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Discussions

Characterising hydrological response in urban watersheds based on inter-amount time distributions

Marie-claire ten Veldhuis[1,2] and Marc Schleiss[2]
[1]Delft University of Technology, Watermanagement
[2]Princeton University, Hydrometeorology Group
Correspondence to: Marie-claire ten Veldhuis (j.a.e.tenveldhuis@tudelft.nl)

Abstract. Urban watersheds are typically characterised by a more flashy nature of the hydrological response compared to natural watersheds. Predicting the degree of flashiness associated with urbanisation is not straightforward, as it is influenced by interactions between impervious cover, basin size, drainage connectivity and stormwater management infrastructure. In this study, we present an alternative approach of analysing hydrological response variability and basin flashiness, based on the distribution of inter-amount times. We analyse inter-amount time distributions of streamflow time series for 17 (semi)urbanised basins in North Carolina, US, ranging from 13 km^2 to 238 km^2 in size. We show that in the inter-amount times analysis, sampling frequency is tuned to the local variability in the flow pattern, resulting in more balanced representation of high and low flow periods in the time series. This helps to stabilize the variance of the distribution across scales and leads to more robust scaling behaviour. We show that inter-amount times distributions can be used to detect regulation effects on flow patterns, identify critical sampling resolutions and characterise flashiness of hydrological response. The possibility to use both the classical approach and the inter-amount time framework to identify minimum observable scales and analyse flow data opens up interesting areas for future investigation.

1 Introduction

Hydrological response in urban watersheds tends to be more flashy compared to natural watersheds as a result of the higher degree of imperviousness. Increase in flashiness is typically characterised by shorter response times to rainfall, higher runoff ratios and higher peak flows. On the other hand, high impervious degrees may induce a reduction in base flows and ultimately lead to intermittent flow during dry periods. At the same time, urbanisation is usually tied to development of urban drainage infrastructure, leading to controlled flow as well as higher drainage connectivity. Predicting the degree of flashiness or base flow reduction associated with urbanisation is not straightforward, as it depends on the interplay of impervious cover, basin size and shape, soil properties, basin slope, drainage connectivity and control structures such as detention ponds, weirs and pumps (Berne et al., 2004; Smith et al., 2005; Emmanuel et al., 2012; Fletcher et al., 2013; Smith et al., 2013).

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1.1 Approaches for characterising hydrological response

Many authors have investigated methods for characterising hydrological response, including statistical approaches as well as hydrograph analysis and multivariate regression. Most of these studies have used daily flow time series, while more recently hourly and sub-hourly flow data series have increasingly been used. Traditionally, flow duration curves, representing the frequency distribution of flows, have been used to characterise hydrological response of a given basin. Wood and Hebson (1986) developed dimensionless flood frequency curves and investigated relations with basin and rainfall characteristics, length ratio, a geoclimatic scaling factor and dimensionless mean storm duration. Others have investigated the use of regional flood frequency curves to predict flood response in ungauged basins (Holmes et al., 2002; Castellarin et al., 2004; Booker and Snelder, 2012). Similarly, low flow frequency curves have been used to characterise the influence of prolonged periods of drought, see for instance Smakhtin (2001) for an extensive review. More recently, authors have concluded that univariate flood frequency curves are insufficient to describe flow response and multivariate approaches have been developed, combining several hydrograph properties such as flood peak, flood volume and flood duration (e.g., Salvadori and De Michele, 2004; Favre et al., 2004; Grimaldi and Serinaldi, 2006; Vittal et al., 2015). Other approaches for characterising basin flow response and flood probability include establishment of Instantaneous Unit Hydrographs (e.g., Jakeman et al., 1990) and design flood hydrographs (e.g., Yue et al., 2002; Serinaldi and Grimaldi, 2011; Graler et al., 2013). At the other end of the spectrum, base flow indices and subflow separation techniques have been developed to characterise low flow conditions (Clausen and Pearson, 1995; Willems, 2009). Others have investigated whether statistical properties derived from flow time series are still valid under changing climate conditions (Koutsoyiannis and Montanari, 2007). One of the problems in analysing watershed response across different events and basins is that hydrological response variables need to be normalised for comparison. This is usually done by dividing instantaneous flows and cumulative flow volumes by basin area. The downside of this approach is that definition of basin boundaries is prone to errors and that, especially for basins with inhomogeneous urbanisation coverage, basin area may imperfectly represent flow generation.

Several authors have investigated scaling behaviour of river flows. Tessier et al. (1996) analysed time series of daily river flows for 30 natural river basins in France, with areas of 40 to 200 km^2 and time series length ranging from 11 to 30 years. They found a scale break at approximately 16 days and based on this distinguished two regimes, one for 1-16 days and another for 30-4096 days ($\sim$ 11 yrs). They suggested a possible explanation of this 16-day period being associated to the atmospheric synoptic maximum, the typical lifetime of atmospheric structures at planetary scale. Koutsoyiannis (2003) discussed hydrological statistics in view of climate change and the Hurst phenomenon, i.e. dependence of observed variability on scale. He argues that signals such as trends and jumps detected in long-term time series of atmospheric and hydrological variables using classical statistics are not correct, as they fail to account for this scale dependence. This leads to an underestimation of variance and autocorrelation, especially for large time scales (>10 years), resulting in incorrect detection of trends. Cheng et al. (2001) used statistical and multifractal approaches and GIS to characterize stream networks (up to stream order four) and drainage basin systems of 322 drainage basins in southern Ontario, Canada. They detected a scale break for total stream length at a spatial resolution of around 700 m (different scale dependence for higher resolution, mostly covered by lower order streams, than

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for lower resolution). Based on this analysis, they identified main geological and geomorphological factors including bedrock topography, lithology and slope of drainage basins influencing the evolution of stream networks in the area. Sauquet et al. (2008) analysed scaling properties of hourly river flow time series ranging from 16 to 37 years, for 34 rivers in France draining areas between 12.7 and 703 km^2. They analysed hydrograph shape and flood duration curves across a range of aggregation windows and applied two types of fractal analysis: spectral analysis and moments analysis (for moments q [0.1-4]). In spectral analysis they identified two scaling ranges, with a scale break that ranged from 8.7 hours to 7 days, with a median of 27 hours across stations. They performed the same analysis using daily instead of hourly data and found a scale break at approximately 12 days. Pandey et al. (1998) performed spectral analysis for daily river flow data over 9 to 73 years, for 19 river basins in the USA, with basin areas of 5 to 106 km^2.For most of the rivers, a scale break was observed at approximately 8 days, possibly associated with half of the atmospheric synoptic maximum. Scaling results were independent of basin size and geology. Labat et al. (2002) analysed flow from three karstic watersheds located in the Pyrenees in France and found a scale break at 16 days. In Labat et al. (2013), they revisited this analysis, using time series of 3 minutes (1.5 year period) and 30 minutes (2-10 years periods). with areas of approximately 13 km^2. Based on a spectral analysis of 30 minutes time series, they identified a scale break at approximately 1 day; using Trace Moment analysis they found a scale break at 16 hours. Using 3 minute times series, a scale break was identified at approximately 1 hour. Zhou et al. (2006) analysed daily flow time series of 4 agricultural watersheds in the USA, incl 31 subwatersheds, ranging in size from 0.01 to 334 km^2, with approximately 30 years of records. They found a scale break at 365 days, which could be attributed to seasonality, yet the break persisted even if the seasonality effect was removed. These analyses show that scaling behaviour is found in many flow time series, over a restricted range of scales. For daily flow time series, scale breaks are found in most cases at approximately 16 days. For higher resolution time series, different scale breaks are found, indicating that scaling and scale breaks are dependent on the original resolution of the data and method of analysis.

In this paper we present an alternative approach of analysing hydrological flow variability, that characterises basin response based on the distribution of inter-amount times. The approach is inspired by survival analysis and is based on the use of waiting times between successive amounts of accumulated flow. Inter-amount times were used in a recent study to characterise rainfall regimes (Schleiss and Smith, 2016). They characterised rainfall regimes in terms of two parameters derived from inter-amount time series: burstiness and memory. Burstiness provides a normalised measure of inter-amounts dispersion, memory characterises temporal ordering of inter-amounts and together they quantify the degree of rainfall intermittency. Results showed that distinct regional patterns of rainfall and intermittency regimes could be identified based on burstiness and memory values.

The aim of this paper is to explore how inter-amounts can be used to characterise hydrologic response for a range of (semi)urban watersheds in North Carolina, US. To do this, we analyse the distribution and scaling properties of inter-amount times and compare our results with traditional analysis techniques based on flow time series.

We find that one of the advantages of the inter-amounts approach is that it automatically deals with varying observation time intervals, as the time resolution of flow measurements is often increased during periods of high flow compared to periods of low flow. Also, it allows comparison between basins without the need for normalising by basin area. A problem that arises in analysing watershed response across different events and basins is that hydrological response variables need to be normalised

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for comparison. This is usually done by dividing flows by basin area. The downside of this approach is that definition of basin boundaries is prone to errors and that, especially for basins with inhomogeneous urbanisation coverage, basin area may imperfectly represent flow generation. A conceptually elegant aspect of the inter-amount times approach is that it allows comparison of statistical properties of flow times series, independent of basin size.

This paper is organised as follows, in section 2 we present the flow datasets used for analysis. The methodology for deriving normalised inter-amount times is explained as well as properties of flow time series and inter-amount times we used to characterise hydrological response and compare response across the different basins. In section 3, results of the analyses are presented and discussed. Conclusions and suggestions for further work are summarised in section 4.

2 Data and Methods

2.1 Flow datasets

The data used in the study were collected at 17 USGS stream gauging stations in Charlotte-Mecklenburg county, North Carolina. Gauging stations are located at the outlet of hydrological basins that range from 13 km^2 to 238 km^2 in size. The area is largely covered by low to high intensity urban development, covering 60% to 100% of basin areas. Percentage impervious cover varies from 8% in the least developed to 48% in the most urbanised basin covering the city centre of Charlotte. Figure 1 shows a map with the location of the area, watershed boundaries and location of stream gauges used in the analysis, table 1 summarises the main characteristics of the 17 basins.

Stream gage data were collected at 5 to 15 minute intervals over the period 1986-2011. Table 1 summarises the characteristics of the basins associated with each basin as well as the time period covered by the data. The temporal sampling resolution changed from 15 to 5 minutes between 2010 and 2014, at different times for each gauge; overall 20-30% of the total observation record was covered by 5 minute intervals. Gauges measure water depth using pressure transducers and flow is derived using stage-discharge curves. These curves were established based on manual flow measurements during site visits and curves were checked and recalibrated during site visits several times per year. The percentage of missing flow data was smaller than 5% for all gauges included in the analysis; missing data were treated like zeros.

2.2 Definition of inter-amount times

The following definition of inter-amount time (IATs) is based on Schleiss and Smith (2016): Let $\Delta q > 0$ denote a fixed flow amount. We define the series of inter-amounts times $\tau_k(\Delta q)$ with respect to q as follows:

$$\tau_k(\Delta q) = t_k(\Delta q) - t_{k-1}(\Delta q) \tag{1}$$

where $t_k(\Delta q)$ denotes the time at which the cumulative flow amount first exceeded k times (Δq):

$$t_k(\Delta q) = min\{u : y(u) \geq k \cdot (\Delta q)\} \tag{2}$$

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A steady flow pattern with constant flow has equal inter-amount times for all values of Δq. A variable flow pattern, on the other hand, is characterized by a more variable inter-amount time distribution.

2.3 Normalized inter-amounts

Flow magnitudes strongly vary from one gauge to another. To overcome this scale dependence and compare flow inter-amount times across basins with different sizes and flow amounts, one needs to normalize IATs with respect to a common timescale. A possible way to do this is to fix an average inter-amount time $\bar{\tau}$ (e.g., 24 h) and determine the inter-amount $\Delta q_{\bar{\tau}}$ at this timescale:

$$\Delta q_{\bar{\tau}} = \bar{\tau}\frac{Y}{L} \tag{3}$$

where Y denotes the total cumulative flow amount at the considered location and L is the length of the studied time period. In other words, instead of comparing inter-amount times for a fixed accumulation, we choose the mean inter-amount time $\bar{\tau}$ and compute $(\Delta q)_{\bar{\tau}}$ such that the series of inter-amount times $\{\tau_k(\Delta q_{\bar{\tau}}) : k = 1,..,n\}$ has mean $\bar{\tau}$. Two locations with different cumulative flow amounts over a given period of time, e.g. over a year, therefore have different normalized inter-amounts.

2.4 Sample estimates and minimum inter-amount scale

Inter-amount times can be estimated from a sample flow time series $r_1,..,r_N$ with temporal resolution $\Delta(t)$ that may vary along the time series. A key step in this procedure is the determination of the first passage times $t_1,..,t_n$ in equation 2. This is done by considering the sample accumulated flow amounts $Q_1 < .. < Q_N$ at times $t_n = t_0 + n\Delta(t)$:

$$Q_n = \sum_{i=1}^{n} q_i \tag{4}$$

where n=1, ..,N

The exact passage times $t_1,..,t_n$ are likely to be unknown due to the limited sampling resolution of the data. We approximate them based on linear interpolation:

$$\hat{t_n}(nq) = \Delta t\left(i_{nq} - \frac{Q_t, nq - nq}{q_i, nq}\right) \tag{5}$$

where i_{nq} denotes the index (in the sample) at which the total cumulated flow first exceeded n.q:

$$i_{nq} = min\{i \in \mathbb{N} | R_i \geq nq\} \tag{6}$$

The sample inter-amount time estimates are then given by:

$$\hat{\tau}_n(q) = \hat{T}(nq) - \hat{T}(nq - q) \tag{7}$$

where $n \in \mathbb{N}$

A key point here is to know how the linear interpolation in equation 5 affects the accuracy of sample inter-amount time estimates. The most severe interpolation errors arise during periods of peak flow, when inter-amount times are short, possibly shorter than the measurement interval Δt. To identify the range of scales over which inter-amount times can be reliably estimated, we consider the worst case scenario in which all interpolation errors are equal to +/- Δt. In this case, the maximum relative error affecting IAT estimates is given by:

$$\varepsilon_n(q) = \frac{\Delta t}{\hat{\tau}(q)} \tag{8}$$

The minimum value of q for which inter-amount times can be reliably estimated depends on how strictly we want to control the estimation errors in 8. In our analysis, the minimum inter-amount Δq was based on the following rule:

$$q_{min} = min\{q > 0 \quad \text{and} \quad \overline{\varepsilon}_q < 0.5\} \tag{9}$$

This implies that the mean of absolute relative errors must be smaller than 50%. This is a rather conservative approach as the estimation errors in 9 represent the worst case scenario and actual errors are likely to be much smaller than that.

In addition to the lower bound, we also impose an upper bound on the inter-amount to ensure inter-amount time series are long enough to compute relevant statistical moments. Typically, there should be at least 100 consecutive inter-amount times, which yields the following upper bound for inter-amount Δq:

$$\Delta q_{max} = \lfloor \frac{Q_N}{100} \rfloor \tag{10}$$

where: $\lfloor\rfloor$ denotes the lower integer part and Q_N is the total cumulative flow for the considered time series.

As can be seen from equation 5, the lower bound for the inter-amount provides an indication of the lower-tail properties of inter-amount time distributions, thus of the degree of flashiness of the hydrological response. After all, the flashier a watershed is, the quicker the flow can rise, resulting in lower inter-amount times during times of heavy rain. Conventionally, flashiness is characterised by (normalised) peak flow magnitude and response time (e.g., Smith and Smith, 2015). 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. In this work we defined a flashiness indicator as follows: basin flashiness (unit: hours) is computed as the ratio of the 1% quantile of inter-amout times with respect to the mean inter-amount time.

Incidentally, the minimum observable inter-amount represents the smallest scale at which flow variations can be studied given a fixed temporal resolution. By extension, the lower tail of the inter-amount time distribution provides a good indication of what resolution is necessary to adequately capture the most extreme flow variations.

Analyses were conducted for all gauges over the entire period of available data, without distinguishing between year, season or hour of the day. This was necessary as time series would otherwise be too short to study IATs across different scales. We investigated characteristics derived from inter-amount time and flow distributions and compared results across the 17 basins based on two properties: area size and imperviousness degree. Additionally, we looked into potential influence of flow regulation and stormwater detention facilities, as far as this information was available for the 17 basins. In this study we refrained from investigating long-term trends, as our time series were restricted to maximum 30 years. In a recent study by Villarini (2016) it was shown that no long-term trends were detected in flow series from 7506 gauges in the contiguous US over a period of 30 years. Our own analyses revealed no long-term trend in mean inter-amount time or flow variability over the considered 30 years.

2.5 Distribution of inter-amount times versus flows

One possible way of getting new insight into the variability of flow time series across different basins is to look at the sample histograms of inter-amount times. An advantage of inter-amount times analysis is that periods of low flows, which typically constitute a major part of traditional flow time series, form a much smaller part of the inter-amount times distribution. Also, while traditional flow analysis puts a lot of emphasis on peak flows and upper-tail properties of flow rates, the part of inter-amount times that relates to peak flow is located in the lower tail of the distribution. Upper-tail properties of inter-amount times on the other hand are associated with rare occurrences of prolonged low flow. And, although inter-amount times and flow rates are related, they reflect different aspects of flow variability. Hence, comparing the two types of distributions provides insight into different aspects of the flow regime.

We plotted sample histograms for all gauges, for flows and inter-amount times. Scott's rule was used to determine an appropriate width for the histogram bins (Scott, 1979). We computed the coefficient of variation, defined as μ/σ, as a summary indicator for variability, as well as skewness and medcouple (Brys et al., 2004), a more robust measure for skewness that is less sensitive to outliers. We compared CV, skewness and medcouple values for inter-amount times with those for traditional flow time series and investigated relationships of the three statistics with basin area and imperviousness degree of the basins.

2.6 Distribution of changes in inter-amount times

Changes in inter-amount times indicate how fast flow hydrographs rise or fall and thus provide another way of characterising flow behaviour. We computed first-order differences of IATs. Because inter-amount times are measured on an inverted scale, positive differences are associated with the falling limb of the hydrograph and negative differences with the rising limb of the hydrograph. Differences were computed at the 24-hour time scale, imposed by the minimum inter-amount scale rule. Selection of bin widths was based on Scott's rule (Scott, 1979). Studying the rising and falling limbs of hydrographs using inter-amount times is facilitated by the fact that, since IAT time series are based on accumulated flow volumes, both limbs are equally sampled, which is not the case for traditional flow analyses based on fixed-sampling time representations.

Narrow range of histogram values for IAT differences indicates slowly varying flow, wide range histogram indicate more flashy behaviour. Positively skewed histograms for inter-amount times differences indicate that the distribution is dominated by values on the rising limb and short recession limbs, while negatively skewed histograms indicate a larger part of the flow is associated with flow recession, i.e. long, slowly receding hydrographs, for instance induced by a strong groundwater flow component.

2.7 Scaling of inter-amount times across inter-amount time resolutions

We investigated how CV values and distribution quantiles depend on scale, over a range of 3 to 12 hours up to 32 to 128 days (depending on the length of the data series for each gauge). Additionally, multi-fractal analysis techniques were applied to analyse scaling behaviour of the inter-amount time series across different inter-amount resolutions. Multi-fractal analysis is based on the notion of generalised scale invariance, in which case the following relationship applies (see Schertzer and Lovejoy (1987) for a more elaborate explanation of the multifractal framework):

$$\langle X_\lambda^q \rangle \sim \lambda^{K(q)} \tag{11}$$

Where: X_λ^q: moments of inter-amount time series, λ : scaling ratio, q : moment order, K(q) : scaling moment function.

For conservative Universal Multifractals (UM) (Schertzer and Lovejoy, 1987, 2011), K(q) is characterised with the help of only two parameters, α and C_1. Parameter C_1 is referred to as the intermittency co-dimension and characterises the clustering (intermittency) of the time series at smaller and smaller scales. C_1 = 0 for a homogeneous field that fills the embedded space and approaches 1 for an extremely concentrated field. Parameter α is the multi-fractality index ($0 < \alpha < 2$) and determines how quickly the underlying distribution changes across scales. When $\alpha = 0$, intermittency does not change with scale and the field is fractal, i.e. it can be defined with the help of a unique fractal dimension.

For the case of multi-fractal analysis of inter-amount times, the relation between mean inter-amount and scaling ratio is as follows: $\mu = E[T_\mu]$, where $\mu \sim 1/\lambda$

$$K(q) = \frac{C_1(q^\alpha - q)}{\alpha - 1} - qH \tag{12}$$

The case $\alpha = 1$ is derived from (12) for $\alpha \to 1$:

$$K(q) = C_1 q log(q); \alpha = 1 \tag{13}$$

Where α and C_1 are parameters defined in the framework of Universal Multifractals (UM):
C_1 : UM parameter characterising intermittency, i.e. the degree at which statistical properties of the time series (statistical moments, this case) change with scaling ratio.
α: UM parameter characterising multifractality, i.e. not a single scaling relationship, but multiple scaling relationships characterise scaling behaviour (scaling moment function K(q) changes with scaling ratio). Values vary between 0 and 2, where the two extreme cases correspond to the monofractal and lognormal models respectively.
H : Conservation parameter. For $H = 1$, the 1^{st} moment (mean) changes linearly with scale; for $H = 0$, 1^{st} moment is constant.

If (11) is true, the log-moments (for a given q) should be a linear function of the log-scale. Hence log-log plots can be used to study scaling. We plotted the moments X_λ^q as a function of mean inter-amount scale Δq, i.e. the inverse of the scaling ratio λ, on a log-log scale, for moments of order 0.4 to 2.5, based on Lombardo et al. (2014). The range of scales we used was determined by the length of the time series and the minimum inter-amount time defined by equation 9. It varied from 0.1 to

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0.6 days up to 28 to 100 days for the longest time series. We applied the same procedure to flow times series and plotted the log-moments of the flow volumes as a function of log time scale. We then analysed the log-log plots to assess the scaling quality, fit the values of α and C_1 and detect possible scale breaks.

3 Results

3.1 Time series and variability analysis of inter-amount times and flow values

Figure 2 shows an example of times series for flow and for inter-amount times for the gauge at Taggart Creek, a 13.6 km^2 basin in the Charlotte watershed, for 24 hour resolution. The associated inter-amount Δq is 13,559 m^3.

The two graphs bring out different aspects of flow variability: flow time series have most of their data points concentrated in the low flow region, with intermittent peak flows characterising storm events. For inter-amount times, peak flows can be identified as minima, while periods of low flow show up as maxima in the time series. The mean inter-amount for Taggart Creek at daily resolution is 13,559 m^3, equivalent to 0.9977 mm when normalised by basin area. Hence, in inter-amount analysis, the time series is sampled each time 0.9977 mm of normalised flow has been accumulated. For the flow time series, sampling frequency is constant. Hence small flow amounts correspond to low flow and large amounts correspond to peak flow. Both time series show seasonal variability associated with the summer and winter seasons, as well as inter-annual variability associated with wetter and dryer years. The main difference with the classical sampling is that in the inter-amount times formalism, the sampling rate is adapted to local variations in flow volumes rather than on an arbitrary fixed time interval.

Figure 3 illustrates how the choice of flow amount as a unit of analysis instead of fixed time steps influences sampling of the time series. The graph show cumulative flow over a week, where a storm event occurred on 7 August. In conventional flow time series analysis, flow would be sampled daily (in this example), resulting in one sampling during the peak period of the event (7 August). In inter-amount times analysis, flow accumulation determines the sampling frequency, so periods of low flow are sparsely sampled, while the storm event is represented by eight samples. Thus, in inter-amount times analysis, data sampling frequency is in accordance with the degree of variability in the time series, also referred to as adaptive sampling.

Histograms of flow time series and inter-amount times are plotted in figure 4, for Taggart Creek and LSugarA, for temporal aggregation scale, respectively inter-amount time of 24 hours. The figure shows that the histograms are all positively skewed: for flows, low flow values are prevalent, while for inter-amount times, low inter-amount time values associated with periods of high flow are sampled more frequently. Rare periods of low flow are represented in the right tail of the inter-amount times distribution. The first bin in the flow histogram for LSugarA has very low density: this reflects the effect of low flow regulation for this basin. The same effect is reflected in the bi-modal shape of the inter-amount times histogram. Note that the low density 0-0.5 bin in the flow histogram for LSugarA corresponds to the >3.5 day bins in the inter-amount time histogram. Table 2 summarises statistics of time series for flow and inter-amount times, at 24 hour resolution. The results show that mean inter-amounts vary from 12,275 m^3 for the smallest to 269,534 m^3 for the largest basin. Associated mean normalised inter-amounts vary from 0.68 mm for Irvins Creek, the least urbanised basin (8.2% imperviousness) to 1.79 mm for Little Sugar Creek at Archdale, one of the largest basins with a high degree of imperviousness (32%). Coefficients of variation are consistently lower for inter-amount times than those for flows; on average, CV values are 1.7 times larger for flows than for inter-amount times. This reflects the influence of the different sampling strategies: inter-amount times are tuned to the local variability of the times series, sampling rare high flow events more frequently than common base flow events. This results in more balanced representation of high and low flows and lower coefficients of variation. This is further confirmed by values for skewness and medcouple values of the flow and inter-amount times distributions. Skewness values for flows are 3.6 times higher than those for inter-amount times, on average and even up to a factor of 15 higher for 1 basin, Stewart Creek. On the contrary, medcouple values being less sensitive to outliers, are lower for flows than for inter-amount times, by a factor 0.47 on average. This shows that the statistical distribution of flows is strongly influenced by a few very large values (e.g., outliers), making results strongly sensitive to sampling issues and record length. Inter-amount time distributions are less skewed and less sensitive to outliers, making it easier to derive relevant statistics and interpret results.

Subsequently, we compared properties of inter-amount time and flow distributions across the 17 basins. Figure 5 shows scatter plots of mean normalised inter-amounts, coefficient of variation (CV) and medcouple values for flow and inter-amount times as a function of basin area and imperviousness degree. The results show a positive correlation of 24-hour mean normalised inter-amounts cq mean flows with basin size (Spearman correlation 0.55), which is mainly explained by a lower likelihood of low flow extremes during dry periods, the latter having a large influence at this scale (24 hours). Mean normalised flows correlate positively with imperviousness degree (Spearman correlation 0.58), indicating that higher imperviousness is generally associated with lower likelihood of low flow extremes during dry periods.

Looking at CV values across all basins, we found that CV values for both flows and inter-amount times generally decrease with basin size (figure 5. c, d) and with imperviousness degree (Spearman rank correlations -0.33 and -0.57 for inter-amount times; -0.75 and -0.30 for flows, respectively). Negative correlation of CV values with basin size is significant for flow (not for inter-amount times) and can be explained by an increased smoothing effect for larger basin areas on flow variation, especially a lower likelihood of low flow extremes during dry periods. CVs of inter-amount time distributions are negatively correlated with imperviousness, which is associated with more uniform runoff during rainy periods. Inter-amount times during these periods concentrate relatively more closely to the mean and show fewer extreme values during dry periods (especially for LSugarM, 409). Scatter plots for medcouple values (figure 5. e, f) show generally weak correlation with basin area and imperviousness (Spearman correlations not significant at the 5% level). Medcouple values for inter-amount times clearly show three outliers: for Stewart Creek (970), LSugarP (530) and LSugarA (507). In these basins, low flow control is applied[1]. The effect of flow regulation is clearly reflected in the skewness (medcouple) values for inter-amount times and shows up in associated histogram that have a bi-modal shape for these basins. Interestingly, the effect is not visible in the histograms of flow values.

In this section we discussed distributions of inter-amount times and flows at the 24 hour scale, by looking at histograms, mean, CV and skewness values. Results showed that larger basins are generally characterised by stronger smoothing of flows, resulting in higher mean flow, lower CV and lower skewness of the histograms (both for flow and IAT). Relation with basin size is therefore mainly a result of smoothing of low flows, in the left tail of the flow histogram, respectively right tail of inter-amount times histogram. Results showed that larger imperviousness is associated with higher mean flow and lower CV for

[1]USGS, water year reports

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IATs, indicating that larger imperviousness is generally associated with lower likelihood of low flow extremes, at the 24 hour scale. CV and skewness for flows are much higher than for IATs, while medcouple values are lower for flows, indicating high sensitivity of the flow distribution to outliers. These could be interpreted as a result of anomalous flow behaviour, occurring under extreme conditions (river bank overtopping or other conditions really different from normal flow), but given that IAT distributions are much more stable/less characterised by such outliers, one could conclude it is (at least partly) a result of the sampling strategy. Medcouple values for IATs identified three basins where regulation of low flows is applied, resulting in bi-modal shape of the IAT histogram. No significant correlations were found for medcouple values of flow distributions versus area or imperviousness pointing toward possible flow control. The IAT analyses on the other hand appear to be much more sensitive to these types of flow control measures.

3.2 Distribution of changes in inter-amount times

Figure 6 shows histograms of first-order differences in inter-amount times and flows, at 24 hour analysis resolution, for Irvins Creek, the most natural basin, LSugarM the most impervious basin, Stewart Creek, a basin with low flow regulation and McAlpine, the largest of all studied basins. Negative differences in inter-amount times occur during flow rise, positive differences during flow recession. Conversely, for flows, negative differences are associated with recession, positive differences with flow rise. Most of the flow differences, for most basins, are concentrated in the 0 to -0.5 mm bin, associated with slow flow recession of 0.5 mm/day. Most of the IAT differences are concentrated in the 0 to 0.1 or 0.2 day bin, associated with flow recession of approximately 5 to 10 mm per day, indicating relatively higher sampling of rapid flow response as compared to conventional flow sampling. Most of the histograms for inter-amount times differences are negatively skewed, with a longer left tail than right tail, i.e. IATs can decrease quicker than they can increase. Conversely, histograms for flow differences are positively skewed for most basins. Skewness expressed as medcouple values shows a different picture: medcouple values for IAT differences are positive, while those for flow differences are negative for all basins. Medcouple is less influenced by extreme decreases in IATs cq increases in flow than skewness. Since decrease of IAT, resp. increase in flow, can only occur during rainy periods, while during dry periods both increase and decrease can happen, IAT medcouple values are positive and flow values negative. This indicates once more a strong sensitivity of the results to the tails of the distribution. Comparing skewness and medcouple values across basins, we found only significant correlation between differences in IATs and imperviousness (Spearman correlation 0.75 for skewness and 0.55 for medcouple). Strong negative skewness of the inter-amount times differences histogram is indicative of flow behaviour characterised by long and slow flow recession, mainly found for basins with low imperviousness (e.g. 975, Irvins Creek). Figure 7 shows scatter plots for skewness and medcouple values versus basin size and imperviousness. The three basins with low flow regulation (970, 530, 507) can be recognised by their relatively low medcouple values for inter-amount times difference relative to their imperviousness.

3.3 Inter-amount times variability across inter-amount scales, from sub-daily to seasonal resolution

In this section we analyse variability in inter-amount times and flows across a range of scales. Figure 8a shows boxplots of flows for scales between 12h and 60 days. The bold black line denotes the mean. The boxplots indicate median and 25-75 percentiles, with solid horizontal black lines for the median, whiskers for the 10 and 90 percentiles and crosses for the 1 and 99 percentiles. Figure 8b shows similar boxplots for inter-amount times τ, over the same range of scales. On the horizontal axis is the time resolution of analysis, or, equivalently, the mean inter-amount time. At each aggregation scale, the mean inter-amount Δq is computed by dividing the total accumulated flow volume by the total time of observation. Mean inter-amounts are normalised by basin area size and reported in mm. For instance, for 0.83 days (19.9 hours) resolution, Δq is 11,560 m^3, corresponding to 0.85 mm when divided by basin area. Hence the time series is sampled each time 0.85 mm of normalised flow has been accumulated. The vertical axis shows the inter-amount times corresponding to Δq.

Comparing figures 8a and 8b we see that the spread of the 10-90% percentiles of inter-amount times gradually increases as we move towards smaller scales. For flows, the 10-90% percentile range remains approximately constant, however, left and right tails rapidly increase, as indicated by the 1% and 99% percentile values. By contrast, for inter-amount times, the upper tail as well as other upper percentiles (75%, 90%, 99%) change approximately log-linearly with scale, i.e. they follow a power law of scale. This indicates that these values are associated with rare periods of low flow and that values refer to the same low flow periods across all scales, hence the scale of these periods approaches the maximum analysis scale of 60 days. Stronger departures from power-law scaling can be seen in the left tail of the interamount time distribution (1%, 10%, 25% and median). These indicate a rapid shift of the inter-amount time distribution towards lower values. The range over which this happens depends on the percentile and considered gauge. In this example, the median shifts roughly over the range of 1 to 14 day scale (1 to 14 mm of normalized flow), which corresponds to the range of scales over which inter-amount times transition from being inter-event to intra-event dominated. Indeed, inter-amount times at coarser scales mostly combine the properties of multiple storms, resulting in a more symmetric distribution closer to a Gaussian. At smaller scales, the distribution of inter-amount times broadens, with individual storm properties and intra-event variability playing an increasingly dominant role. For example, 10-percentiles of inter-amount times in figure 5b change more or less log-linearly with scale below a resolution of 7 days (7.1 mm of normalized flow). The frequency of occurrence of this amount of flow at the event scale, i.e. at sub-daily scale, is 2.9%, as shown in the plot of flow quantiles. The 10-90% range of inter-amount times associated with this scale is approximately 1.8 to 513 hours. This indicates that inter-amounts of 7.1 mm can occur over a range of 1.8 hours during peak flow to 513 hours during low flow, equivalent to 3.9 mm/h resp. 0.014 mm/h. At the daily scale, the 10-90% range of inter-amount times is approximately 0.18 to 74 hours, for 1 mm inter-amounts, or 5.6 to 0.014 mm/h. At coarser scales however, the 10-90% range decreases, as variations at sub-daily scale can rarely be captured. This is evidence of different scaling at large and small scales, depending on whether inter-amount times are mostly inter- or intra-event dominated. In between lies a transition range where aggregated flow values increasingly relate to a smaller number of events, down to single events. Flows sampled over fixed time intervals as shown in figure 5a do not exhibit such a strong transition. The fixed temporal sampling strategy means only phenomena occurring above the sampling resolution can be resolved. Peak flow variability remains poorly sampled, even at small scales where the vast majority of the samples come from base flow. Inter-amount times adapt the sampling rate depending on the level of activity and therefore still capture a fair amount of peak flow statistics and intra-event properties at coarser scales.

Boxplots of inter-amounts over range of scales were created for all 17 gauges included in our analysis. This allowed us to compare transition ranges between inter-event dominated and intra-event dominated inter-amount times distributions for the different basins. Results show that for the 10% quantiles, the lower end of the transition range lies between 2 and 10 days. Low values are found for basins with high imperviousness and for basins where low flow control is applied. High values generally indicate slow response and are associated with low imperviousness. They imply response to single rainfall events is stretched over multiple days. Results for basins with low flow control show deviating results, due to the multi-modal nature of inter-amount times histograms for these basins, as was discussed in section 3.1. Similar results were found for the higher end of the 10% transition range, as well as for 25% transition range. Another characteristic of flow response is the amount of flow that can be generated in an hour, compared to the mean flow. This can be derived from the quantile plots as the scale at which a given inter-amount time percentile, for instance 1%, equals 1 hour. For example for Taggart Creek, a 1% inter-amount time of 1 hour is associated with an observation scale of 18 mm of mean normalised flow or equivalently, 18 days of mean inter-amount time. This means there is a 1% probability of exceeding 18mm of flow accumulation in 1 hour or less. Or, in terms of time it implies that there is a 1% chance to accumulate the amount of flow measured on average over a period of 18 days in 1 hour or less. Thus, higher values in this case indicate stronger flashiness of basin response. Comparing values across basins, we found that higher values of 1%, 1 hour accumulations were strongly correlated with basin area. No significant correlation with imperviousness was observed. We investigated scaling behaviour from the perspective of higher-order statistical moments, by looking at coefficients of variation for flows and inter-amount times across scales. Figure 9 shows coefficients of variation for four gauges, across a range of sub-daily (3 to 12 hours) up to bi-monthly (60-68 days) scale. Results show that coefficients of variation for flows vary non-linearly with scale, while they approximately follow a power law with scale for inter-amount times. Figure 9a shows results for Irvins Creek, the most natural of all basins used in this study (8.2% imperviousness). CV-values of inter-amount times and flows are similar over a range of 10 to 50 days; below this scale, CV-values for flows increase more rapidly than for inter-amount times. Figure 9b show results for Upper LSugar Creek, the most impervious basin; CV-values are lower than for Irvins Creek, as flows are constrained by the stormwater drainage system. Figure 9c shows that for LMcAlpine, the largest basin (238.4 km^2) CV-values for flow are more or less stable between 3 and 12 hour scale, due to strong smoothing of peak flows at this basin scale. In contrast, CV-values for inter-amounts increase over this range, associated with increasing variability in the rising and recession limbs of hydrographs at small inter-amount scales (0.1 to 0.6 mm for 3 to 12 hours), which shows up more clearly because of the way short and long inter-amount times are broken up as we move towards smaller scales. The rising limb of the hydrograph is relatively steep, thus associated with short inter-amount times that are broken up more or less uniformly at smaller scales, while long inter-amount times on the recession limb are broken up more unevenly, creating greater imbalance between short and large values, hence increased CV and skewness. CV-values for Stewart Creek in figure 9d clearly show the effect of low control applied for this basin, which results in low sensitivity of inter-amount times to scale, an effect that is not visible in CV-values for flows due to the different sampling strategy that results in low sensitivity for low flow variations.

3.4 Minimum observable scale, flashiness indicator

In figure 8a, for Taggart Creek, it can be seen that the 1% IAT values fall below the 15 minute scale of flow observation at the 118.75 hours (4.95 days) analysis scale. This implies that at this scale, 1% of flow accumulations Δq occurs in less than 15 minutes, typically associated with heavy rainfall events leading to a steep rise in flow. At higher resolutions, a growing percentage of flow accumulations occurs in less than 15 minutes, hence cannot be analysed at the given observational resolution of 15 minutes. This implies that from the perspective of flow accumulation, the observational resolution is too low to measure flow changes during peak events. In this way, inter-amount times can be used to identify critical resolution for flow observations, if a given peak flow accumulation is of interest, for instance in association with capacity of detention ponds or occurrence of flooding by exceedance of stormwater drainage capacity. For Taggart Creek, this scale is associated with 4.76 mm inter-amount, so flow changes of 4.76 mm in less than 15 minutes, or equivalently, peak flows above 19.0 mm/h cannot be observed 1% of the time. Flashiness values of the order of 100 hours imply that, as for Taggart Creek, flow peaks upward of 15-20 mm/h cannot be measured 1% of the time, at 15 minute observational resolution. This value can be interpreted as an indicator for flashiness of basin response: higher flashiness values indicate larger differences between the rising and recession components of the hydrological response.

Table 2 summarises flashiness values for all gauges, as well as minimum and maximum observable inter-amounts (as defined in section 2, equations 9 and 10). As explained in the Methods section, a threshold for minimum observable inter-amounts is derived from the ratio of observational resolution (15 minutes) and sampled inter-amount times for a given mean inter-amount and can be interpreted as an indicator of basin flashiness. Maximum observable inter-amounts are mainly determined by the length of the available observational record. Results in table 3 show that the minimum observable scales vary between 2.75 and 13.75 days and generally decrease for larger basins. Flashiness values vary between 12.5 and 165 hours, higher values being associated with smaller basins. Correlation between minimum observable scale and flashiness is high (Spearman correlation 0.9), as for most gauges the 90-percentiles (for minimum observable scale) and 99-percentiles (for flashiness) decrease log-linearly with scale along a similar gradient. Figure 10 shows scatter plots of flashiness versus basin area and imperviousness, for all gauges. They show a clear relationship between flashiness and basin area (Spearman correlation -0.83), with a large range of flashiness values for the smallest basins. The anomalously low value for Six Mile Creek (gauge 800) is probably due to a much shorter length of the data period for this gauge (8 years compared to 15-29 years for the other gauges). No correlation was found between flashiness and impervious degree. The most impervious basin, LSugarM (gauge 409, 31.7 km^2, 48% imperviousness) has a relatively low flashiness value of 48.8 hours, while the least impervious basin, Irvins Creek (gauge 975, 21.8 km^2, 8% imperviousness) has a high flashiness value of 102.8 hours. This shows that basin size has a stronger effect on flow variability than imperviousness degree: differences between the rising and falling limb of the flow hydrographs are much stronger for smaller basins. While higher imperviousness leads to higher mean runoff flows (1.5 mm for LSugarM versus 0.68 mm for Irvins Creek, at 24 hour scale), rainfall in impervious basins runs off relatively more quickly and uniformly. As a result, most of the inter-amount times during rain are concentrated relatively close to the mean. Flashiness index was defined in this study for 15 minute observational scale but further analyses showed that flashiness indexes computed for different sampling resolutions remain almost unchanged up to a transition range (8-16 days). After that, they progressively break down and no longer become representative of the catchment's response to single rainfall events.

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3.5 Scaling of inter-amount times across scales: multifractal analysis

As a first step in multifractal analysis, we plotted moments for inter-amount times as a function of mean inter-amount scale $\bar{\tau}$, i.e. the inverse of the scaling ratio λ, on a log-log scale, for moments of order 0.5 to 2.5. We applied the same procedure for flow time series and plotted log-moments of flow volumes as a function of logarithm of the time scale. Log-log plots were analysed to detect departures from linearity. Figure 11 shows examples of log-log plots for flow volumes and inter-amount times for McAlpine Creek. The plots show stronger departures from linearity for flows than for inter-amount times, especially for higher order moments. The log-log curve for moment $q = 2.4$ shows that a scale break was detected at 22 hours for flows and subtle departures from linearity at 20.4 days for flows as well as 11.2 hours and 17.3 days for inter-amount times.

For flows, most gauges exhibited a scale break between 8 and 20 days. Similar departures, between time scales of 8 to 16 days, were found in scaling analyses of flow data by other authors based on daily resolution flow data (Tessier et al., 1996; Labat et al., 2002; Sauquet et al., 2008). Labat et al. (2013) and Sauquet et al. (2008) found scale breaks in the range of 16 to 27 hours, for 30 minutes respectively hourly resolution. On the other hand, we did not detect any strong departures from multifractality in the IAT framework except for the 3 gauges where low flow regulation is applied (LSugarA, 507, LSugarP, 530, Stewart Creek, 750). This is confirmed by higher R^2 values (mean R^2 0.9999 over all gauges for inter-amount times, mean R^2 0.9985 for flows), indicating better log-log linear fits.

Using the empirical log-moments, we fitted the multifractal parameters C_1 and α for IATs and flow amounts. Table 3 summarises C_1 and α values for all basins, for flows and for inter-amount times. Results show that C_1- values, characterising intermittency, are lower for inter-amount times than for flows, a result of the difference in sampling strategy. Values of the multi-fractality index are generally lower for inter-amount times, too, with the exception of four basins. Two of these basins are characterised by low flow regulation, one basin has anomalous land-use distribution with a high concentration of imperviousness in the upper part of the basin. Time series of the 4^{th} basin is short (8 years), which might influence outcomes of the scaling analysis. C_1 and α values for flows are in the range of values found by other authors. Figure 12 shows scatter plots of values for C_1 and α for flow and for inter-amount times versus basin size and imperviousness. C_1- values are clearly negatively correlated with basin area. Rank correlations for IATs are -0.67 and -0.85 for flows. No significant correlation of C_1 with imperviousness was found. Alpha values for IATs are positively correlated with area (0.6) and negatively with imperviousness (-0.56). Alpha values for flows have no significant correlation with area nor imperviousness. Negative correlation of alpha IAT with imperviousness comes from the fact that IATs are split more evenly when going from large to small scales (due to high imperviousness). The three basins with low flow control stand out with lower than average C_1 values. This shows up both in the IAT analyses and in the classical approach based on flows.

4 Summary and conclusions

In this study, we presented an alternative approach of analysing hydrological flow variability and scaling, based on the distribution of inter-amount times. We analysed distributions of inter-amount times for streamflow time series for 17 (semi)urbanised basins in North Carolina, US. The main difference between flow time series and time series for inter-amount times is the rate at which low and high flows are sampled; the unit of analysis for inter-amount times is a fixed flow amount, instead of a fixed time window. Thus, in inter-amount times analysis, data sampling rate is adapted, according to the local variability in the flow time series, as opposed to time series sampling using fixed time steps. The following conclusions were drawn from the analyses.

1. Histograms for flows and inter-amounts showed that coefficients of variation were consistently lower for inter-amount times than for flows. This reflects the influence of the different sampling strategies: sampling frequency in inter-amount times analysis is tuned to variability in the flow pattern, taking frequency samples at high flow and sparse samples at low flow conditions. This results in more balanced representation of high flow and low flow periods in the time series, hence lower coefficients of variation.

2. Statistical analysis of empirical flow and inter-amount time distributions showed that flow distributions tend to be highly skewed. The mean and other higher-order moments are therefore dominated by a few exceptionally large values, hiding crucial information about the majority of the data. Inter-amount times help stabilize the variance of the distribution across scales and are therefore more attractive from a statistical point of view.

3. Significant negative correlation of CV values with basin size was found for flows (not for IATs), associated with an increased smoothing effect for larger basin areas on flow variation. CVs of inter-amount time distributions were negatively correlated with imperviousness. This was attributed to more uniform runoff during rainy periods, i.e. smaller differences in inter-amount times between the rising and recession components of the hydrological response.

4. We found a bi-modal histogram shape for three basins, which could be attributed to low flow regulation applied for these basins. This was also clearly reflected in the skewness (medcouple) values for inter-amount times. The effect was not visible in histograms or skewness values for flows.

5. Histograms of first-order differences showed negative skewness of inter-amount times, respectively positive skewness of flow differences for most of the basins, indicating long and slow flow recession. The three basins with low flow regulation could be recognised by their relatively low medcouple values for inter-amount times difference relative to their imperviousness.

6. Based on quantile plots for inter-amount times, we found that at smaller scales, the distribution of inter-amount times broadens, with individual storm properties and intra-event variability playing an increasingly dominant role. This is evidence of different scaling at large and small scales, depending on whether inter-amount times are mostly inter- or intra-event dominated. In between lies a transition range where aggregated flow values increasingly relate to a smaller number of events, down to single events. 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. Inter-amount times adapt the sampling rate depending on the level of activity and therefore still capture a fair amount of peak flow statistics and intra-event properties at coarser scales.

7. The minimum observable inter-amount also represents the smallest scale at which flow variations can be studied given a fixed temporal resolution. By extension, the lower tail of the inter-amount time distribution provides a good indication of what resolution is necessary to adequately capture the most extreme flow variations. At higher resolutions, a growing percentage of flow accumulations occurs in less than the given observational resolution of 15 minutes. This implies that from the perspective of flow accumulation, the observational resolution is too low to measure flow changes during peak events. In this way, inter-amount times can be used to identify critical resolution for flow observations for a given flow accumulation of interest. For instance, this can be done in association with the capacity of detention ponds or occurrence of flooding by exceedance of stormwater drainage capacity.

8. A flashiness indicator was defined as the inter-amount scale at which 1% of flow accumulations occur in less than 15 minues. We found a clear relationship between flashiness and basin area (Spearman correlation -0.83), with a large range of flashiness values for the smallest basins. No correlation was found for imperviousness, indicating that flashiness of hydrological response is dominated by basin size. Flashiness index was defined for 15 minute observational scale but further analyses show that flashiness indexes computed for different sampling resolutions remain almost unchanged up to the transition range (8-16 days). After that, they progressively break down and no longer become representative of the catchment's response to single storm events.

9. Multifractal analysis of inter-amount times and flows was applied over a range of sub-daily to seasonal scales. Flows exhibited departures from multifractality for most basins, while inter-amount times systematically scaled better than flows and showed departures from multifractality only for three basins subject to low flow regulation. 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.

Results of this study showed that inter-amount times distributions can be used to identify characteristics of hydrologic response that conventional flow time series sampling could not reveal. In particular, effects of low flow regulation on hydrological response could clearly be identified. The lower tail of inter-amount time distribution was shown to provide a good indication of what resolution is necessary to adequately capture the most extreme flow variations for given basin; conversely to estimate the error made in flow measurement given the observational resolution. Sampling frequency in inter-amount times analysis being tuned to variability in the flow pattern results in more balanced statistical distributions. More balanced sampling of flow rise and recession of flow peaks allowed to shed new light on characterising the flashiness of watersheds. Conventionally, flashiness is characterised by (normalised) peak flow magnitude and response time. 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. More balanced distributions were also reflected in better scaling behaviour of inter-amount times compared to conventional flow sampling. Scaling analysis showed that inter-amount times provide a promising way to better predict peak flow characteristics at small unobservable scales from coarse resolution data. Analyses in this study identified minimum observable scales below which flow variability cannot be captured at the given measurement resolution, leading to errors in especially peak flow estimation. The combination of being able to identify these minimum observable scales and downscale flow data based on inter-amount times is an interesting area for future investigation. Another aspect that remains to be investigated is how inter-amounts times computed on flow data compare to inter-amount times of rainfall. Because flow is linked to rainfall, the comparison of the two could help better distinguish which aspects of flow variability are due to rainfall and which relate to storm water management. Future work will mostly focus on these issues and on possible ways to use inter-amount times to downscale coarse resolution flow data with the help of multifractals and multiplicative random cascades.

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the 25-75 percentile range, upper and lower whiskers 10-90 percentile range, crosses the 1-99 percentile range.

Figure 9: Coefficients of variation for flows and inter-amount times scales across a range of sub-daily (3 to 12 hours) up to bi-monthly (60-68 days) scale, for Irvins Creek, LSugarM, Stewart Creek and McAlpine

Figure 10: Scatter plots of flashiness versus basin area and imperviousness, for all gauges

Figure 11: Example of log-log plots for flows and inter-amount times (11a, 11b), for Mc Alpine Creek, illustrating departures from linearity at high order moments. Curve for moment q=2.4 illustrating scale breaks for flows and inter-amount times (11c, 11d)

Figure 12: Multifractal parameters C1 and alpha for scaling analysis of flows and inter-amount times, as a function of drainage area and imperviousness degree

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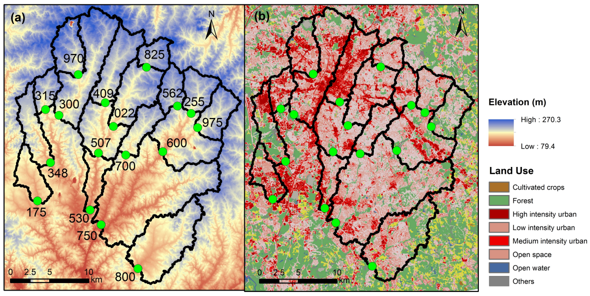

Figure 1. Map with the location of the area, watershed boundaries and location of stream gauges used in the analysis

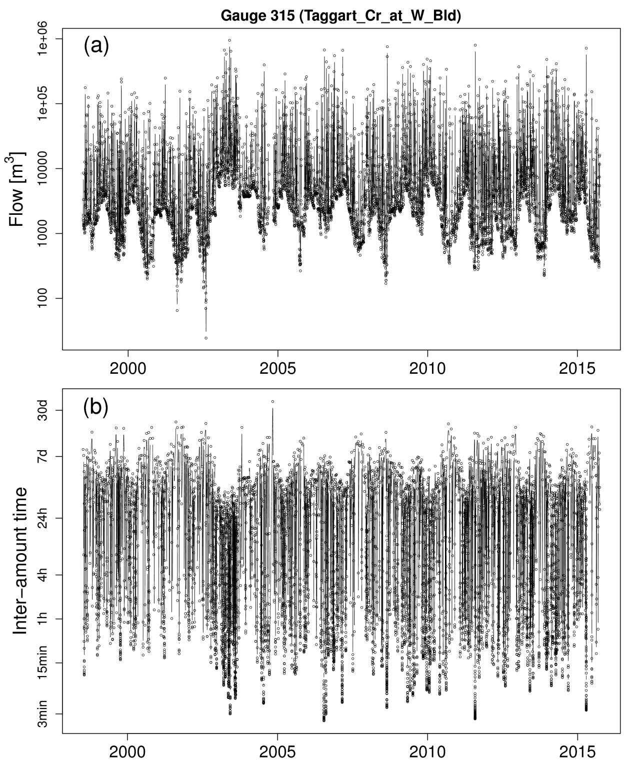

Figure 2. Example of times series for flow (a) and for associated inter-amount times (b) for the flow gauge at Taggart Creek, a 13.6 km^2 basin in the Charlotte watershed.

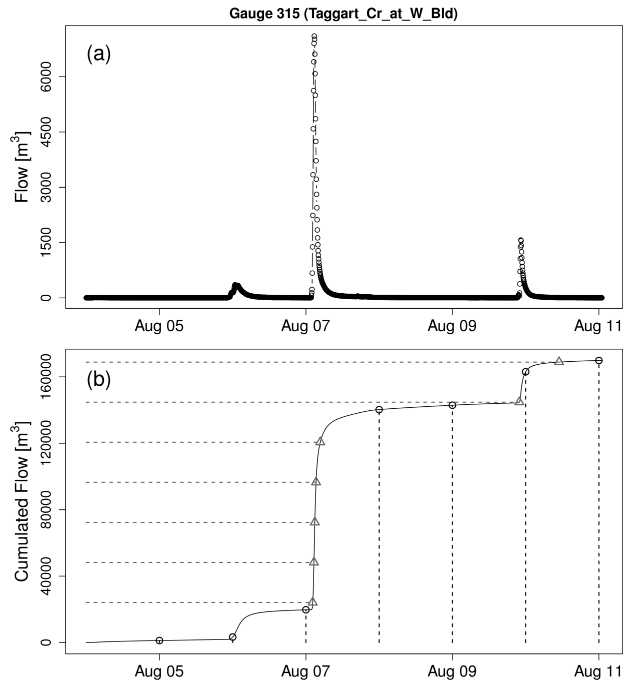

Figure 3. Illustration of inter-amount data sampling for cumulative flow over a period of 7 days, for Taggart Creek. 3a Flow time series; 3b Cumulative flow time series and inter-amount sampling (for mean inter-amounts at 24 hours resolution).

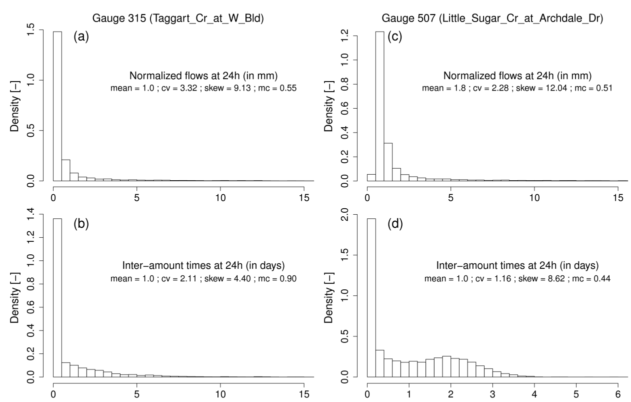

Figure 4. Histograms of flow time series (a) and time series of inter-amount times (b) for Taggart Creek and Little Sugar Creek at Archdale (LSugarA), for 24 hour scale.

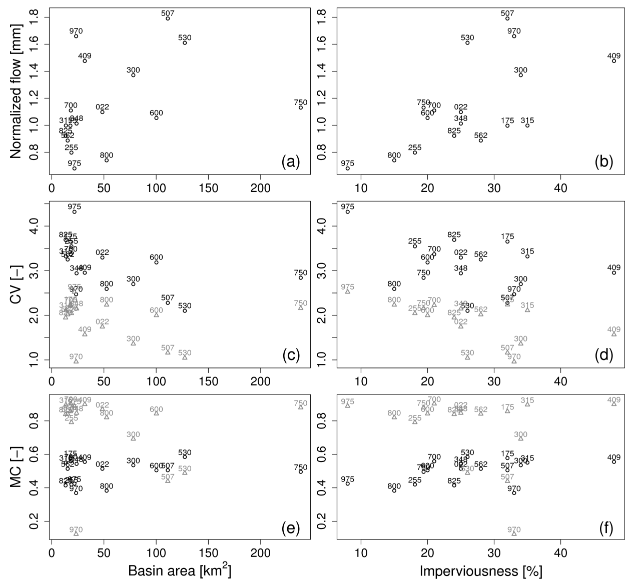

Figure 5. scatter plots for mean normalised flows inter-amounts (a, b), coefficient of variation (c, d) and medcouple values (e, f) for flows and inter-amount times versus basin area and imperviousness degree.

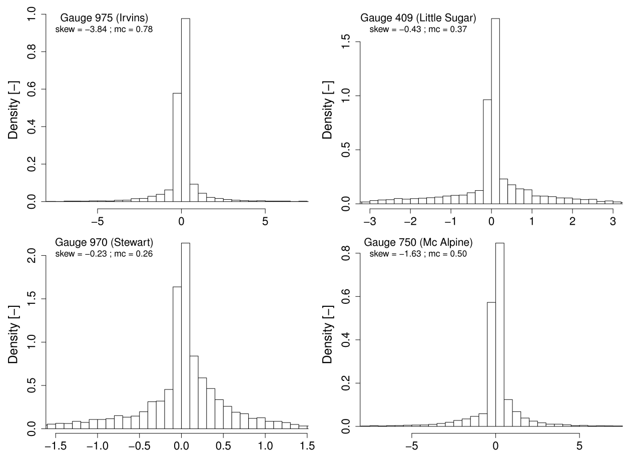

Figure 6. histograms of first-order differences in inter-amount times and flows, at 24 hour analysis resolution, for Irvins Creek, LSugarM, Stewart Creek and McAlpine.

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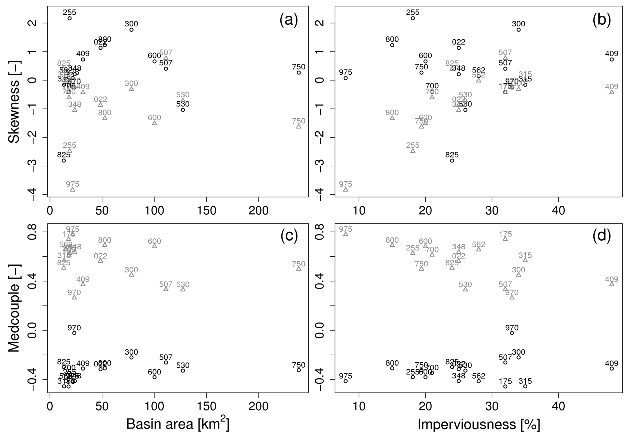

Figure 7. Scatter plots of skewness (a, b) and medcouple values (c, d) of histograms for differences in flows and inter-amount times, plotted versus basin size and imperviousness degree. Grey triangle symbols represent inter-amount times, black circles represent flows.

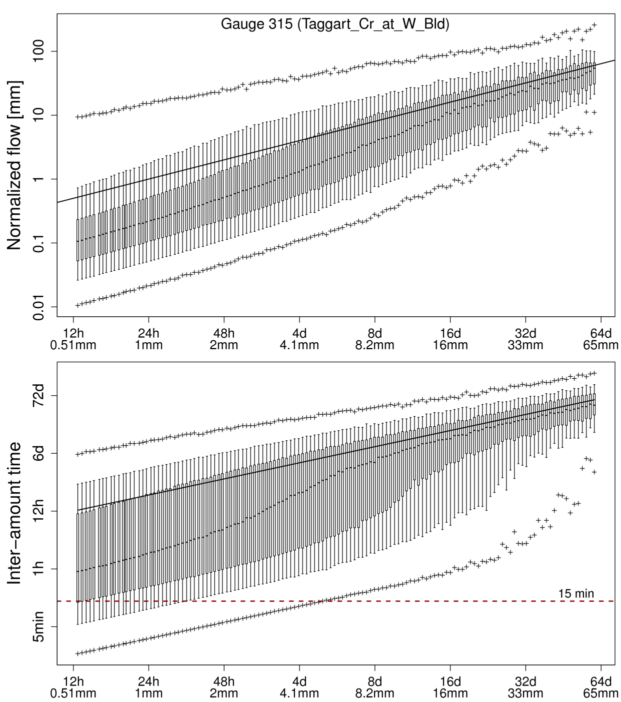

Figure 8. Boxplots of flows (a) and inter-amount times (b) for Taggart Creek for a range of scales, from 12 hours to 60 days. The bold black line denotes the mean values. The dotted black line shows median values. The central part of boxplots represents the 25-75 percentile range, upper and lower whiskers 10-90 percentile range, crosses the 1-99 percentile range.

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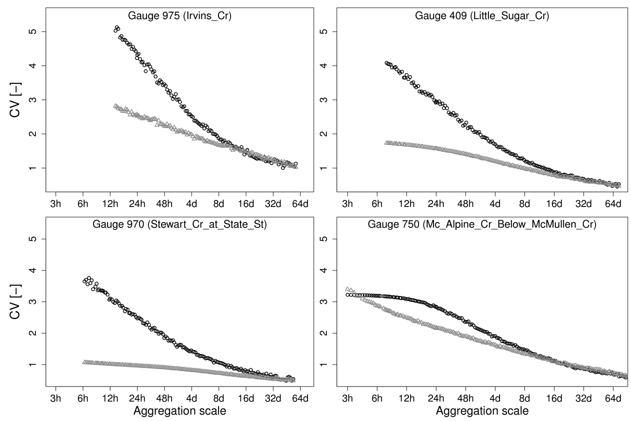

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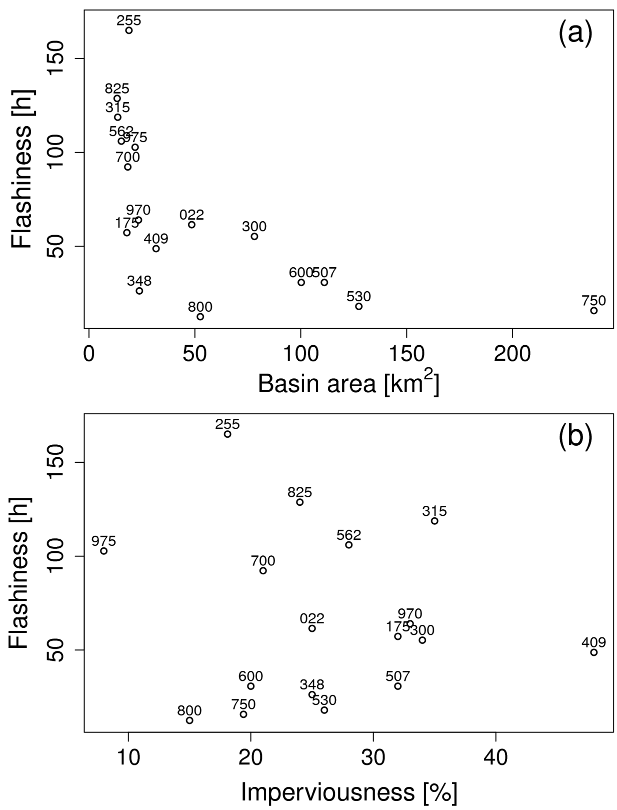

Figure 10. Scatter plots of flashiness versus basin area and imperviousness, for all gauges.

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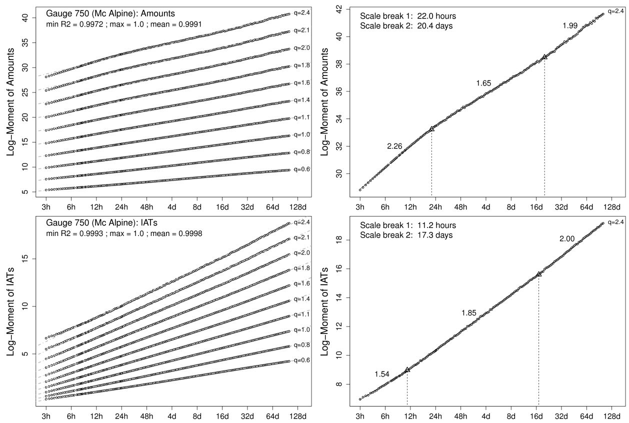

Figure 11. Example of log-log plots for flows and inter-amount times (a, b), for Mc Alpine Creek, illustrating departures from linearity at high order moments. Curve for moment q=2.4 illustrating scale breaks for flows and inter-amount times (c, d).

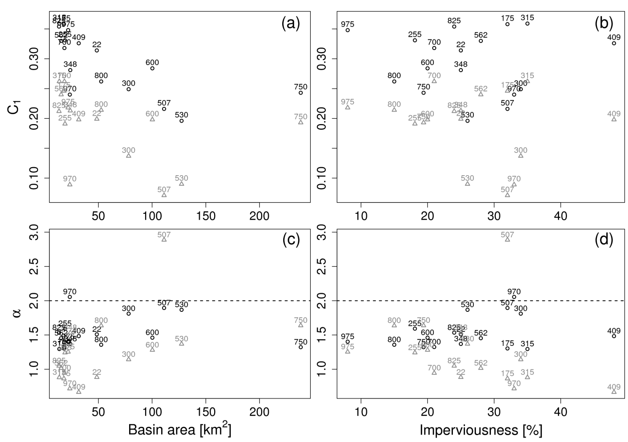

Figure 12. Multifractal parameters C1 and alpha for scaling analysis of flows and inter-amount times, as a function of drainage area and imperviousness degree.

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Table 1. Summary of hydrological basins in the Charlotte area: basin area [km^2], imperviousness [%], average 24 h flow [m^3], average 24 h flow normalized by basin area [mm] and length of observation in years.

ID	name	area	imperv	dams	mean flow	mean normalized flow	Nyears
825	LBriar	13.3	24.0	22	12275	0.92	17.4
315	Taggart	13.6	35.0	3	13559	1.00	17.2
562	Campbell	15.3	28.0	48	13567	0.89	16.2
175	Steele	17.9	32.0	21	17838	1.00	17.4
700	McMullen	18.3	21.0	15	20348	1.11	29.0
255	LMcAlpine	18.9	18.1	100	15061	0.80	16.3
975	Irvins	21.8	8.0	62	14821	0.68	16.3
970	Stewart	23.4	33.0	55	38800	1.66	15.3
348	Coffey	23.8	25.0	72	24104	1.01	17.0
409	LSugarM	31.7	48.0	2	46775	1.48	21.0
022	UBriar	48.5	25.0	17	53246	1.10	19.8
800	SixMile	52.6	15.0	-99	38914	0.74	8.0
300	UIrwin	78.1	34.0	39	107119	1.37	29.0
600	MMcAlpine	100.2	20.0	51	105640	1.05	29.0
507	LSugarA	111.1	32.0	24	199002	1.79	29.0
530	LSugarP	127.4	26.0	-99	205202	1.61	18.3
750	UMcAlpine	238.4	19.4	-99	269534	1.13	29.0

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Table 2. Summary statistics of time series for flows and inter-amount times, at 24 hour resolution: coefficient of variation (CV), skewness (skew) and medcouple (mc).

name	CV IAT	CV flow	skew IAT	skew flow	mc IAT	mc flow	skew dIAT	skew dflow	mc dIAT	mc dflow
LBriar	1.95	3.69	4.91	14.79	0.84	0.41	0.39	-2.81	0.51	-0.30
Taggart	2.11	3.32	4.40	9.13	0.90	0.55	0.00	-0.16	0.57	-0.46
Campbell	2.02	3.25	4.26	10.40	0.84	0.51	-0.02	0.15	0.66	-0.41
Steele	2.24	3.65	4.39	10.21	0.86	0.58	-0.43	-0.41	0.74	-0.46
McMullen	2.22	3.37	5.35	10.10	0.90	0.56	-0.61	-0.40	0.61	-0.35
LMcAlpine	2.04	3.55	5.53	13.51	0.79	0.42	-2.48	2.17	0.63	-0.38
Irvins	2.52	4.32	8.37	11.74	0.89	0.42	-3.84	0.07	0.78	-0.41
Stewart	0.96	2.47	0.84	12.90	0.12	0.37	-0.23	-0.25	0.26	-0.02
Coffey	2.15	2.94	7.34	8.44	0.85	0.54	-1.05	0.21	0.64	-0.41
LSugarM	1.57	2.95	2.06	11.55	0.90	0.55	-0.43	0.73	0.37	-0.31
UBriar	1.74	3.30	3.13	13.77	0.87	0.51	-0.87	1.13	0.56	-0.32
SixMile	2.23	2.59	6.29	6.42	0.82	0.38	-1.34	1.23	0.69	-0.31
UIrwin	1.36	2.70	2.65	14.43	0.69	0.53	-0.32	1.77	0.45	-0.22
MMcAlpine	2.00	3.19	5.42	10.30	0.84	0.50	-1.51	0.66	0.68	-0.38
LSugarA	1.16	2.28	8.62	12.04	0.44	0.51	0.77	0.40	0.33	-0.26
LSugarP	1.04	2.10	1.52	9.20	0.49	0.58	-0.71	-1.04	0.33	-0.33
UMcAlpine	2.16	2.84	6.56	7.65	0.88	0.50	-1.63	0.27	0.50	-0.32

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Table 3. Minimum and maximum observable scales (in hours), flashiness index for 15 min observation time (in hours) and fitted multifractal parameters α and C_1 for inter-amount times respectively flows.

ID	min scale	max scale	flash	alpha IAT	alpha flow	C1 IAT	C1 flow
LBriar	13.75	1462	128.75	1.05	1.53	0.21	0.35
Taggart	12.50	1443	118.75	0.88	1.30	0.26	0.36
Campbell	9.25	1360	106.00	1.01	1.45	0.24	0.33
Steele	9.50	1457	57.25	0.86	1.30	0.25	0.36
McMullen	11.00	2420	92.25	0.94	1.32	0.26	0.32
LMcAlpine	10.00	1367	165.00	1.24	1.59	0.19	0.33
Irvins	13.75	1367	102.75	1.25	1.40	0.22	0.35
Stewart	6.25	1284	64.00	0.72	2.06	0.09	0.24
Coffey	4.75	1422	26.25	1.53	1.37	0.21	0.28
LSugarM	7.50	1752	48.75	0.66	1.48	0.20	0.33
UBriar	6.75	1658	61.50	0.88	1.51	0.20	0.31
SixMile	3.00	672	12.50	1.64	1.36	0.21	0.26
UIrwin	5.00	2420	55.25	1.14	1.81	0.14	0.25
MMcAlpine	5.50	2420	30.75	1.28	1.46	0.20	0.28
LSugarA	3.50	2420	30.75	2.89	1.89	0.07	0.22
LSugarP	2.75	1532	18.00	1.37	1.87	0.09	0.20
UMcAlpine	3.00	2420	15.75	1.64	1.32	0.19	0.24