial dense networks for a robust extreme values estimation.

An overestimation for $T > 6\text{yrs}$ is identified for $D=1\text{h}$ as well. This overestimation is attributed to the shortness of the time series with 15yrs, which allows only an uncertain estimation of precipitation quantiles for return periods larger than one-third of the time series length.

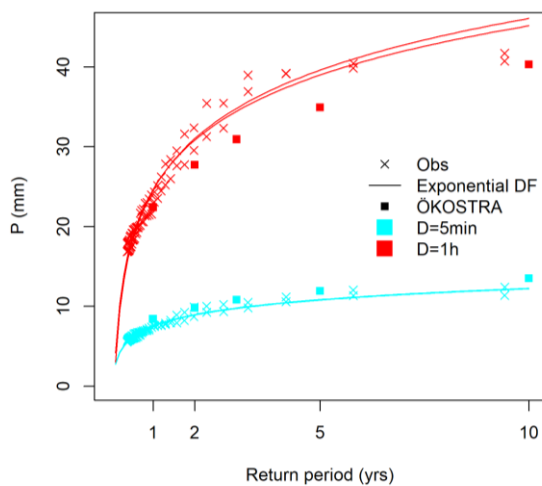


Fig. S1: Observed extreme values (Obs) and fitted distribution functions (Exponential DF) for two precipitation gauges in the Feldbach raster field, along with the ÖKOSTRA design values for $D=5\text{min}$ and $D=1\text{h}$ (entry 5433 in the eHYD catalogue).

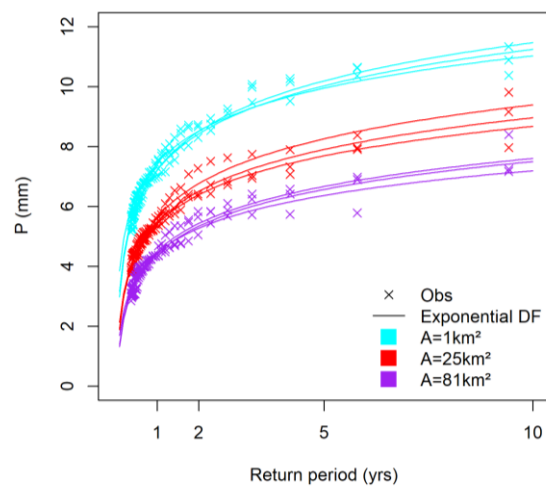


Fig. S2: Observed extreme values (Obs) and fitted distribution functions (Exponential DF) for three raster fields within the Feldbach raster for $A=\{1\text{km}^2, 25\text{km}^2, 81\text{km}^2\}$ for $D=5\text{min}$.

In Fig. S2, for three raster fields within the Feldbach raster the observed precipitation amounts for areas of $A=\{1\text{km}^2, 25\text{km}^2, 81\text{km}^2\}$ and the precipitation quantiles from the fitted exponential distribution functions are shown. For none of the studied areas a systematic underestimation or overestimation can be identified.