Answer to Referee #2

1) I already reviewed the initial version of this paper, which aims at highlighting the values of high density rain gauges networks for hydrological purposes in a small catchment of mountainous areas. I still believe that the topic is interesting and relevant for the community. It furthermore has other potential applications in urban areas which are also small and quickly reactive catchments where rainfall variability has strong consequences.

Thank you very much for agreeing to review our paper a second time. Indeed, we did not mention urban hydrology in the new version. We will add references to this topic in the introduction (e.g. Cristiano et al., 2017) and discuss it in the conclusion.

2) The minor difficulties with regards to the presentation and understanding of the paper have been corrected. Results are now better presented with the new figures. However, the main point was not addressed, i.e. the fact that the authors aims at showing the importance of grasping the spatio-temporal variability of the rainfall process in the prediction of flows, but the chosen indicators are only event based averages.

First of all, we would like to point out that we accidentally used the formulation “runoff prediction” rather than “runoff coefficient prediction” in the abstract. This having said, we did not mean to pretend that we study the predictability of streamflow but well the relation between rainfall field characteristics and runoff event characteristics, which has indeed a long tradition in hydrology as a basis for model development and comparative hydrology (Merz et al., 2006).

We believe that a focus on the scale of runoff response events is fully justified. We use for our event-based analysis descriptors of two fundamental properties of runoff events, which refer to the time until a response occurs and the magnitude of the response; we choose here the runoff coefficient and a lag time.

We agree that these average streamflow event properties hide other interesting aspects of the hydrological response namely referring to the shape of the response and including e.g. the occurrence of double-peak response. A further detailed analysis of such double-peaked events versus single peaked events is however not possible for this small data set (see Figure showing all streamflow events at the end of this document)..

One additional descriptor of hydrograph shape could be what Tarasova et al. (2018) call the runoff event time scale, i.e. the ratio of runoff volume in mm and the runoff event peak flow in mm/day (see also Gaál et al., 2015). This descriptor could potentially shed light on the mixture of fast and slow runoff response processes. The identification of peak runoff is however extremely challenging for this case study because the moment of peak flow occurrence is often not well defined (see Figure 4 and our response to the point 8 of this document).

Another descriptor for this mixture could be the rising time of an event, quantifying the time to peak (normalized by the event duration). We refrained however from using descriptors requiring a precise quantification of event duration since the identification of an exact start and end time remains extremely challenging (Tarasova et al., 2018) and could largely affect the results in presence of a relatively small data set.

We would be happy to receive any further suggestions to find an additional runoff response shape descriptor.

Finally, this comment can also be read as a critic regarding the fact that we only use average indicators for the rainfall characterization. Please refer to our response to comment 7 for an answer to this point.

3) Furthermore, the main rainfall variability (which is at the core of the paper) indicator used is too simplistic since it is basically an asymmetry indicator on the total depth splitting the catchment in two. So I still think that indicators actually accounting for the spatiotemporal variability of the rainfall and hydrologic response should be implemented to actually address the stated topic of the paper. Implementing them requires major

modifications of the paper. I guess that this would enable to highlight more precisely the importance of dense networks of rainfall measurement devices.

We agree I_{ASYM} is a simple indicator to capture the key rainfall field properties for the hydrological response. In other studies and namely in urban hydrology such an indicator is typically based e.g. on the variogram (Berne et al., 2004) or on the spatial moments of rainfall (Zoccatelli et al., 2011;Mei et al., 2014) of continuously observed rainfall fields (radar images).

The asymmetry indicator is just one of the indicators used in the study, along with the geomorphological distances, which correspond to the above first order spatial moments, albeit decomposed according to hillslope and stream network flow distances. We did not explicitly mention the link to the spatial rainfall moments since we were not aware of the link before writing this comment.

The link to rainfall spatial moments opens new perspectives: the first order moment captures the location of the rainfall centroid, the 2nd order moment would assess the dispersion of the rainfall field relative to its mean location. We will test the usefulness of the 2nd order moment for the revised version.

Furthermore, we would like to emphasize here that compared to e.g. the rainfall width function (see Figure 7 in the public discussion of the earlier version https://hess.copernicus.org/preprints/hess-2019-683/hess-2019-683-AC2-supplement.pdf), the asymmetry indicator has the potential to efficiently discriminate between different event types since it shows a considerable variability between the recorded events. We will provide additional evidence (figures in the Supplementary material) to underline this point.

Please refer also to our response to comment 7 below, referring to a similar topic.

4) l. 110 – 115: "The actual extent of the stream network is based on observations during dry and wet periods during Summer 2017 and its exact path was calculated using the Swiss digital elevation model at a resolution of 2 m (swissALTI3D, 2012)." I think that the intrinsic fractal nature of river networks should be mentioned and discussed. The concept of variable network used after also seems interesting.

Thanks for this interesting comment. As discussed by Rinaldo et al. (1995), the fractality of the basin shape response of the stream network extent is not transferred to the dynamics of the hydrological response, in other words, as Rinaldo et al. put it "one can distinguish from the hydrologic response whether the basin is large or not simply from the regularity of the gauged record (the larger the basin the smoother the gauged trace)."

Our catchment (13.4 km²) is, however, likely not large enough to have a significantly different filtering effect for different network extents. This having said, it would be extremely tempting to develop a method to infer the network extent from the runoff event characteristics. We will mention this exciting outlook in the discussion of the revised version.

5) l. 150-151: "Some additional artefacts were recorded, probably generated by strong winds creating resonance. These periods have been manually removed from the data". It should clarified how the data was selected for being removed and what portion was removed.

We will give more details in the revised version. The removed periods are identified as artefacts because some stations were recording a signal representing a very strong and highly variable rainfall over hours, happening during periods that did obviously not have any actual rainfall. We checked therefore MeteoSwiss RADAR data (that, at least qualitatively, could not have miss such a major event) for confirmation. The weather stations recording wind within the catchment have shown a high wind velocity during these periods, leading to the suggestion of the resonance effect of the device. These details will be added to the revised version of the paper.

6) 1. 154-157: It is a great improvement to use this stochastic procedure. Nevertheless, I believe that more details on the interpolation procedure are needed. It should be clarified how the 20 samples are used (computing the error bars in 8-10)?

The rainfall fields are spatially interpolated from the point measurements. The stochastic model generates 20 different realizations that respect the spatial and temporal structure of rainfall measured by the raingauge network. The amount of precipitation is then spatially averaged, giving 20 possible values for each time step. The mean and standard deviation are computed at each time step based on these 20 realizations, and later at the event scale. These details will be added to the revised version of the paper.

7) Eq. 1 on I_ASYM. As already mentioned, it seems a too simplistic indicator to grasp spatio-temporal variability of the rainfall process. An initial simple suggestion could for instance be to look for the temporal evolution of I_ASYM during an event. But other indicators are needed.

The I_{ASYM} indicator is specific to the elongated catchment shape, and the dimensions of the two defined areas match in our view the temporal scale (event scale) considered in this case. It complements the spatial moments based on geomorphological distance (D_{HILLS} and D_{STREAM}).

The temporal evolution of I_{ASYM} (see Figure 1) shows indeed interesting patterns. For individual events, it sheds further light on what might have caused e.g. a double peak response shape.

For the double peak runoff event #8 (see Figure 4), corresponding to the double rainfall peak event #16 (see Figure 1) stationary on the northern part of the catchment (I_{ASYM} highly negative throughout the event), we can conclude that the double peak runoff response is due to its location within the northern part of the catchment, remaining close to the outlet during its entire duration. The geomorphological distances (see event #16 on Figure 2 for D_{HILLS} and Figure 3 for D_{STREAM}) shows indeed the stationarity of the rainfall field center relatively to the stream network, but not its location within the catchment.

Unfortunately, some of the rainfall events with very clear temporal evolution of I_{ASYM} did not give any significant runoff response (e.g. rainfall event #5 and #21).

A comparison of the I_{ASYM} and the geomorphological distances evolution during these events will shed further light on these events (to be done for the revised version). We will add at least a qualitative discussion of the temporal evolution of the rainfall indicators and how they are linked to the observed runoff responses. The I_{ASYM}, D_{HILLS} (computed using wet and dry networks) and D_{STREAM} (computed using wet and dry networks) for all the 48 rainfall events are in Appendix 1 of this document.

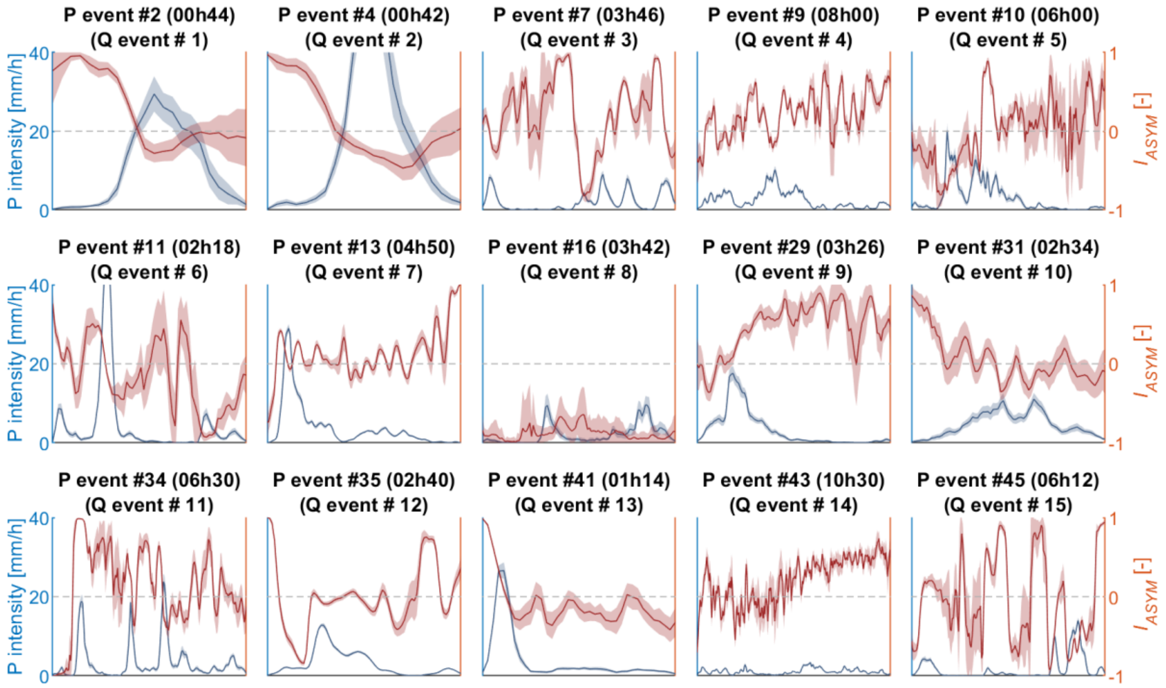

Figure 1. Evolution of rainfall intensity and I_{ASYM} for the 15 rainfall events (P event) associated with a river reaction (Q event).

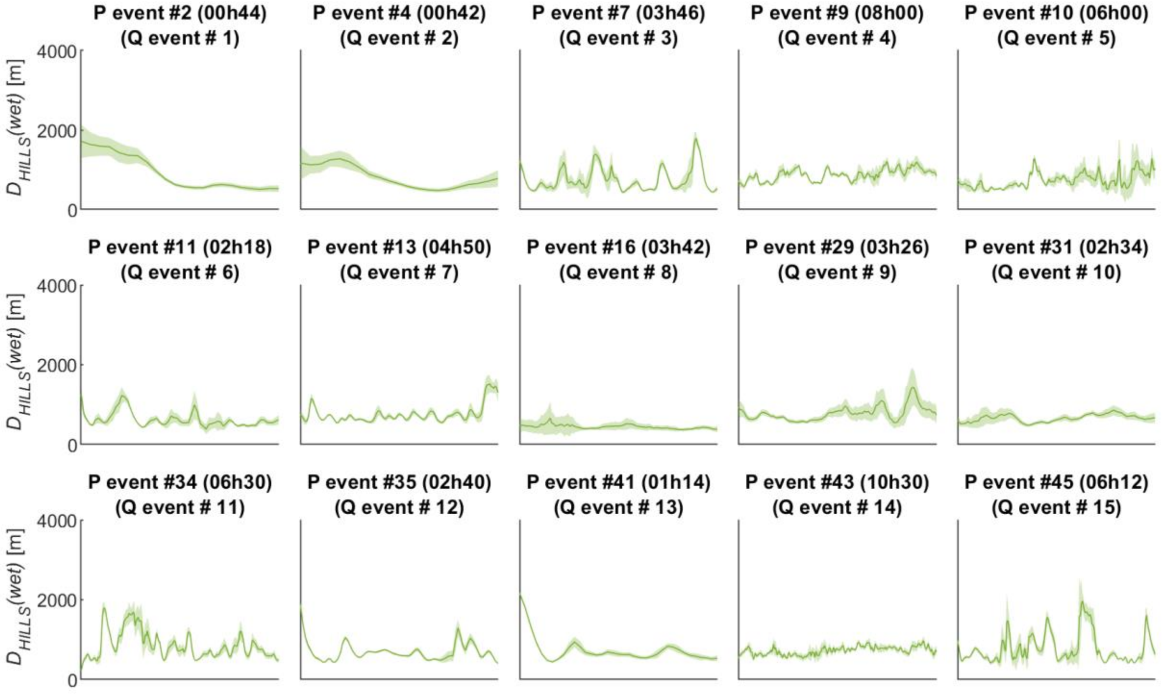

Figure 2. Evolution of D_{HILLS} for the 15 rainfall events (P event) associated with a river reaction (Q event).

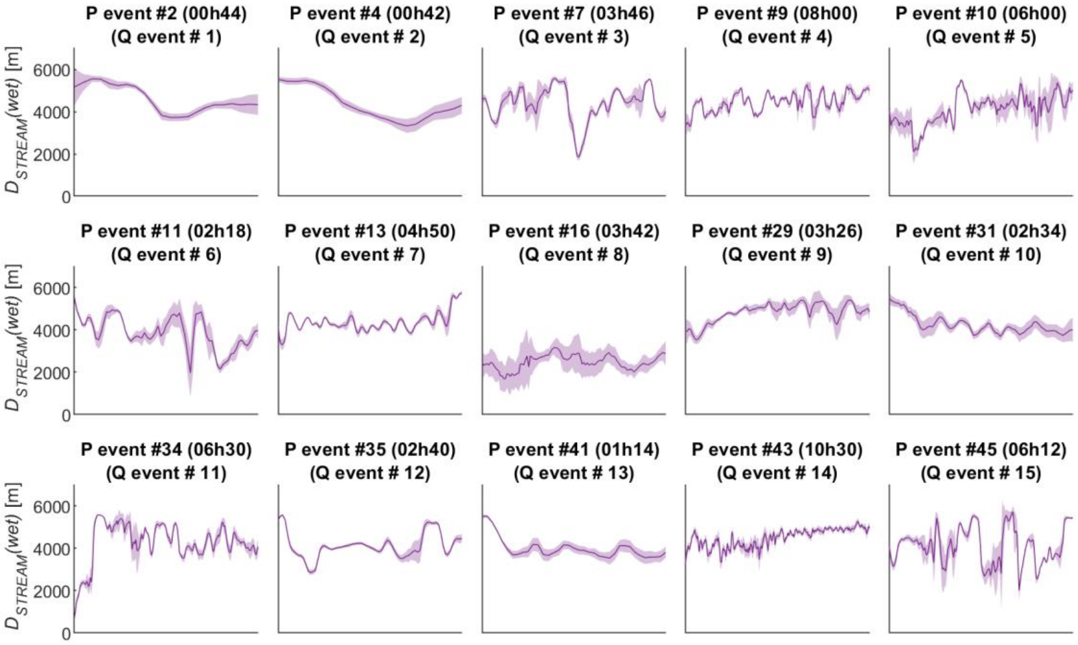

Figure 3. Evolution of D_{STREAM} for the 15 rainfall events (P event) associated with a river reaction (Q event).

8a) l. 212-215 : the explanation on why not using streamflow variations (notably peak flow) is not very convincing.

The timing of peak value is difficult to identify. As visible on the Figure 4 this metric can be used for few events only (Q event #1, #2, #6, #14 and #15). Thus, the hydrograph shape of the observed events is explained more by the fluctuations of the rainfall amounts than by the dynamic of the hydrological processes as is e.g. clearly visible for rainfall event#16 (double peak rainfall event) and runoff response event #8 (double peak runoff response). This observation led us to use event-scale metrics for the hydrological response. In the revised version, we will clearly make this point (based on observed data) at the start of the presentation of the developed methodology and the Figure 4 will be added to the supplementary material.

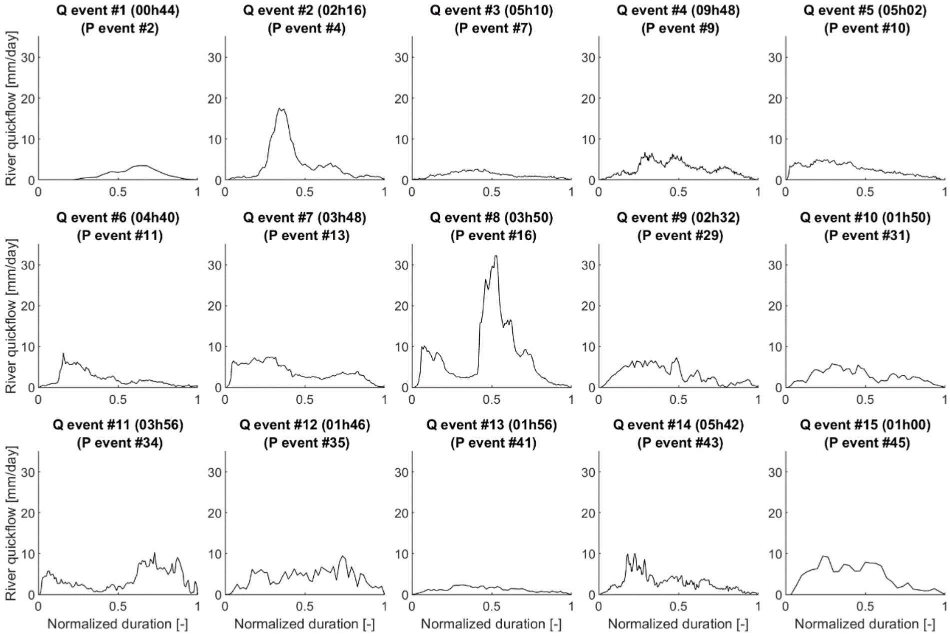

Figure 4. River quickflow for 15 rainfall events (P event) causing a noticeable river reaction (Q event). The length of events is normalized.

8b) If the purpose is to investigate the importance of spatiotemporal variability, I guess studying the temporal variability of the simulated streamflow is needed.

Following this suggestion and the suggestion of the referee #1, we implemented an event-based modelling approach (note: the following answer is identical to the answer 2 given to the referee #1). The runoff response of Vallon de Nant to rainfall forcing is modeled by a semi-distributed model. This model first simulates the mobilization of water at the sub-catchment scale (here 25 sub-catchments are defined over the Vallon de Nant) using a SCS runoff curve number approach. Next, stream discharge is obtained by convoluting the resulting hillslope responses with a travel path distribution derived from the stream network geometry (Schaefli et al., 2013). In the current version (to be refined) the subcatchments and the stream network geometry are identified using *TopoToolbox* (https://topotoolbox.wrrdpress.com) (Figure 5)[1], in which travel paths correspond to the distance between the bottom part of each sub-catchment and the catchment outlet. In this model we focus on the fast response (i.e. runoff) of the catchment, and baseflow (defined here as the average discharge during the 30 min preceding event start) is subtracted from the actual discharge prior to runoff modeling. For calibration, the model is run using the mean of the 20 stochastic rainfall realizations as reference input; it is then calibrated against observed runoff (i.e. discharge - baseflow) through likelihood maximization assuming that the model residuals are normally distributed (e.g. Schaefli et al., 2007). After calibration the event-based runoff model is applied to the different network configurations to test how rain gauge network geometry influences the simulated runoff response. As the stochastic rainfall interpolation cannot be performed with a number of observation points as low as 3 stations (or less), we use the Thiessen polygons method to interpolate the rainfall fields from the 1 to 3-station raingauge network. The results of this model are all shown in the Appendix 2 at the end of this document.

What we can say at this stage is that this kind of typical conceptual event-based hydrological model cannot reproduce all observed events equally well (Appendix 1). This would require in-depth analysis of different subsurface flow mechanisms related also to snow melt and shallow-groundwater recharge, work that is ongoing in this catchment. What is clear is that the simulations with the worst 1 station network are completely off. In exchange, the simulations with the best 1-station, 2-station or 3-stations network is always close to the simulations obtained with the stochastic rainfall fields, which underlines the value of the station network selection methodology in the submitted paper. The analysis furthermore shows that an ill-placed weather station can result in completely erroneous runoff simulation, whereas a network of at least 3 stations results in much better runoff simulations. This conclusion would not have been possible without the high density network observations. However, this model experiment cannot shed further light on the value of the high density networks as the ability of the model to reproduce streamflow responses is not good enough for clear conclusions. This cannot be easily solved with another conceptual model (we tried already other conceptual model structures, e.g. Benoit, 2020) nor with any “out-of-the-shelf” model, which do not exist for high alpine headwater catchments. The development of a fully distributed high resolution (e.g. 10 m x 10m) physical model with the inference of distributed model parameter fields is beyond the reach of this study.

In any case, we can try to include some key results from the modelling study in the revised version.

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[1] An automatic identification of subcatchments corresponding to a manually identified stream network (i.e. identified in the field) is non trivial; solution to be found.

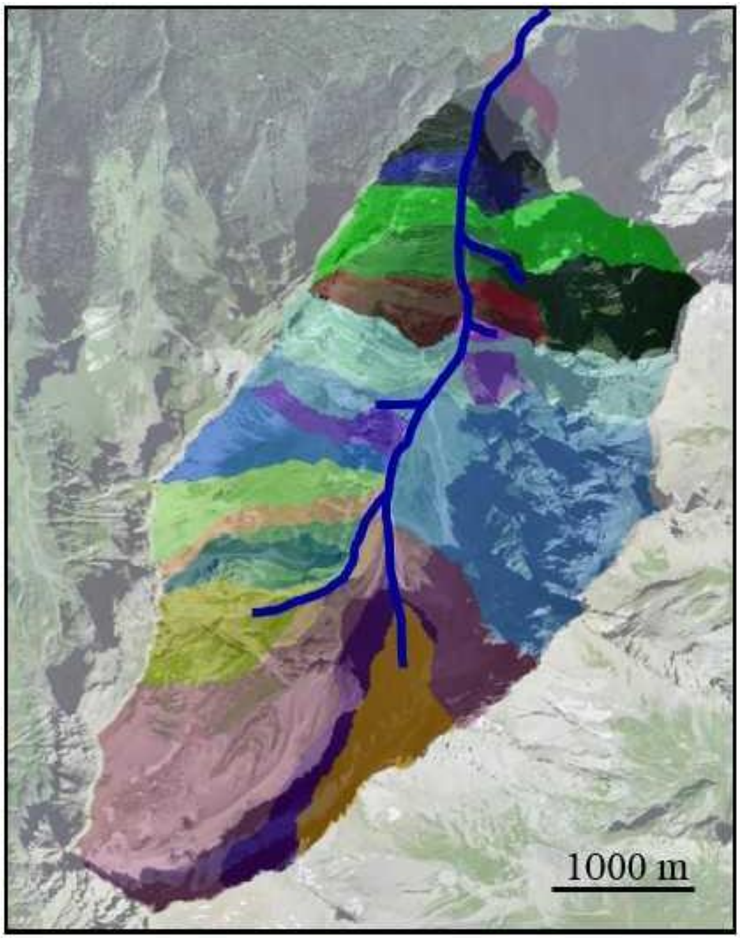

Figure 5. Map of the Vallon the Nant showing the 25 subcatchments and the stream network geometry used for the modelization.

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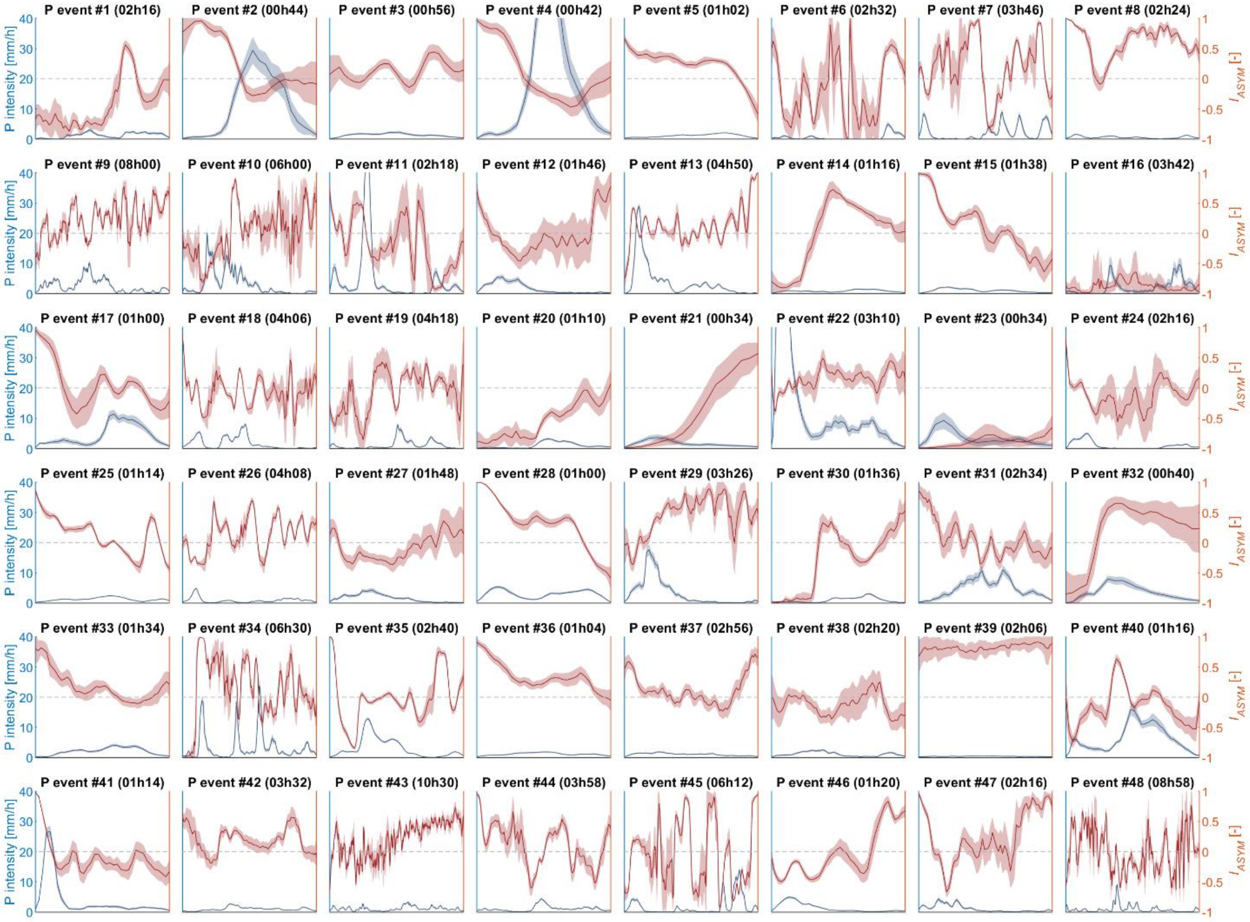
APPENDIX 1: I_{ASYM}, D_{HILLS} and D_{STREAM} for all 48 rainfall events



P event #1 (02h16) P event #2 (00h44) P event #3 (00h56) P event #4 (00h42) P event #5 (01h02) P event #6 (02h32) P event #7 (03h46) P event #8 (02h24)

P event #9 (08h00) P event #10 (06h00) P event #11 (02h18) P event #12 (01h46) P event #13 (04h50) P event #14 (01h16) P event #15 (01h38) P event #16 (03h42)

P event #17 (01h00) P event #18 (04h06) P event #19 (04h18) P event #20 (01h10) P event #21 (00h34) P event #22 (03h10) P event #23 (00h34) P event #24 (02h16)

P event #25 (01h14) P event #26 (04h08) P event #27 (01h48) P event #28 (01h00) P event #29 (03h26) P event #30 (01h36) P event #31 (02h34) P event #32 (00h40)

P event #33 (01h34) P event #34 (06h30) P event #35 (02h40) P event #36 (01h04) P event #37 (02h56) P event #38 (02h20) P event #39 (02h06) P event #40 (01h16)

P event #41 (01h14) P event #42 (03h32) P event #43 (10h30) P event #44 (03h58) P event #45 (06h12) P event #46 (01h20) P event #47 (02h16) P event #48 (08h58)

Figure 6. Evolution of rainfall intensity and I_{ASYM} for the 48 rainfall events (P event).

Figure 7. Evolution of D_{HILLS} (computed with the "wet" network) for the 48 rainfall events (P event).

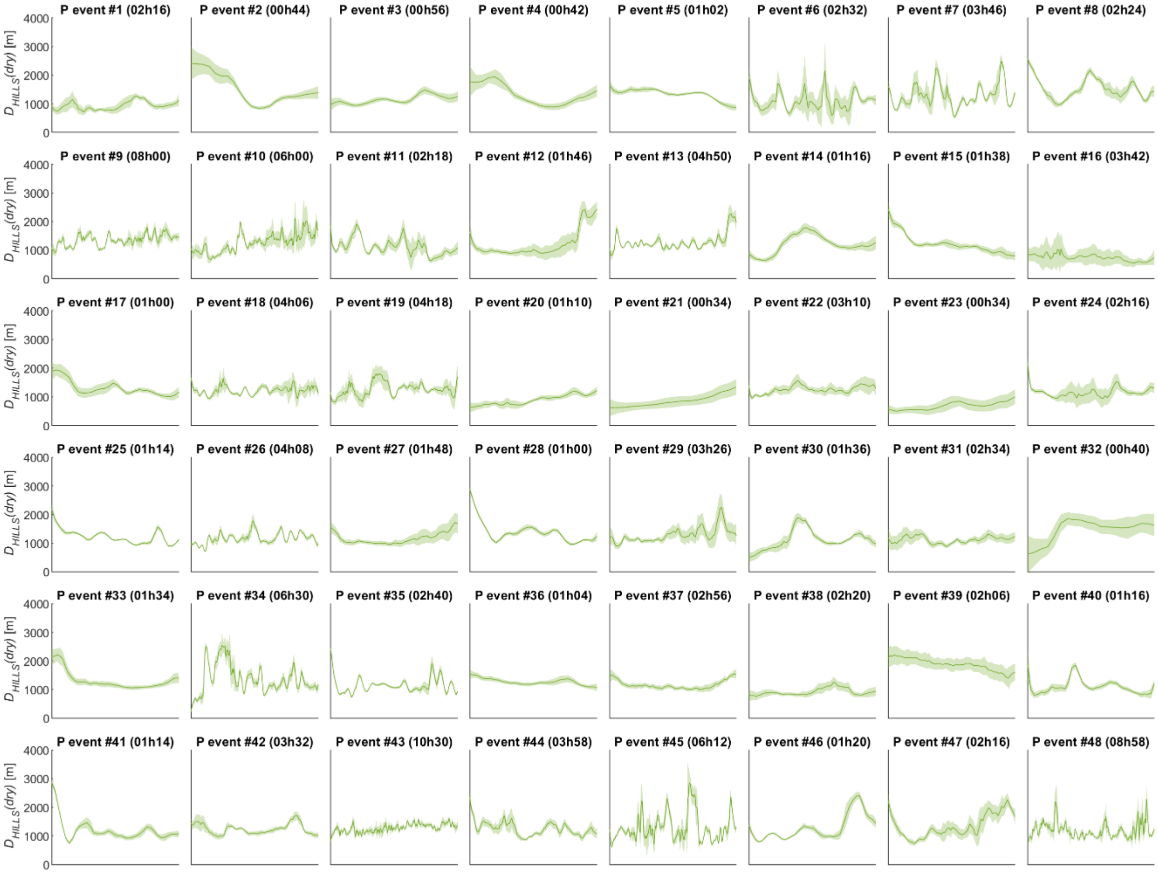


Figure 8. Evolution of D_{HILLS} (computed with the "dry" network) for the 48 rainfall events (P event).

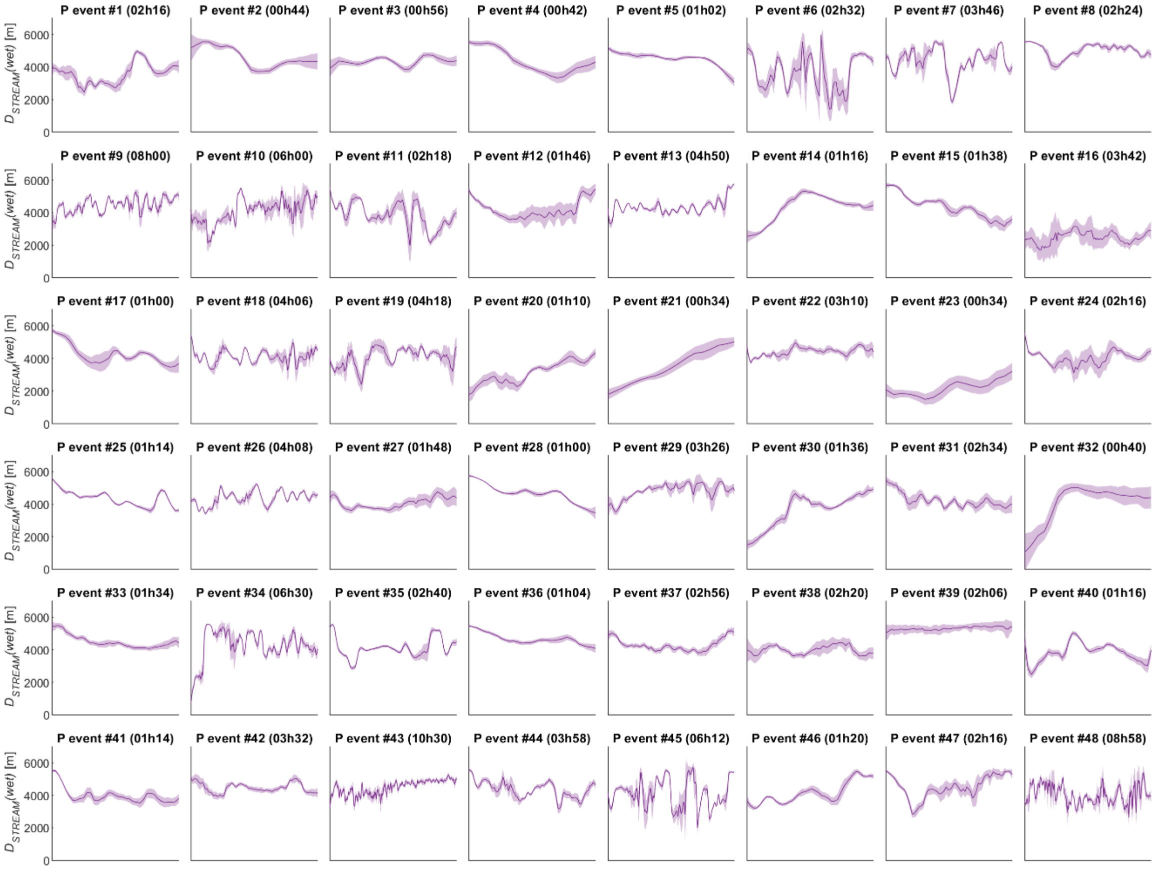


Figure 9. Evolution of D_{STREAM} (computed with the "wet" network) for the 48 rainfall events (P event).

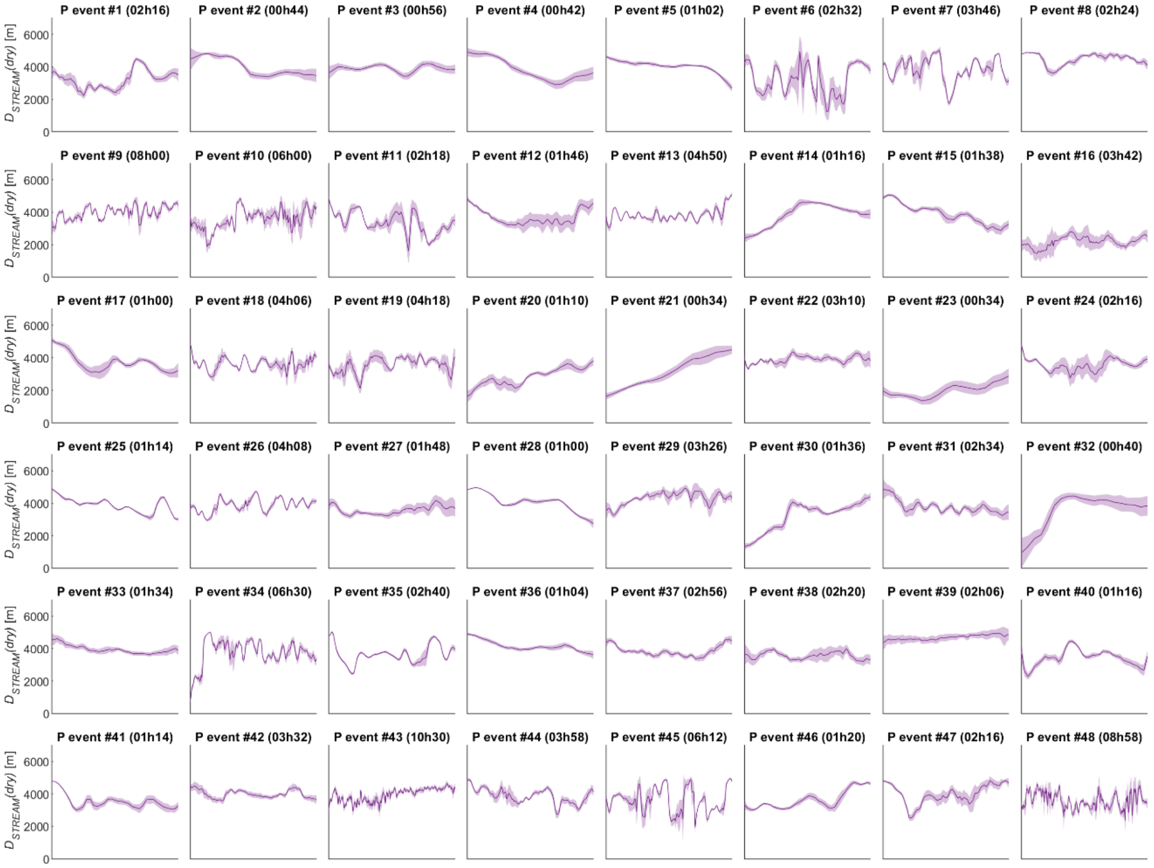
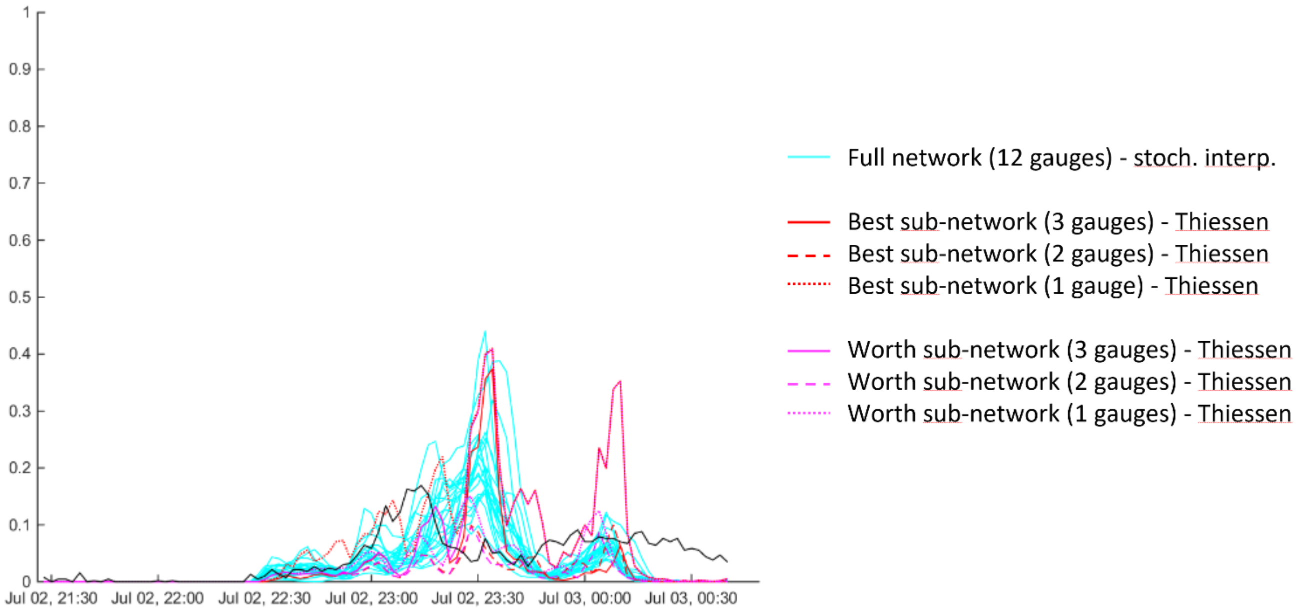


Figure 10. Evolution of D_{STREAM} (computed with the "dry" network) for the 48 rainfall events (P event).

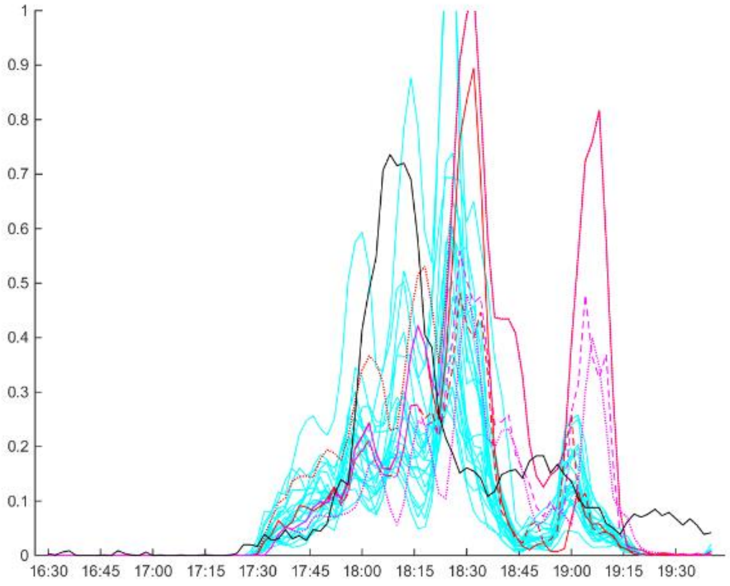
APPENDIX 2: Model results for all of the 15 events



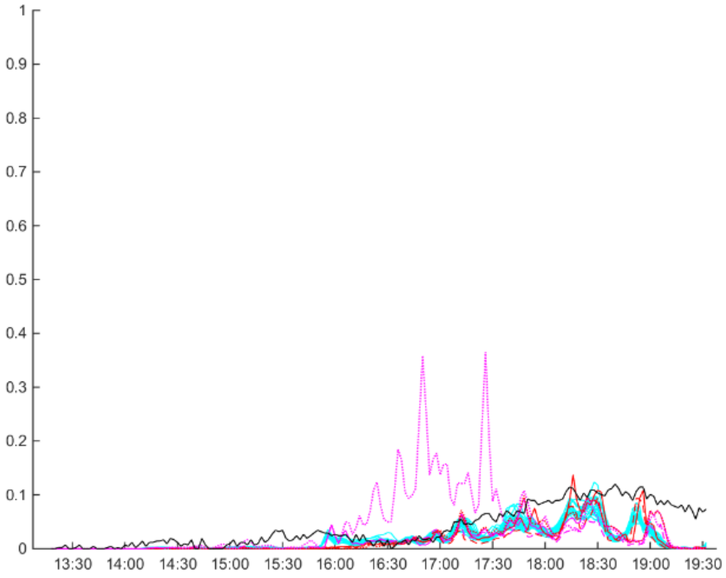
Q event #1 (July 2nd)

On each figure the Y-axis of each hydrograph is in m^3/s.

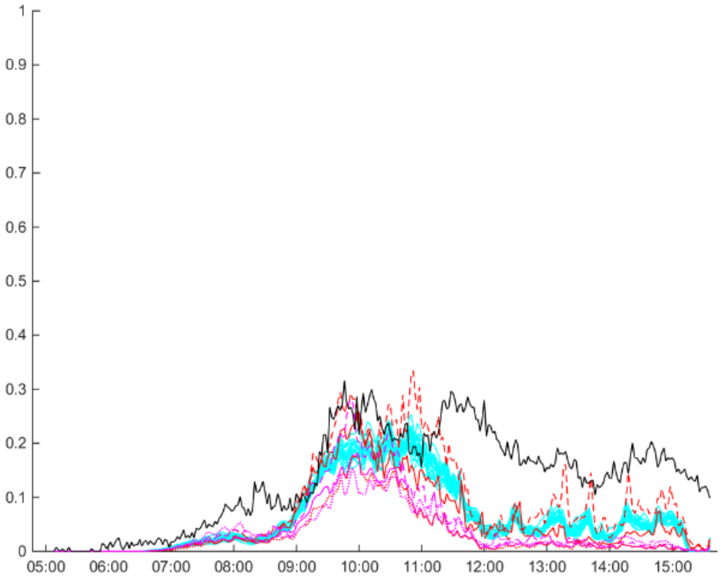
- The black curve is the observed streamflow.
- The 20 blue curves correspond the simulated streamflow based on the 20 possible rainfall fields from the stochastic interpolation method (12-station raingauge network).
- The plain, dashed and dotted red lines are resp. the simulated streamflow using the best 1-station (station #5), 2-station (stations #2 and #9) and 3-station (stations #2, #5 and #11) raingauge network, using the Thiessen polygons interpolation method.
- The plain, dashed and dotted purple lines are resp. the simulated streamflow using the worst 1-station (station #1), 2-station (stations #1 and #3) and 3-station (stations #1, #3 and #4) raingauge network, using the Thiessen polygons interpolation method.



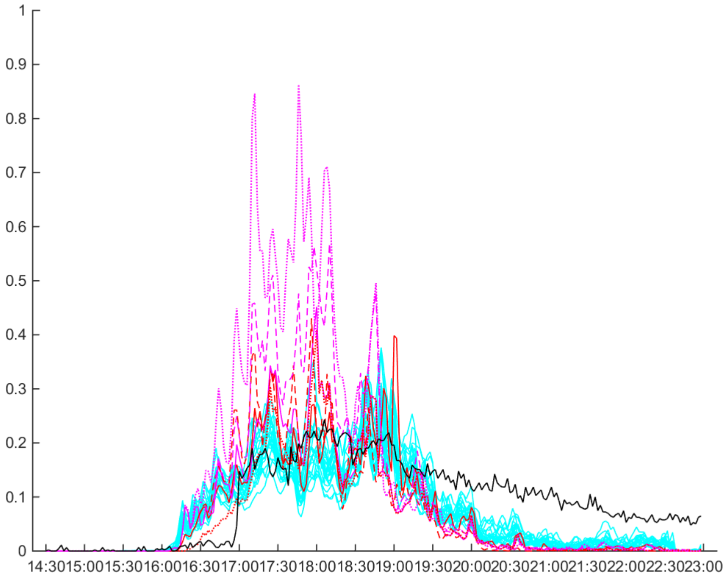
Q event #2 (July 3rd)



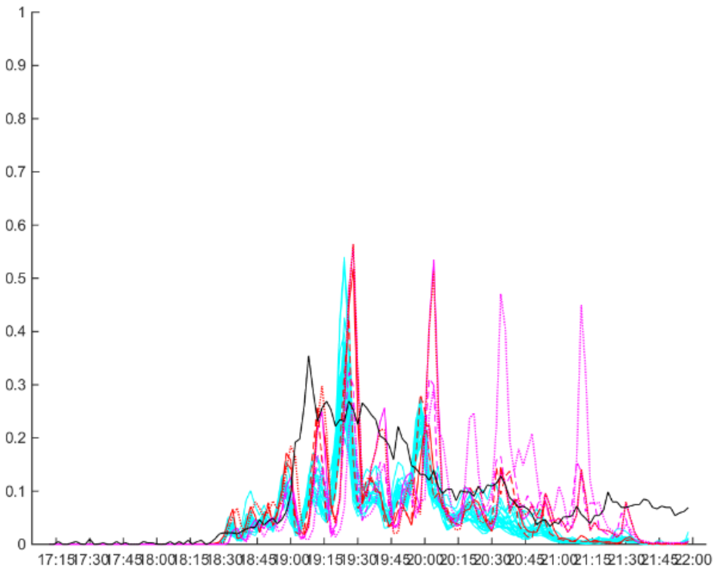
Q event #3 (July 5th)



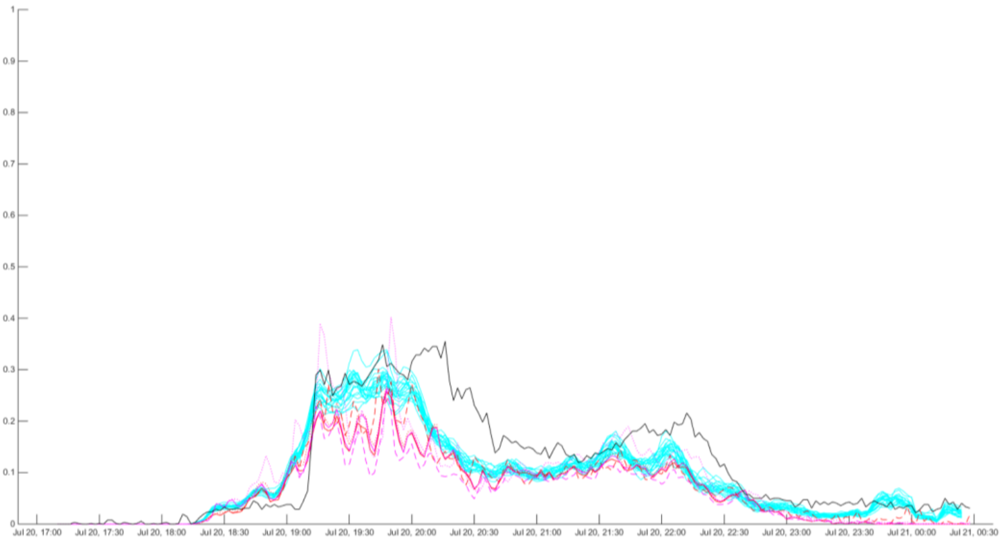
Q event #4 (July 6th)



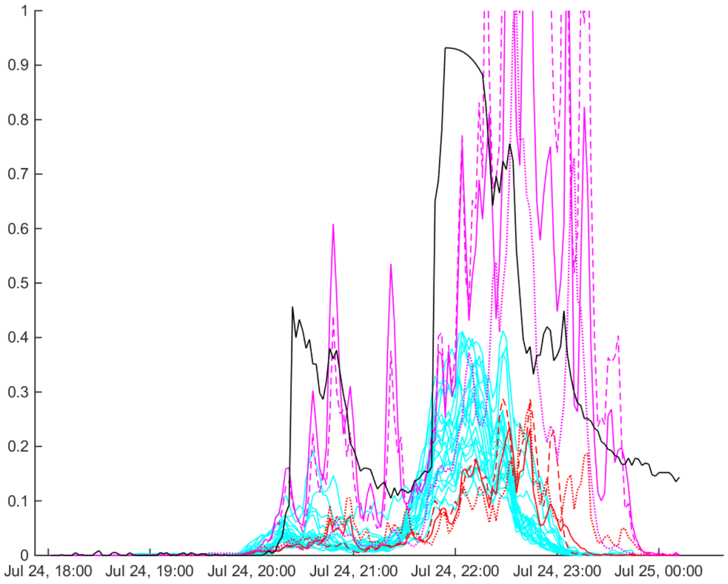
Q event #5 (July 14th)



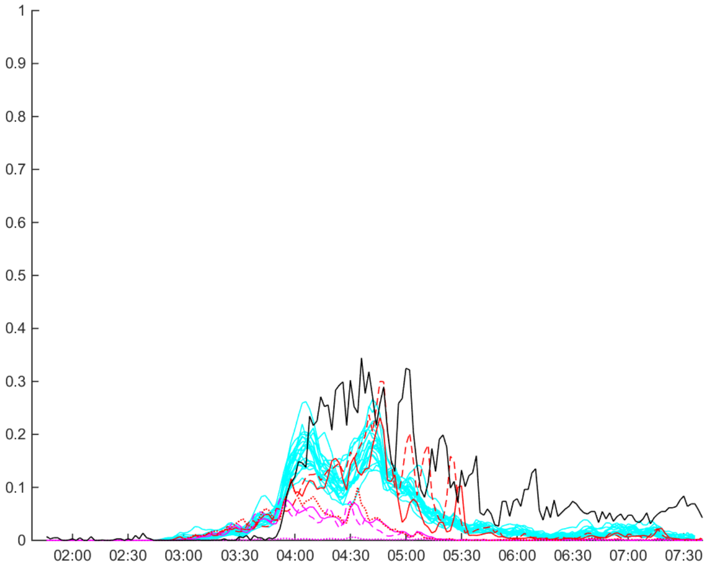
Q event #6 (July 15th)



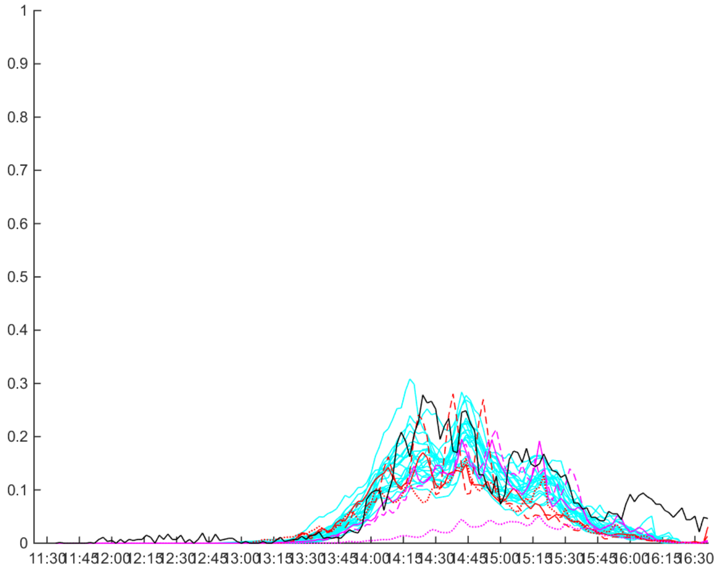
Q event #7 (July 20th)



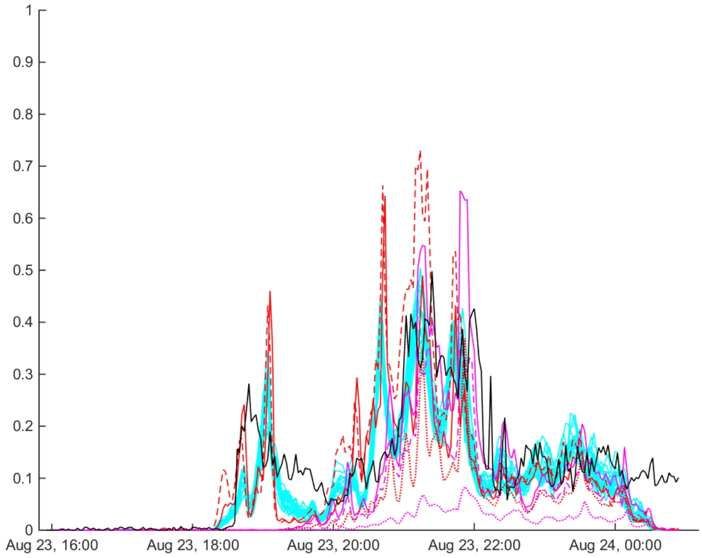
Q event #8 (July 24th)



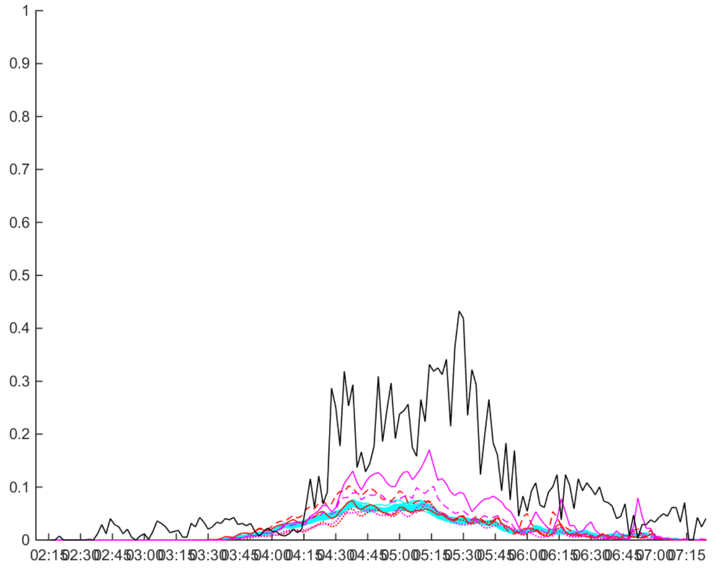
Q event #9 (August 14th)



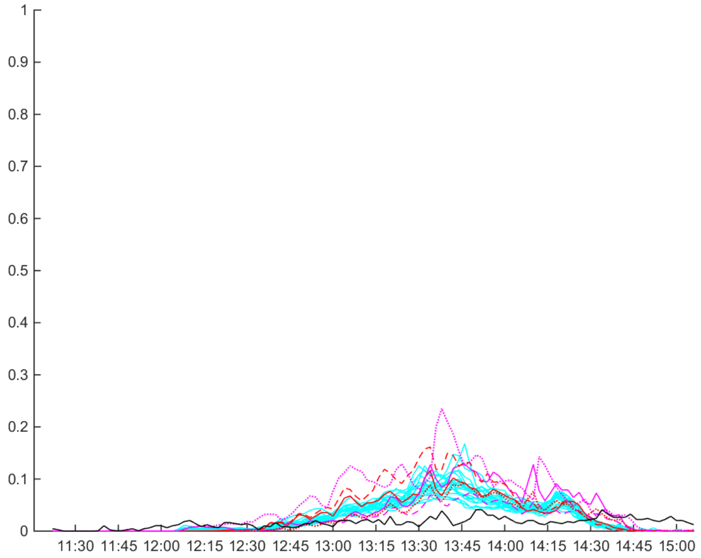
Q event #10 (August 17th)



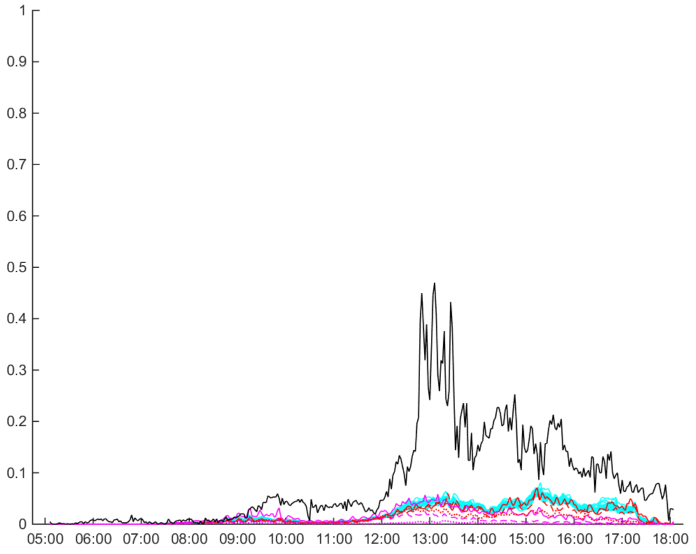
Q event #11 (August 23rd)



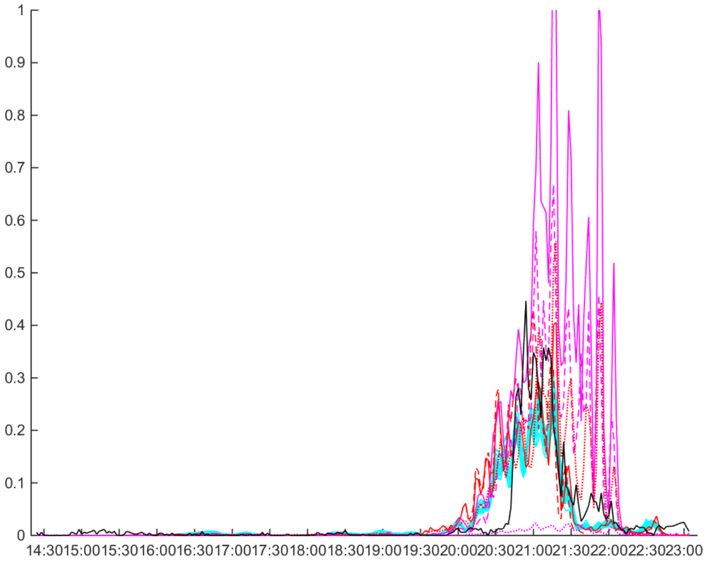
Q event #12 (August 24th)



Q event #13 (August 29th)



Q event #14 (September 1st)



Q event #15 (September 13th)