

**Reference Code:** hess-2018-393

**Title:** Spatially dependent Intensity-Duration-Frequency curves to support the design of civil infrastructure systems

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## Response to the Reviewer #2

*The manuscript describes a statistical framework based on an inverted max-stable process allowing to account for the spatial dependence of rainfall across durations. Application is made for a case study in New South Wales, Australia. Using the proposed framework, the authors are able to compute conditional and joint return levels of rainfall. Through the use of rainfall ARFs and of a hydrological model, the authors also derive conditional and joint return levels of river flows. Finally the authors derive the failure probability of a highway section, defined as the probability that flood magnitude at any of the five river crossings exceeds a given threshold, assuming a 1-1 correspondence between flood magnitude and rainfall over a catchment.*

*Main comments: The article is well written and mainly clear. The two risk applications of Section 5.1 and 5.2 are very interesting, particularly 5.2 (failure probability of a highway section) which seems to me to be more related to “real” issues than 5.1. The subject is absolutely worth publishing in HESS. However I raise below a couple of major issues to be addressed before publication:*

**Response:** Thank you for your comments. We respond in detail below (your comments in italic font and our responses in normal font).

### Major comment #1:

*The use of “Intensity-Duration-Frequency curves” in the title seems at the moment misleading. I would have expected from this expression to see e.g. joint or conditional IDF curves at a given station/catchment, i.e. the IF curves for several durations. Here actually only one duration is used for every catchment – basically the concentration time of the catchment. So I’d be tempted to replace “IDF” in the title (and the text) by “return levels”.*

**Response:** As the reviewer comments, the use of “Intensity-Duration-Frequency curves” suggests plots of IF with respect to duration, which we have not shown, and we instead showed return level maps. We propose to use “Intensity-Duration-Frequency relationships” in the title, since the method involves these three elements, but hopefully avoids the suggestion of traditional IDF curves.

The model can produce IDF curves at any given location as well as exceedance relationships of a conditional distribution. We will provide an additional figure showing this relationship across multiple durations based on the example in Figure 10 of the existing manuscript which focused only on the 9-hour to 36 hour conditional relationship.

### Major comment #2:

*I’m puzzled about the GPD fits. If I understood correctly, GPD are fitted to 9 and 36 hr rainfall exceedances. If moving windows are considered, then there is a very strong auto-correlation for both the 9 and 36 hr rainfall values. Have you taken this into account in the fits? A declustering method should be applied. This may be the reason why the fits for 36 hr extremes are usually poorer than for 9 hr extremes (see Figs S5 and S6).*

**Response:** Thank you. We did not consider moving windows; instead, we used restricted time periods for 36 hr rainfall (e.g. 01/01 00:00 to 02/01 12:00; 02/01 12:00 to 04/01 00:00; ...). The use of a restricted

estimates avoids the need for declustering to undo the effect of a moving window. We used a conversion factor of 1.13 to account for the difference between sliding (unrestricted)  $d$  hr rainfall maxima and restricted  $d$  hr maxima. This value is based on guidance from Australian Rainfall and Runoff (where Table 2.3.4. from Green et al. (2016) gives the 24-hr factor as 1.15 and the 48-hr factor as 1.11).

Inside the 36 hr period we also restricted the period for 9 hr rainfall (e.g. 01/01 00:00 to 01/01 09:00; 01/01 09:00 to 01/01 18:00; ...). This is to align concurrent occurrences of 36 hr and 9 hr rainfall when analysing the spatial dependence across durations. We also used a conversion factor of 1.13 for this period (Figure 5 from Jakob et al., (2005) suggests the fitted conversion factor is relatively stable).

Regarding the fits to the 36 hours extremes, the shape parameter of the GEV has greater uncertainty for some sites (e.g. Fig S5, site 3, 36 hours) which can be seen in the deviations of the observed points from gumbel quantiles. Explanation for variability is unclear to us, but we do not consider it is related to temporal dependence in the extremes.

References used for this response:

Green J, Johnson F, Beesley C, The C, 2016, Chapter 3. Design Rainfall, Book 2 in Australian Rainfall and Runoff - A Guide to Flood Estimation, Commonwealth of Australia

Jakob D., Taylor B.F. and Xuereb K.C. (2005). A Pilot Study to Explore Methods for Deriving Design Rainfalls for Australia - Part 1., HRS No. 10, Hydrometeorological Advisory Service, Bureau of Meteorology, June 2005, (59 pp). <http://www.bom.gov.au/water/designRainfalls/hrs10.shtml>

### Major comment #3:

*The part regarding the ARFs seems obscure to me (Section 4.5). Basically I isn't clear to me what the ARF allow for. I interpret between the lines that they allow to transform point return levels to spatial return levels over a catchment. However the way ARFs are described is very confusing to me. For example I. 346 states that "the rainfall extremal estimates need to be converted to the average spatial rainfall using an ARF". First I don't understand what are the "rainfall estimates" (rainfall return levels?). Second I guess that "average spatial rainfall" should be "spatial rainfall return levels". I recommend clarifying Section 4.5 and part of the Introduction dealing with ARFs.*

**Response:** Areal reduction factors (ARFs) were employed to make the adjustment of rainfall depth at a point for a given return level estimate, to an effective (mean) depth over a catchment with the same probability of exceedance as that of the point extreme (Le et al., 2018).

We will clarify the text relating to the explanation of ARFs based on your observations.

References used for this response:

Le, P. D., Davison, A. C., Engelke, S., Leonard, M., and Westra, S.: Dependence properties of spatial rainfall extremes and areal reduction factors, Journal of Hydrology, 565, 711-719, <https://doi.org/10.1016/j.jhydrol.2018.08.061>, 2018.

### Major comment #4:

*Expressions such as "10-year conditional return level map given a 20-year event happen at x" are confusing to me. Wouldn't it be less confusing to say this is the levels. expected to occur on average once every 3650 times when a 20-year event happen at x. The "10-year" is misleading to me in that case due to the conditioning.*

**Response:**

On review, we agree that this terminology of return periods is misleading. Our general design intent is introduced as: “What flood flow needs to be used to design a bridge that will fail only once on average every M times that a neighbouring catchment is flooded?” However, we then suggested that if M=10 this implies a 10-year event. On review, we see the use of return periods is confused and are grateful the reviewer has raised the matter.

For the example of daily events (365 days per year), a 10% exceedance of a conditional distribution cannot be used to imply there were 10 years equivalent or 3650 instances – because the condition only applies to a subset of days. As the reviewer has indicated, a descriptive frequency is more transparent and we will remove all instances referring to conditional “return periods”. We will exclusively retain descriptive phrases such as “once on average every M times” or “one in M chance” in discussion, figure labels and figure captions.

**Major comment #5:**

*I'm confused with the reference to “annual maxima”, whereas the article considers peaks-over-threshold. For example Fig 1 illustrates the case of annual maxima (GEV), which is not the case here. L. 421-423 talks about annual maxima instead of exceedances.*

**Response:** Thank you for pointing this out. We use the peaks-over-threshold model in this paper. So we will fix Fig. 1 and the text in L. 421-423, they should be peaks-over-threshold model and generalized Pareto distribution (GPD).

**Major comment #6:**

*I haven't understood what is the AEP of Fig 12 and 13. I guess it would be clearer to replace AEP by return periods.*

**Response:** The reviewer is correct that it is not clear what an AEP means for a conditional distribution (as with Major comment #4 for return periods). For example, a 10% chance of exceedance in a conditional distribution is not a 10% *annual* exceedance. For this reason, Fig. 12 is confusing and we will remove it along with associated discussion. The use of AEP in Fig. 13 is correct and we will retain it.

**Minor comment #1:**

*l. 111: Le et al → no brackets.*

**Response:** Thank you. We will fix this.

**Minor comment #2:**

*l. 113 AFR → ARF*

**Response:** We will fix this. Thanks.

**Minor comment #3:**

*l. 116-117: I may be clearer to exemplify (i) in terms of evacuation route design as you do in Section 5.1.*

**Response:** The phrase in question is: “What flood flow needs to be used to design a bridge that will fail only once on average every  $M$  times that a neighbouring catchment is flooded?”

As with the response to major comment #4, we have addressed the main ambiguity by removing the invalid reference to return periods. Whereas the evacuation route is a general example, phrasing the research question this way allows us to introduce the need for a probability into the design specification.

**Minor comment #4:**

*Fig. 3: add the station numbers 1, 2, 3...*

**Response:** We will fix this. Thanks.

**Minor comment #5:**

*Fig. 4 estimate conditional rainfall → estimate conditional probability rainfall*

**Response:** We will fix this. Thanks.

**Minor comment #6:**

*l. 277: where → to be removed*

**Response:** We will fix this. Thanks.

**Minor comment #7:**

*l. 294-296: why don't you estimate all parameters (beta, q, c) together?*

**Response:** This method is adopted from the paper of Le et al. (2018). If we fit all parameters ( $\beta$ ,  $q$ , and  $c$ ) jointly, there will be a bias in the estimated  $c$  parameter because of the dominance of data points at longer distances, which underestimates the tail dependence coefficients at short distances. The main interest is in short distances, especially at  $h = 0$  for the case of dependence between two different durations at the same location (see Figure 8 in the manuscript). Therefore, we estimate  $\beta$  and  $q$  first, and then we use fitted  $\beta$  and  $q$  to estimate  $c$ .

References used for this response:

Le, P. D., Leonard, M., and Westra, S.: Modeling Spatial Dependence of Rainfall Extremes Across Multiple Durations, *Water Resources Research*, 54, 2233-2248, doi:10.1002/2017WR022231, 2018.

**Minor comment #8:**

*l. 333-334 it is also noted .. 9 hrs → is it useful here?*

**Response:** Yes, it is useful because it indicates that we need to analyse extreme rainfall for different durations.

**Minor comment #9:**

*Section 4.5: to be rewritten to clarify the ARFs as said above*

**Response:** Thank you. We will clarify this.

**Minor comment #10:**

*l. 346: rainfall estimates: what are they?*

**Response:** Thank you. We mean the extreme rainfall intensities at a given location, quantile and duration. We will fix this when revising the manuscript.

**Minor comment #11:**

*l. 353-354: the BR process → for what duration? With which parameters?*

**Response:** In this paper, we need to calculate areal reduction factors for rainfall of 36 h and 9 h, so we only need to do the simulations for 36 h and 9 h separately. The parameters used are those for the variograms in Eq. (3) for rainfall of each durations, which is  $\gamma(h) = \|h\|^\beta / q$  for  $q > 0$  and  $\beta \in (0,2)$ . So we need to fit Eq. (3) separately to observed rainfall of 36 hr and 9 hr to get the fitted parameters. We will provide the parameter values for each duration in the revised version of the manuscript.

**Minor comment #12:**

*l. 360: empirical distributions → I'm confused here. If you use empirical distributions below the threshold, how can you have rainfall at ungauged sites (maps)?*

**Response:** Thank you for your comment. The empirical distributions at ungauged sites are derived through the following steps:

- Step 1: We use a response surface for threshold for the case study catchments based on covariates including longitude and latitude.
- Step 2: We use the data of the nearest gauged sites and extract the empirical distributions of rainfall below the interpolated threshold in Step 1.

This method is not perfect, but we think that this is acceptable for this study, and for studies of extremes in general because the non-extremes contribute insignificantly (Thibaud et al., 2013). We will improve the explanation in the revised version of the manuscript.

References used for this response:

Thibaud, E., Mutzner, R., and Davison, A. C.: Threshold modeling of extreme spatial rainfall, *Water 737 Resources Research*, 49, 4633-4644, 2013.

**Minor comment #13:**

*I. 373: multiple durations → Is the algorithm of Dombry still applicable in this case? I'm not sure to see how it works for multiple durations.*

**Response:** Yes, we think the algorithm of Dombry works properly for multiple durations in the following way. The covariance matrix of the simulation procedure provided by Dombry is calculated from the variogram in Eq. (4) of our paper. The covariance element for a pair of locations with the same duration (e.g. 36 and 36 hr) is calculated from the variogram of identical durations for 36 and 36 hr. The covariance element for a pair of locations with different durations (e.g. 36 and 9 hr) is calculated from the variogram across durations for 36 and 9 hr.

References used for this response:

Dombry, C., Engelke, S., and Oesting, M.: Exact simulation of max-stable processes, *Biometrika*, 103, 303-317, 2016.

**Minor comment #14:**

*I. 373 in this case... pair of locations → I don't understand it at all. What covariance matrix are you talking about?*

**Response:** This comment follows from minor comment #13, indicating that we have been ambiguous in this part of the method. We will improve the text to be clearer about how the covariance matrix is constructed.

**Minor comment #15:**

*I. 378 rainfall hyetographs → what rainfall are you talking about? Spatial rainfall over the catchments?*

**Response:** In event-based design methods, template rainfall hyetographs are applied to the areal rainfall total of a catchment for a specified frequency and duration. We will add a brief explanation and reference to design guidelines in the revised version of the manuscript.

**Minor comment #16:**

*Fig. 6: is it useful here? It could be in the supplementary material.*

**Response:** We will move it to the supplementary material.

**Minor comment #17:**

*I. 385 & 387: hydrological models → hydrological model layouts*

**Response:** We will fix this when revising the manuscript.

**Minor comment #18:**

*I. 398: did you apply declustering before estimating the GPDs?*

**Response:** In short, we used estimates based on restricted totals (rather than a moving window) and did not apply declustering. Please also see our response to your major comment #2.

**Minor comment #19:**

*Fig. 7 and SM: there is a huge difference between the extremes at the different stations, e.g. station 2 vs station 6. Could you comment on this? Also what method did you use to produce the confidence bands?*

**Response:** Yes, there is a difference between the extremes at different stations. We can comment on this in the paper. We appreciate it is possible to improve the spatial model with additional covariates (and/or additional data such as daily rainfall observations), but the fidelity of the spatial model is not the main focus of the paper. We feel that the case study is sufficiently plausible to introduce the idea of conditional and joint relationships in hydrologic design.

We used the CAR package in R (qqPlot function). This function produces the confidence bands based on the SEs of the order statistics of an independent random sample (Fox, 2015).

References used for this response:

Fox, J., 2015. Applied regression analysis and generalized linear models. Sage Publications.

**Minor comment #20:**

*I. 421-423: I'm lost here. Do you fit the BR process to annual maxima or exceedances?*

**Response:** Thank you for pointing this out. We fit the BR process to exceedances. We will address this when revising the manuscript.

**Minor comment #21:**

*Caption of Fig 8: Abbreviation TDC is useless*

**Response:** Thanks, we will fix this.

**Minor comment #22:**

*Fig. 9: I don't understand how you get the maps. For this you need the marginal distribution of rainfall at every pixel. How do you get this?*

**Response:** We get the response surface for the marginal distribution parameters of rainfall at every pixel using a thin plate spline regression against longitude and latitude. We unintentionally omitted these details in the original version, but will include them in a revision of the manuscript.



**Minor comment #23:**

*I. 469: average spatial rainfall: I'm confused. How can you transform return levels to averages?*

**Response:** We use areal reduction factors ARFs for this conversion and will clarify the text. ARFs a standard design method used to transform an intensity of extreme rainfall at a point to an average rainfall intensity over a spatial domain with an equivalent probability of exceedance (Ball et al., 2016; Myers, 1980; Omolayo, 1993; Shaw et al., 2011; Siriwardena and Weinmann, 1996).

References used for this response:

Ball, J. et al., 2016. Australian Rainfall and Runoff: A Guide to Flood Estimation. © Commonwealth of Australia (Geoscience Australia).

Myers, V.A., 1980. A methodology for point-to-area rainfall frequency ratios. In: Zehr, R.M. (Ed.), Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. Silver Spring, Md.

Omolayo, A.S., 1993. On the transposition of areal reduction factors for rainfall frequency estimation. J. Hydrol. 145 (1), 191–205. [https://doi.org/10.1016/0022-1694\(93\)90227-Z](https://doi.org/10.1016/0022-1694(93)90227-Z).

Shaw, S.B., Royem, A.A., Riha, S.J., 2011. The relationship between extreme hourly precipitation and surface temperature in different hydroclimatic regions of the United States. J. Hydrometeorol. 12 (2), 319–325. <https://doi.org/10.1175/2011jhm1364.1>.

Siriwardena, L., Weinmann, P., 1996. Derivation of areal reduction factors for design rainfalls in Victoria for Rainfall Durations 18–120 hours. Report, 96(4): 60.

**Minor comment #24:**

*Fig. 11 at the river crossing: which crossing are you talking about? There are several.*

**Response:** Thanks, we will clarify it when revising the manuscript.

**Minor comment #25:**

*I. 495-497: Although Fig 11 ... not part of the method → I don't understand these two sentences. What do you mean by "this is not a physical timing difference"?*

**Response:** This text means that our method focuses on the peak of the conditional design hydrograph and does not consider the difference in the timing of the peak. We will improve the explanation to clarify this.

**Minor comment #26:**

*Fig. 12: I don't understand the AEP. Wouldn't it be clearer with return periods instead of AEP?*

**Response:** As with major comment #6, we consider that AEP is a confused term for the conditional probability in Fig. 12. We will remove this figure and associated discussion.

**Minor comment #27:**

*l. 511: extreme rainfall intensity → over a catchment?*

**Response:** Thanks, we will fix this.

**Minor comment #28:**

*l. 520: and → as a function of?*

**Response:** Thanks, we will fix this.

**Minor comment #29:**

*Fig. 13: as for Fig. 12, would be clearer to show return periods in the x-axis?*

**Response:** Unlike minor comment #26 focussed on Fig. 12, we think the term “annual exceedance probability” (AEP) is straightforward when applied to the joint probability shown in Fig. 13. The AEP and return period are interchangeable as an inverse relationship, but we expect some readers are more familiar with the terminology of return periods. We will audit our use of these terms throughout the manuscript and will apply a consistent terminology.

**Minor comment #30:**

*Caption of Fig. 13: please explain what are the green segments*

**Response:** The green segments are to indicate the interpolation of the individual element failure probability to a system failure probability (discussion line 530). We will add this detail to the figure caption so the description is self contained.

**Minor comment #31:**

*l. 529: 1% annual exceedance prob → 1% AEP*

**Response:** Thank you. We will fix this.

**Minor comment #32:**

*l. 573: 1.74 → I guess this number depends on the considered levels*

**Response:** Yes, this number depends on the pair of locations that we analyse the conditional probability as well as the considered levels, so we will add a clarification of the considered levels in the revised version of the manuscript.

**Minor comment #33:**

*I. 611: inverted max-stable → inverted max-stable process*

**Response:** Thank you, we will fix it when revising the manuscript.

**Minor comment #34:**

*Fig. S1: I don't understand the figure. Could you please explain what a given point represents? Given Table 1, I would have expected to have points at A=91, 294, 341, 771, 1020, which is not the case.*

**Response:** Fig. S1 provides relationships between areal reduction factors (ARFs) and area (in km<sup>2</sup>) for different return periods for the case study catchments. These relationships are calculated through the simulation of inverted Brown-Resnick process over equally sized grid points. To get the ARFs for each of subcatchments in the case study (corresponding to area A=91, 294, 341, 771, 1020), we need to interpolate these relationships. We will improve the explanation in the revised version of the manuscript.