

Interactive comment on “Characterising hydrological response in urban watersheds based on inter-amount time distributions” by Marie-Claire ten Veldhuis and Marc Schleiss

Marie-Claire ten Veldhuis and Marc Schleiss

j.a.e.tenveldhuis@tudelft.nl

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Review of “Characterising hydrological response in urban watersheds based on inter-amount time distributions” by ten Veldhuis and Schleiss Referee #1 RC: referee comment; Reply: authors’ reply.

Reply (general): Some of the review comments made us realise that the motivation for exploring inter-amount times (IAT) statistics for flow data needs better explanation. In order to make the context and motivation for IAT analysis more clear, we will restructure and focus the introduction section (see also reply to Reviewer#2) and rephrase the objective of our study.

C1

Firstly, IAT analysis is not meant to replace conventional analyses based on flow data, rather to complement it. Secondly, the complementary value of IAT analysis lies in its different sampling strategy: sampling frequency for computation of IATs is adapted to the amount of flow that passes the sampling point. That is, more samples are taken during periods of high flow and fewer samples are taken during low flow conditions. As a result, statistical distributions give more weight to high flow periods (and less weight to low flow periods) compared to statistics for conventional flow data based in fixed temporal sampling windows. Previous studies of IAT analysis for rainfall data have shown to provide additional insights to conventional rainfall analysis. The aim of our study was to explore what additional information can be derived from IAT sampling. Sentences have been added to more explicitly explain these aspects, see Replies to comments below.

RC: The study propose a methodology for sampling flow data sets from water courses in urban watersheds based on samples of equal volume.

RC: Data The stream gauge data used in this study has a temporal resolution of maximum 15 minutes (p4117) but all results reported are for longer aggregation periods: in Figure 8 minimum of 12 hours and in Figure 9 and 10 a minimum of 3 hours. With data available at 15 minutes resolution it should be possible to detect rapid changes in the flow and the manuscript seriously lack comparisons at the sub-hourly scales.

Reply: This is a misunderstanding that we will address in the revised manuscript. The reason why longer aggregation periods were used is that sub-hourly scales cannot be analysed (directly) in the IAT framework. We refer to the definition of minimum observable scale in equation 9: to limit estimation errors of inter-amount times, we allowed an average interpolation error smaller than 50%. Only inter-amount results associated with smaller average interpolation errors were included in the analysis. As can be seen in table 3, minimum observable scales vary between 2.75 and 13.75 hours as a result of this requirement. One key aspect of IAT analysis is that sampling frequency is not fixed, but varies depending on flow variability. Because of this, the time between two

C2

consecutive samples can be very short, even at large scales. What we call the "scale" of analysis is nothing else than the average time between two consecutive samples. But it should be clear that during periods of high flows, much shorter IATs than 24 hours (e.g., 15 minutes or less) are observed. So one of the interesting aspects of IATs is precisely that it helps identify situations in which rapid changes in flow cannot be detected as a result of a too low observational resolution. We will add the following sentences to explain this more explicitly: Introduction (p3, l24): While conventional sampling of flow time series is based on fixed time windows, inter-amount times are based on an adaptive sampling strategy: time series are sampled at higher frequency during periods of high flow and gives relatively little weight to periods of low flow. Inter-amount times sampling results in statistical distributions with different properties compared to conventional flow sampling and can provide different insights that complement traditional analysis Introduction (p3, l34): We find that (...) in intervals, as sampling is based on accumulated flows, independent of the original observation interval. The minimum resolution at which inter-amount times can be reliably sampled depends on the magnitude of flow peaks in the relation to the observation time interval, as explained in section 2.3.

RC: One exception is in Table 3 where the flashiness index is reported for 15 min observational resolution; but here it is unclear whether the 99%-tile of the flow measurements at 15 minutes resolution would give the same answer. Please investigate this and add the results to the discussion.

Reply: The flashiness indicator that we derived in our IAT analysis defines the scale at which 1% of flow accumulations occurs in less than 15 minutes. At higher resolutions, a growing percentage of flow accumulations occurs in less than 15 minutes, hence cannot be detected at the given observational resolution of 15 minutes. Quantiles of conventional flow time series do not provide this information. The 99%-tile gives a flow value that was exceeded 1% of the time, thus tells something about occurrence of peak flows at the sampled resolution (or at the observed resolution, for the 15 minutes time-

C3

scale). By nature of the sampling strategy this does not tell us to what extent observed values are able to capture flow variability in between sampling times.

RC: As illustrated by Figure 3 the inter-amount time methodology result in much less data points than the original data set, but it is very unclear why it provides a better data basis for discussing the hydrological properties than the original 15 minute resolution data.

Reply: This is a misunderstanding that we will clarify better in the figure caption: 3a shows original observed time series, 3b compares flow data and inter-amount data at a same resolution to illustrate how sampling strategies differ.

RC: "Missing data were treated as zeros" (p4l23): how does this influence the results and the estimation error?

Reply: As reported, the percentage of missing data was smaller than 5% for all gauges. Their effect on IATs is difficult to predict as this depends on the pattern of missing values and whether or not they occur during a period of low or peak flow. Sensitivity studies by Schleiss and Smith (2016) have shown that the general effect of replacing missing values by zeros is that a few sample IATs will be overestimated. This mostly affects the right tail of the distribution and tends to have limited impact on peak flow characteristics. We feel this is not a major issue here because (a) there are relatively few missing values and (b) by treating them as zeros, we always assume the worst case scenario.

RC: The catchments used in the study are to some degree sub catchments of each other. This could mean that some stream gauges are correlated (e.g. 507 and 530 (Figure 1)) but this is not discussed in the manuscript. This should be discussed in general and specifically in relation to the results where all catchments are discussed (e.g. Tables 2 and 3 and Figures 5, 7, 20 and 13).

Reply: The reviewer is right in that correlation between basin response may play a role,

C4

through connections in the basin network and in the case of large storm events affecting multiple basins in the region. Previous studies have also shown that these relations are vastly complex, especially in urbanised basins. Spatial distribution of rainfall, flowpath network structure and regulation by stormwater management infrastructure all play a role. The interest of this analysis is in identifying and characterising differences and similarities in response between basins, which could help to gain better insight into where to look for possible hydrologic/hydraulic explanations, basin-to-basin response correlation being only one of the many possible factors.

RC: Figure 1 is very hard to read and could benefit from being enlarged. Also, some will not know where in the world Charlotte, NC, is and it would be beneficial to add a panel of the North American East Coast with a marking of where the study area is.

Reply: thanks for this comment, we will make sure to improve the figure.

RC: Figure 2 is not providing any insight and should be removed.

Reply: Figure 2 visualises times series of flows and associated inter-amount times and shows how the inter-amount times have lower variability and fewer outliers as a result of the different sampling strategies. These aspects are discussed later in relation to the respective statistical distributions. Since many readers will never have seen IAT time series we would prefer to keep this figure.

RC: Inter-amount times The definition of inter-amounts (p4124-p512) is brief and to the point. The section on normalization of inter-amounts (p5113-12) is also brief and the arguments for the methodology are good. The section on sample estimate (p5113-p6118) is somewhat harder to follow. The section thoroughly explain how to convert a time series of flow measurements to a series of inter-amount times and the possible error introduced by the approach but in the results section a measure of the error associated with the present 15 minute resolution data and the present catchments is not reported. This is really needed as it should be really limited how important this is at this fine temporal resolution of the flow data.

C5

Reply: The error in flow measurement associated with temporal observational resolution, in relation to the real flow variability, is not known for these datasets. For this, a set of observations at higher temporal resolution would be required, for comparison. As reported in the paper, flow data are derived from water depth measurements using flow-rating curves that regularly recalibrated by USGS. Documentation reporting quantitative error estimates is not available to the authors.

RC: CV, skewness and medcouple are used to compare inter-amount time and flow distributions. In general the discussion of the results (p915-p1119) are for daily values. This section could be much more interesting by adding results for higher resolution since the native data resolution is so much higher than the daily scale.

Reply: see previous comment, the resolution of IAT analysis is limited by our definition of acceptable error in IAT estimation. We agree that IAT analysis at higher resolution would be very interesting, but this would require much higher observational resolution during peak flow periods. Conversely, our IAT analysis shows that conventional analysis of flow data at 15 minute resolution during periods of peak flows is flawed, since variability in flow extremes cannot be captured at this resolution.

RC: At p10128-29 a bi-modal histogram for catchments with low flow regulation is discussed but not shown, please add these in a supplement.

Reply: An example of a bi-modal histogram is shown for basin 409, in figure 4d. We will make sure to add histograms for the other 2 basins (507, 970) as a supplement

RC: From p10130 to the end of the section is repetition that could and should be left out of the manuscript.

Reply: this is a brief summary of the section and is meant to help the reader recap the main messages of this section. Given the complexity of the analysis and the fact that few readers will be familiar with the notion of inter-amount times, we would prefer to keep this paragraph.

C6

RC: The distribution of changes in inter-amount times is used to identify rapidly increasing and decreasing trends (p11110-30). Figure 6 summarizes the results (again at daily scale) between flow based and inter-amount time based investigations but I cannot see how there can be both inter-amount times and flows in the figure. And it is not clear how to quantitatively get more knowledge from the inter-amount times since the qualitative conclusions will be the same between flows and inter-amount times (even though the skew will be in opposite directions). Please elaborate on this and correct the figure.

Reply: The reviewer is right, histograms for flows were missing. We apologise for this mistake and will make sure it is corrected. The reviewer asks what more knowledge we gain from differences in inter-amount times compared to flows. We will look into this during the revisions and provide more quantitative conclusions or if indeed there is insufficient new quantitative insight, we will remove it.

RC: Inter-amount times are further compared to flows in Figure 8. Figure 8 is a really good example of all the problems you get from having box-plots on a log scale. For both values span several orders of magnitude and is vastly skewed (as indicated by the large difference between the mean and the median). The associated discussion (p11131-13115) is very hard to follow and whether a given percentile is following a power law (p12110-12) or not is effectively impossible to see from the figure. I would suggest a form of normalization of the results to avoid the logarithmic axes in Figure 8 and make the scaling discussion much more accessible.

Reply: The reviewer is correct in that the values span 4 orders of magnitude in scale, hence our choice for visualising the Q-Q plots on a log-scale. Normalisation as suggested by the reviewer has been applied, the current figures are based on normalised values. The distributions are indeed vastly skewed; this is a property of the data and is not associated with visualisation on the log-scale. We will add text to the discussion of the figure, explaining that straight lines on the log plots indicate power-law scaling.

RC: Flashiness From the very first sentences of the abstract (p111-5) flashiness is

C7

highlighted as a key parameter where inter-amount time distributions can really make a difference. In the introduction it is concluded from literature that it is difficult to predict the flashiness of urban watersheds, but no methodologies or results are directly presented. Please add a more thorough introduction on how flashiness is normally calculated from traditional flow data.

Reply: the reviewer has a valid point, we will add a brief literature review on flashiness indicators to the introduction. The most commonly used is the R-B flashiness index, introduced by Baker (2004). We will compute this index for our datasets and compare results with those for the flashiness indicator derived from IAT analysis. An important difference is that the R-B Index essentially measures variance, while the IAT flashiness focuses on high flow accumulations compared to the mean.

RC: The flashiness indicator formulated in the study (p6123-24) is very briefly described and a discussion of why this choice was made and why this is a good indicator for flashiness is completely lacking. Please add these.

Reply: the reviewer is right in that an explicit definition of the flashiness indicator is missing. We will add a clear definition and propose to replace the existing text (p6, l 26-27) by: "In this work, we defined a flashiness indicator based on Inter-amount times, as follows: Def: inter-amount scale at which 1%-tile Inter-amount time falls below the observational resolution of 15 minutes."

RC: The results and discussion for flashiness and minimum observable scale (p13132 +p14) is not easy to follow. In the first section (p13133-p14110) It is discussed that very high peak flows cannot be measured correctly every time with 15 minutes resolution data; but is this interesting at all and is it important to know flow variation at this high resolution? Please add a discussion of this.

Reply: We will rephrase the text to make this point more clear. Essentially, IAT analysis shows at which point flow accumulation within the 15 min observational time window is too high to be properly measured. This is relevant, because it shows that high flow

C8

values occur that are not observed at the given measurement resolution. These values could include critical peak values, for instance for flood generation.

RC: In the next section ('Table 2' should really be 'Table 3') a clear correlation between minimum observable scale and flashiness is reported (p14l18-20) as well as a clear correlation between flashiness and basin area (p14l20-22 + Figure 10); these make perfect sense, but would they be different if flow-based flashiness indicators had been used? Please add a comparison to other flashiness indicators.

Reply: The reviewer is right, we will make sure to correct Table 2 to 3 in the text. We will add results for the most commonly used flashiness indicators, the R-B Index, and compare to our results for IAT-derived flashiness.

RC: In the very end of the section (p14l30-34) a discussion of results not shown is given indicating that the manuscript would benefit from addition of a supplement containing results from all catchments and also the further analysis that has apparently been carried out.

Reply: The reviewer refers to this text in the manuscript "flashiness indexes computed for different sampling resolutions remain almost unchanged up to a transition range (8-16 days)." We will add the results to the supplement in the form of an additional figure.

RC: Multifractal analysis The whole section on scaling (p15l1-29) could really be shortened to one sentence simply stating that scaling is great for both flow and inter amounts accompanied by the left side of Figure 11 unless you can show that there is a statistical significant better fit of one of them. Also the identified departures from linearity (p15l6-88 and the right side of Figure 11) should be statistically significant to be relevant for discussion. Please provide relevant statistics to support the conclusions drawn or shorten the section.

Reply: We propose to keep this section on the results of multifractal analysis and

C9

articulate it around the two main aspects: (1) IATs scale better than flows (e.g., we will provide R2 values in the log-log plots) and (2) UM parameters C1 and alpha are different between the two approaches. Moreover, the C1 and alpha values for IATs are less sensitive to the selected range of scales.

RC: Conclusions In the conclusions it is stated that: "Flows sampled over fixed time intervals did not clearly exhibit this transition. This is result of peak flow variability being poorly sampled by fixed time window sampling." (p16l28-29) but until you add results where you utilize the 15 minutes resolution this cannot be concluded.

Reply: this relates to the comment made for the Data section, where we explained the minimum resolution of analysis or minimum observable scale for IAT analysis is imposed by the definition of a maximum acceptable error.

RC: Another sentence: "Based on inter-amount times distribution we were able to define a flashiness indicator that incorporates both the rising and falling components of the hydrological response" (p17l28-29) seems to be unsupported as the flashiness indicator, as I have understood it, really only tell how many hours of mean flow one can expect as peak flow within a given much shorter time frame (e.g. an indicator of 100 hours for 15 minutes inter-amount times mean that the 99%-tile peak flow is 400 times the mean flow) and how the rise and fall of the peaks are incorporated is not clear.

Reply: the reviewer is right, this way of formulating the conclusion is not correct. We will rephrase the conclusion, make clear that the flashiness indicator is based on 1%-values and we will add a comparison to R-B index values.

RC: It is also concluded from the multifractal analysis that: "This showed that inter-amount times can help better predict peak flow characteristics at small unobservable scales based on coarse resolution data. Additionally, they provide new interesting alternatives for the stochastic modelling and downscaling of flow data." (p17l18-20) and "Scaling analysis showed that inter-amount times provide a promising way to better predict peak flow characteristics at small unobservable scales from coarse resolution

C10

data” (p171131- 32) but this was not discussed at all before in the manuscript and if it is true you should really add results to support this.

Reply: We will make sure to make a clearer distinction in the text between observational resolution and sampling resolution for analysis. The point we want to make is that since IATs are based on fixed flow accumulation values, they will be sampled at higher than the average sampling resolution during peak flows and at low resolution during base flow. Furthermore, since scaling analysis showed better scaling behaviour, especially for higher order moments, downscaling to smaller scales based on IATs is likely to produce more robust results.

RC: Figures In general the figures need some work before publication.

RC: The fonts used are generally very small (e.g. the legend for Figure 1 which is unreadable when printed). Reply: we will make sure to increase the font

RC: The use of sub-figure numbering is inconsistent between text and figures (e.g. Figure 4c and d are not mentioned in the caption and for Figures 6, 8 and 9 the sub-plot labels are missing). Reply: we will make sure to correct figure references

RC: In Figure 9 there is no marking of which color corresponds to which data set. Reply: we add an explanation to the figure caption

RC: Inconsistent use of ‘IATs’ (Figure 11) and ‘inter-amount time’ (Figure 8) as well as ‘Flow’ (Figure 2) and ‘Amounts’ (Figure 11) and ‘medcouple’ (Figure 7) and ‘MC’ (Figure 5). Reply: we will make sure to correct the terms in captions and in figures

RC: What are the units of the x-axes of Figure 6? Reply: we will add the units in the caption

RC: Also put the unit directly on the x-axes of Figure 4 and not only in the text of the figure. Reply: we add unit to the x-axes

RC: For Figure 8 the x-axis seem confusing. For the inter-amount times the volumes

C11

are based on time and should be reported something like “0.51 mm (12h)” but for the flow plot the axis should only be time. Similarly for Figure 11 where the x-axes for flow and inter-amount times should be different. Reply: we will show time only for the axes of the flow plots and show both time and normalised volumes for the axes of the IAT flows, in order to enable easier comparison between the two types of plots.

RC: Concluding remark Indeed, this approach is very interesting as it generate data sets with higher sampling frequency when high flow occur and lower sampling frequency for low flow periods. This is nicely pointed out by the authors. However, from the reported results I am not convinced that the methodology adds so much to the field.

Reply: The method presented here is proposed for analysis of existing datasets, the idea is to complement analysis based on conventional sampling by IAT sampling analysis. The paper shows what additional insights can be obtained, e.g.: flashiness, flow peaks missed at given observational resolution, statistical results less sensitive to outliers, future opportunities for up and downscaling. Additionally, the approach shows that adaptive sampling for collection of flow observations would be beneficial and in which cases most improvements can be expected.

RC: It is also unclear how exactly the authors see that this knowledge can be utilized in future research as 1) very high resolution flow data is used in this study and 2) it is unclear how the results can be used to better describe watersheds with much coarser data available as it is already pointed out that considerable uncertainty is associated with estimation of the peak flow from 15 minutes resolution data; how will than then look if only daily data is available?. Also downscaling of coarse flow data is mentioned, but for the same reasons as just mentioned it is very unpredictable how this will work.

Reply: For opportunities with respect to downscaling of flow data, we refer to previous replies related to the scaling analysis. Regarding the comment on observational resolution, the authors think it safe to say that nowadays automated gauges are replacing manual gauges in many places and with automated gauges observational resolutions

C12

of 15 minutes are quite common and likely to go down to 5 min and 1 min resolution. Especially in urban areas, given the high flow variability at small scales.

References:

Baker, D. B., et al. A new flashiness index: Characteristics and applications to mid-western rivers and streams¹. (2004): 503-522.

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