Master Thesis

by

David Ramírez Infante

in partial fulfillment of the requirements for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology,
to be defended publicly on Tuesday October 30, 2018 at 08:45 AM.

A study of the variability of lag time as measure of hydrological response in urban catchments

Charlotte metropolitan area case

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This thesis is confidential and cannot be made public until October 30, 2018.

TU Delft

A study of the variability of lag time as measure of hydrological response in urban catchments

David Ramírez Infante

19 October 2018

Abstract

The Inter-Amount Times (IAT) adaptive sampling technique has been used for the analysis of hydrological response in urban areas. The analysis of hydrological response often requires the correct use and interpretation of temporal parameters such as lag time adapted to complexities and requirements of urban environments. In this thesis, the development of a hydrological response methodology that avails itself of the statistical framework of IAT for the hydrological response analysis is suggested by proposing a new lag time definition based on IAT. This new definition was evaluated through the analysis of discharge and precipitation time series of fifteen years. The IAT lag time results were compared against classical methods used to define and compute lag time such as centroid-to-centroid (C-to-C) and peak-to-peak (P-to-P) methods. Finally, a validation procedure is carried out to assess the validity of the proposed IAT lag time definition.

Results from the computation of hydrological response values using each of the three methods showed some relevant similarities but also exhibited varying behaviours and limitations based on the proposed methodology for the definition of the hydrological events. Statistical distributions of the IAT lag time method and C-to-C method had similar distributions, in contrast to what was observed for the statistical distribution of P-to-P values. Results from the IAT lag time method suggested a more stable and flexible methodology compared to the classical methods.

The IAT lag time method can potentially be used to have a more dynamic and tailored interpretation of the hydrological response behaviour in urban areas. Experimental work is required to test the method in other urban areas to confirm the validity of the results of this approach used to study the hydrological response of urban catchment.

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Thank you Cassandra for sharing this journey with me and being here believing in me even when it was not easy. This is also yours.

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1 INTRODUCTION

Urban catchments are characterized by a high degree of heterogeneities that shape their hydrological behaviour, which are especially marked by the different arrangements of land cover, topographical characteristics, buildings and (hydraulic) infrastructure(Zhou, Long, et al., 2018). This engineered/altered environment has a big impact on the hydrological response of the basin, in particular for the case of the land cover that is turning into more impervious surfaces limiting the infiltration and generating an increased and faster runoff (Verbeiren et al., 2013). These changes of the hydrological response result from the interaction of rainfall with the urban basin's characteristics such as land cover, slope, imperviousness, drainage network density, population density, soil infiltration capacity, and building density, among others. Researches have focused on investigating the impact of the characteristics of these urban basins on the hydrological response (Zhou, Long, et al., 2018); however, important uncertainties remain regarding the specific contribution of the urban characteristics to the change in hydrological response (Berne et al., 2004). Special attention has been given to the role of imperviousness (Zhou, Long, et al., 2018), and the role of soil moisture in the runoff generation (Destouni and Verrot, 2014). In the end, different percentages of impervious surfaces in different urban environments do not provide a conclusive answer to the change in hydrological response but the suggestion is that the distribution and type of impervious'surface could be a different way to try to explain the real quantitative impact of the urban surface on the hydrological response (Berne et al., 2004).

Vicars-Groening and Williams (2007) acknowledge that results that suggest that urbanization profoundly impacted storm response offer relatively low confidence, mainly due the small sample size and coarse resolution of the data. More research about the impact on the hydrological response of not just land use but also of the relationship of the variability of soil wetness, urbanization and topography with the spatial rainfall variability should be done (Zhou, Long, et al., 2018).

In order to compare and evaluate changes induced in the hydrological response by means of urbanization, the study of three parameters in the hydrological catchment are required: Time of concentration, lag time and time to peak. These parameters offer insights of the discharges behaviour based on the interaction of the characteristics of the urban catchments with rainfall. In this research, the lag time is selected as temporal parameter of the urban catchment for the study of the relationships between it, the characteristics of the urban catchment and the rainfall events.

1.1. OBJECTIVES

In order to set the basis for meaningful discussions, this research will start with a review of the classical methodologies used for defining the hydrological response of any catchment.

Therefore, the main objective of this work is to research the possible relationships between lag time estimation methods and the characteristics defining the urban basins (i.e. imperviousness, land use, vegetation, interception capacity), under different rainfall events at different spatial and temporal scales. This research will be performed by using the Inter Amount Times methodology (IAT) as statistical framework.

1.2. RESEARCH QUESTION

How can the interaction of the characteristics of urban basins with the rainfalls variability in space and time at different scales may explain the suitability of of using a specific lag time method within Charlotte metropolitan area, with Little Sugar Creek catchment as example?

1.2.1. SUB RESEARCH QUESTIONS

1. How do the different lag time methods represent the hydrological response in urban areas defined by the interaction of the urban basin´s characteristics and rainfall events at different scales?
2. How can we estimate lag time based on IAT?

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Background

2.1. Hydrological response in urban areas

Urban areas are especially important because people and the industry are concentrating their lives and economic assets in these small areas called cities, which, in hydrological terms, can also be defined as urban catchments. This category of catchments and their sub-units have a different connection with the hydrological cycle than rural catchments have, as each urban environment responds in a different manner to the changes made to a once natural environment. Due to the unique way in which a hydrological response is generated for each basin, a sense of urgency should be placed on efforts towards a better way to define the hydrological response in urban areas, since these areas are projected to be the home of 70% of the world population by 2050 (UN, 2014).

The hydrological response could be seen as the way water is coming from the outside as precipitation moves in the hydrological system. Once inside the physical boundaries of the basin, precipitation follows a pathway that is defined by the orographic characteristics of the land. Catchments have the ability to work as dampers for precipitation spatial variability. This precipitation could generate overflow or infiltrate into the ground as immediate possibilities. Both possibilities depend on certain characteristics of the surface and the precipitation event(Park et al., 2011).

Runoff is the most visible and measurable result of the hydrological response in terms of volume and time. Temporal estimators of this process serve as indicator of the storage capacity of the catchment, and this process serves as direct indicator of the response time of the catchment. Runoff as a hydrological process is the result of infiltration no longer being possible since soil capacity has already been reached (saturation excess flow) or precipitation intensity being greater than infiltration capacity (Hortonian runoff) causing waterlogging on the surface. For urban catchments, runoff in streets could increase once the drainage capacity is exceeded and runoff evacuation is impossible through the drainage network.

The other principal hydrological process related to the hydrological response is infiltration. It could be described as the physical process of water entering into the soil (Horton, 1933). This process is an important point of analysis when analysing urban catchments because it is directly affected by changes in imperviousness, a situation that limits the infiltration process, creating a situation where the excess amount of water is transformed into runoff.

The other part of the hydrological response is related to the generating factor, in this case the precipitation. This driver mechanism is not well understood and remains an important research area (Cristiano, M.-C. ten Veldhuis, and Giesen, 2017). Changes in precipitation cycles, patterns and intensities have a direct impact on the hydrological response, especially in areas in which surfaces have lost infiltration capacity as is the case of urban areas.

2.2. LAG TIME DEFINITIONS

Hydrological response parameters usually associated with the topic are:

Time of concentration T_c, lag time T_l, time to peak T_p, runoff ratio, and flow to peak. These parameters offer insights on the discharge's behaviour based on the interaction of the characteristics of the urban catchments with rainfall. In this research, the lag time is selected as a temporal parameter of the urban catchment to study the relationships between this variable, the characteristics of the urban catchment, and rainfall events.

Lag time is the difference in time between precipitation, generated runoff, and the characteristics of any catchment. It depends on the slope, area, imperviousness, and soil capacity, among others characteristics. Due the subjectivity of the concept, several definitions have been developed trying to define the lag time parameter.

A summary of different definitions of lag time are listed hereunder:

1. The time difference between the rainfall time centroid (based on 15-min basin-averaged rainfall time series during the period of maximum 12-hour rainfall around the flood peak time) and the time of peak discharge. (Zhou, Long, et al., 2018)
2. The difference between the centroid of hyetograph and the centroid of hydrograph. (Berne et al., 2004)
3. Distance between rainfall and flow peaks. (Marchi et al., 2010)
4. The time from the centroid of effective rainfall to the time of the peak discharge of total runoff. (Heggen, 2003)
5. The time from the centroid of effective rainfall to the centroid of direct runoff. (Heggen, 2003)
6. The difference in time between the centre of mass effective rainfall and the centre of mass direct runoff produced by the effective rainfall. (Viessman, 2003)
7. Lag time is defined as the time difference between centroids of the effective periods from a specific rainfall derived from in a hyetograph and time when peak discharge occurs. (Wu et al., 2016)

Similar to the multiple proposed definitions of lag time, several empirical and analytical methods have been derived to estimate the lag time. Some of the methods are summarised below:

$$\mathrm{L}_t = 7,81 * (L_m * L_{cg})^{0,3} * I_a^{0,57} \qquad \textit{Colorado State University} \tag{2.1}$$

$$\mathrm{L}_t = 0,32 * (L_m * L_{cg} * A^{-0,5})^{0,39} \qquad \textit{Eagleson} \tag{2.2}$$

$$\mathrm{L}_t = 0,49 * (L_m * A^{-0,5})^{0,5} * I_a^{0,57} \qquad \textit{Putnam} \tag{2.3}$$

$$\mathrm{L}_t = L_p^{0,8} * (CN/1000–9)0,7 * (1900 * A^{0,5})^{-1} \qquad \textit{Soil conservation Service SCS} \tag{2.4}$$

$$\mathrm{L}_t = 0,48 * (L_m * L_{cg} * A^{-0,5})^{1,42} \qquad \textit{Snyder} \tag{2.5}$$

$$\mathrm{L}_t = 0,6 * (L_m * L_{cg} * A^{-0,5})^{0,3} \qquad \textit{Taylor and Schwartz} \tag{2.6}$$

$$\mathrm{L}_t = 7,86 * DA^{0,35} * TIA^{-0,22} * S^{-0,31} \qquad \textit{USGS} \tag{2.7}$$

$$\mathrm{L}_t = 3 * A^{0.3} \qquad \textit{Berne et al.} \tag{2.8}$$

$$L_t = 8,9 * A^{0.27} \qquad Cristiano, E.\ et\ al. \tag{2.9}$$

Where:
L_t= Lag time $[hours]$.
A= Area $[km^2]$.
L_m= Length of the stream $[miles]$.
L_{cg}= Distance from the centre of gravity of the basin to the outlet. $[miles]$.
L_p= Length of the stream $[ft]$.
I_a= Rainfall intensity $[mm/hr]$.
D_A= Drainage area $[miles^2]$.
TIA= Impervious area [%].
S= Slope $[ft/miles]$.

All the equations presented above were generated under specific circumstances; and, therefore, their validity should be understood prior to their application. For equation 1, the author specifies that it is valid for watersheds of up to 3km^2 and with urban land use anywhere from 30% to 80%. Equation 5 is a region-generated equation for the North East part of the US. Equation 6 is data driven and based on information from local stations. Equations 7 and 8 are also data driven with data obtained from the Marseille (France) area and London area, respectively.

One important drawback of all the above-mentioned equations is the lack of information about vegetation in the equations defining lag time, and this limits their reliability (Vélez Upegui and Botero Gutiérrez, 2011). The authors of the above-mentioned equations conclude that more information obtained from experimental urban basins is needed to validate the proposed ways to calculate lag time. Along the same lines, Gericke and Smithers (2014) pointed out that the definition of lag time based on empirical methods must be limited to their region of study. In case of using these equations in other areas, studies about correction factors based on local observations and in geomorphological characteristics need to be carried out to minimise considerable errors. The authors of said equations also mention that precedent moisture conditions and non-uniformities in the temporal and spatial distribution of rainfall have to be addressed in future studies.

2.3. INTER-AMOUNT TIMES, IAT

Precipitation and discharge processes vary both in space and time. This variability is the result of several meteorological and physical conditions and its understanding could lead to a better comprehension of the hydrological response process within the basin. This variability of flow and precipitation in time and space could be defined as intermittency in order to assess the availability of water resources in a more comprehensive way.

Intermittency is sometimes not studied because it is not observed at all scales. In the case of precipitation, intermittency is normally just defined as wet or dry period, which is a way of saying whether precipitation occurred or not. In terms of statistics, intermittency is studied by looking at the distribution of time series. In the case of precipitation, these time series present an abundant number of zero values, which correspond to $dryperiods$; and, therefore the statistical distributions are giving more weight to these values. In terms of precipitation, the same happens; but, instead of talking about zero values, low values are observed. These low values correspond to base flow and its behaviour is seasonal rather than constant or intermittent.

The definition of dry or wet periods is an arbitrary process that refers to the days with precipitation above or below an arbitrary threshold in order to refer to the spell as either a dry or wet spell. Values defining thresholds are set using specific definitions of what represents a dry or wet condition based on regional meteorological conditions (Ratan and Venugopal, 2013). Normally these values are presented as minimum non-rain periods or minimum accumulated precipitation over a given period of time. Nevertheless, it is important to notice that this approach is static, and rather another spatial varying threshold, accounting for the non-uniformity of rain, should be used.

At this moment it is realistic to think that any analysis based on dry or wet spell normal technique is subject to an initial error coming from the very first definition of wet and dry thresholds. In that sense, new methods for statistical analysis of intermittent processes, such as precipitation and discharge flow are being proposed. Among them, the methodology of Inter-Amount Times (IAT) proposed by Schleiss and J. A. Smith (2016) is studied and employed in this research.

IAT is based on adaptive sampling technique. The advantage of adaptive sampling is that if it is correctly applied it serves as an aid to avoid overlooking interesting parts of the time series. These interesting parts are mainly situations with high peaks of either precipitation or discharge, shifting the focus away from very low or zero values. The IAT methodology uses a definition of dry and wet periods based on the time before continuous precipitation or a positive change in discharge occur. In that sense, intermittency thresholds are no longer arbitrary but data-driven. Another big advantage of this technique is that more information about the important points is recorded allowing for an analysis at smaller scales that may describe the evolution of such important events.

As explained by Schleiss and J. A. Smith (2016), Inter-Amount Times could be defined as follows:

$$t_k(\Delta q) = t_k(\Delta q) - t_{k-1}(\Delta q) \forall k \in \Re$$

(2.10)

Where:
Δq :Fixed amount of precipitation or discharge> 0
$t_k(\Delta q)$:Times at which the total precipitation or discharge amount first exceeded n times q $[hr]$.

To avoid static values, normalisation is required to eliminate scale dependence and consequently enable the comparison between areas of study. This is done by the authors by using an average inter-amount time $IAT_{\bar{t}}$ (i.e 24 hr). The result is a $\Delta q_{\bar{t}}$ at the selected time scale.

$$\Delta q_{\bar{t}} = \frac{Q_N}{T} \tag{2.11}$$

Where:
Q_N: total cumulative precipitation or flow amount at point of study
T: length of the studied time period $[hr]$.

In this context, different locations with different accumulated values for precipitation and discharge over certain time periods would have different normalised values for IAT time series. More detailed information about the methodology can be found in the works done by Schleiss and J. A. Smith (2016); Marie-Claire ten Veldhuis and Schleiss (2017).

2.4. QUALITY CONTROL OF PRECIPITATION DATA

Using precipitation data series coming from radar observations and from ground observations has different advantages and disadvantages in each case. Spatial distribution of precipitation is better represented by radar records. Despite this advantage, radar observation are subjected to higher probabilities of errors compared to ground observations (Krajewski, 1987; Baeck and J. A. Smith, 1998). Precipitation ground observations such as rain gauges have good accuracy but poor spatial representation of the precipitation fields. For that reason, efforts that aim at having better results coming from radar estimations are attracting more attention.

Generally speaking, one of the most used methodologies for the generation of more reliable radar products is the merging of radar and ground observations and the calibration of this merger by means of comparison against ground observations. Even if the main objective of any research is not to generate better radar based products, a quality control of radar data is expected to occur using ground observations to estimate the magnitude of the systematic error (biases)(Gjertsen, Salek, and Michelson, 2004). The final purpose of this quality control is to assess the reliability of any result generated by using biased precipitation data.

2.5. STATISTICAL ANALYSIS FOR DATA SERIES

Time series are defined by Chatfield (2016) as a collection of observations taken sequentially in time. In hydrology, these series of measurements normally refer to water levels, precipitation, discharge, evaporation, atmospheric pressure, among other processes. The importance of time series analysis stems from the fact that a better understanding of the analysed process is required if this information is intended to be used for further analysis or researches. One may say that any time series analysis must be able to characterise the behaviour over time of a given variable (i.e discharge, temperature, evaporation, precipitation).This kind of analysis are quite important since they allow for the generation of mathematical models that are later used for important activities, such as weather forecasting, occurrence probability or trend analysis(Machiwal and Jha, 2006).

Time series could be classified as continuous or discrete. Continuous time series are those that can have any value between the physical domain of the variable (i.e. temperature, precipitation, atmospheric pressure, discharge). On the other hand, discrete time series normally have integers as unique values (i.e. number of peaks, storm events in a given period, or temperature values above a threshold).

For a correct analysis, the first steps include, but are not limited to, defining if the process is continuous or not, if it is subject to seasonal effects, or if its occurs alone or alongside other processes. Answering these questions, implies an ability to identify homogeneity, trends and/shifts and seasonality for the given time series. Homogeneity means to have a time invariant mean. Trends and shifts are consistently increasing or decreasing gradual changes that are mainly caused by global or regional changes in climate. Seasonality are those changes in values that are generated by the earth´s orbital motion. Since the orbital motion has a duration of 365 days, seasonality can solely be detected using temporal scales of less of than a year.

Descriptive statistics summarising the data and its structure could be generated in terms of skewness, location and spread. (Salas, 1993) Skewness addresses the manner in which a distribution is non-symmetrical around the mean or median, therefore extreme values are present in either the left or right direction. The most common ways of expressing skewness are through the coefficient of skewness and the quartile skew coefficient. Measures of location refer to typical values. The most common indicators of location are the mean and median. In terms of spread, it could be said that it indicates the tendency of the data to cluster towards the center or towards any other part of the distribution. The bigger the spread, the bigger the range of the data. Typical means of measurement are the variance, standard deviation and the interquantile range (Machiwal and Jha, 2006).

3

METHODOLOGY

3.1. URBAN CATCHMENT CHARACTERISATION

In order to be able to produce a meaningful analysis regarding the hydrological response of urban areas, it is extremely important to identify and classify most of the heterogeneous aspects defining the urban environment. The main differences among catchments are those relating to surface use and to the presence of hydraulic infrastructure in different forms (i.e. regulation weirs, retention ponds, drainage system).

LAND USE CHARACTERISATION

The Little Sugar creek catchment was characterised in terms of land use. The land use characterisation was developed using geographic information developed by the National Land Cover Dataset (NLCD). This data set is the result of a collaboration effort between several federal US agencies, such as the U.S. Geological Survey, the U.S. Environmental Protection Agency, the U.S. Department of Agriculture, NASA, and the U.S. Army Corps of Engineers, among others. The result of this collaboration is a consortium called Multi Resolution Land Characteristics (MRLC), which was established in 1992 and generates a 30-meter resolution land cover database for the whole of the United States of America.

This land cover database was generated every 10 years, but in 2006 a new 5-year product cycle was introduced. The database gives descriptive characteristics of different thematic classes such as urban, forest, agricultural, and open water areas. In addition, it also provides information on percentages of impervious surface and tree canopy cover. The result is a 16-land use classification, which is shown in the table below.

The information collected from the NLCD website was processed using the QGIS® software. Once the general and local boundaries of the catchment were set using the WGS 84 coordinate reference system, the information of land use was trimmed and fixed to fit the catchments boundaries.

WATER BODIES AND HYDRAULIC INFRASTRUCTURE

Information related to any water infrastructure was retrieved as digital maps from the website of the City of Charlotte and Mecklenburg County http://charlottenc.gov/maps The retrieved information were maps containing streams, creeks and ponds. Further activities revolved around listing all the streams and creeks per catchment, as well as the amount of water bodies located within boundaries of basin. More information about drainage networks density was researched without positive result.

3.2. HYDROLOGICAL DATA

3.2.1. PRECIPITATION

Precipitation data used in this research were obtained from radar observations. Radar observations have a 15-minute temporal resolution and a 1 km^2 spatial resolution with records from the months of April to September starting in 2001 until 2015. These radar records come from the Hydro-NEXRAD system, which is the result of the collaboration between the University of Iowa, Princeton University, the Unidata Centre Program of the Universities Corporation for Atmospheric Research (UCAR), and the National Climatic Data Centre of the National Oceanic and Atmospheric Administration (NOAA).

Hydro-NEXRAD is defined as a prototype software system that generates and provides weather information based on data archives of the U.S. weather radar network called Next Generation Weather Radar (NEXRAD) (Krajewski et al., 2011). This network of NEXRAD has 160 sites, mainly throughout the United States of America. The National Centre for Environmental Information (NCEI) manages and stores level II and level III type information. Level II type information consists of the original meteorological measurements in terms of reflectivity, mean radial velocity, and spectrum width. The information included in the level III type is related to meteorological analysis products based on level II information.

Level II and III data are available at NCEI website `https://www.ncdc.noaa.gov/dataaccess/radar-data/nexrad` as unit of files that could contain from 4 to 10 minutes of base data. At any given time, there are anywhere from 50 to 100 Level III products available, such as precipitation estimates, hail estimates, storm relative velocity, and echo tops, among many others.

Hydro-NEXRAD uses level II data as input for the generation of products with higher spatial and resolution throughout the development of data-processing modules and the implementation of algorithms for processes, such as radar reflectivity data processing, reflectivity to rainfall convergence, and merging data from multiple radars, among others. The main advantage of the Hydro-NEXRAD project is that it allows generating tailored made products. For the case of the Charlotte metropolitan area, Hydro-NEXRAD was used to yield precipitation time series with a 15-minute temporal resolution and a 1-km^2 spatial resolution from 2001 to 2015, using volume scan reflectivity fields. The supervisor provided this information.

Precipitation ground measurements are given by a network of 72 rain gauges that are part of the network maintained by the USGS. This network provides information with a 15-minute temporal resolution and uses tipping-bucket type rain gauge to measure precipitation for the whole metropolitan area of Charlotte,NC.

QUALITY CONTROL OF PRECIPITATION DATA

As previously explained, radar based information are very prone to have systematic errors in both space and time domains. In order to measure the difference between precipitation radar fields and point ground observations, two ways of representing the estimations of the bias are generated: additive bias and multiplicative bias.

In both processes the main assumption is that the ground observations are taken as reference value . Thus, additive bias is computed as follows:

$$Bias_{add} = RGobservation - Radarobservation$$

(3.1)

$$Bias_{mult} = \frac{Radarobservation}{RGobservation}$$

(3.2)

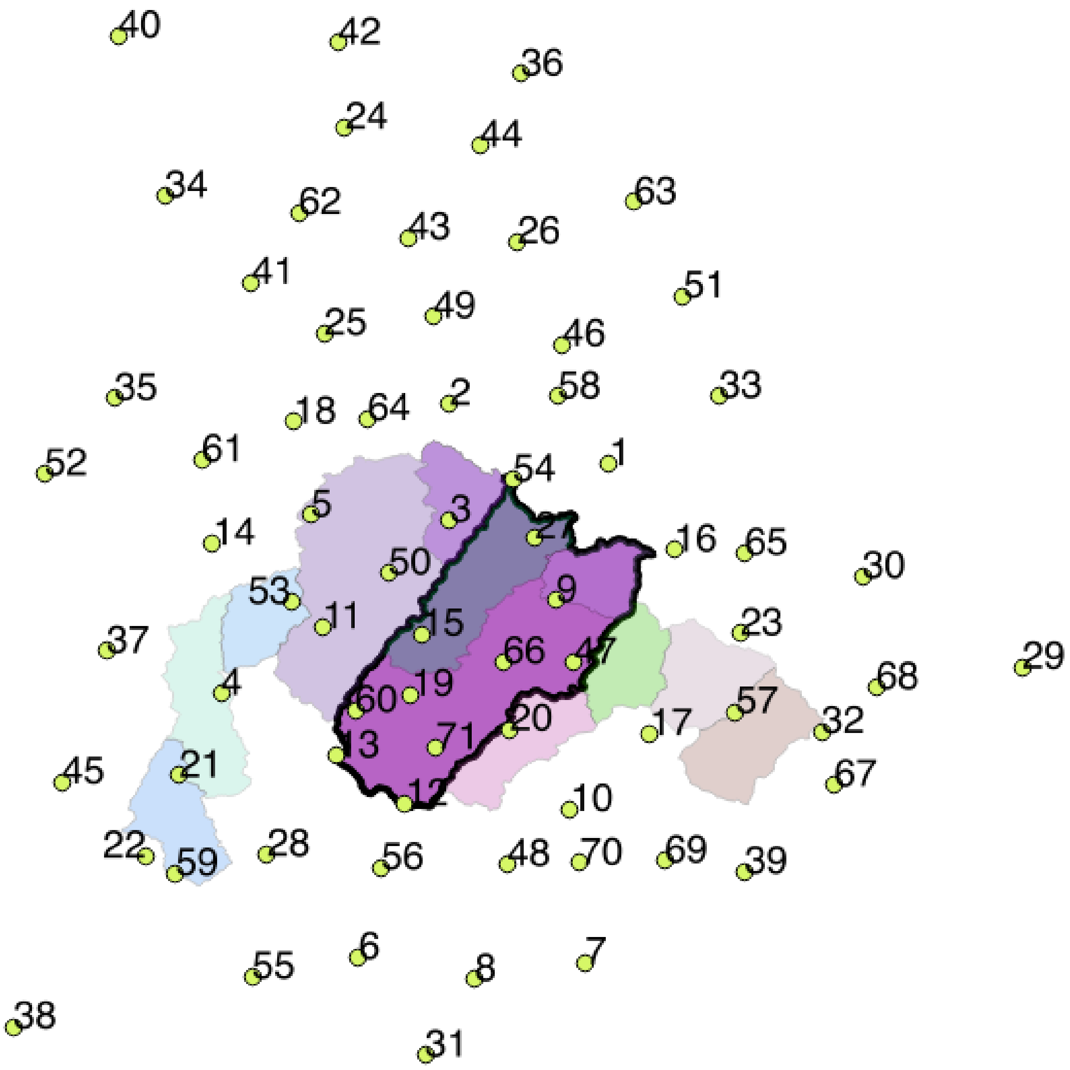


Figure 3.1: Rain gauges network in Charlotte metropolitan area.

Where:
RG Observation: Precipitation rain gauge measurement annual average[mm].
Radar Observation: Precipitation radar measurement annual average [mm].

These estimations serve as first quality control and the results must be interpreted carefully, since they heavily depend on how dense the ground observation network is. In this research, a maximum of one ground observation is located within each sub-catchment; and, therefore the bias is still unknown for locations other than the location of the rain gauge. One way to measure the bias related to the area covered by the rain gauges and the radar is through the point-to-area bias estimation. This procedure generates ground average based on several ground observations within the area of study and compares it against radar average. This was not done in this research, because a maximum of one ground observation is located within the sub-basin, as already shown.

3.2.2. DISCHARGE

Discharge data were obtained from 17 gauges that are part of the United States Geological Survey network installed at the hydrological outlet of each of the catchment and sub-catchments within the Charlotte metropolitan area. The discharge flows are computed reading gauge height values. Some values are transmitted from dual channel ultra high frequency radios to a base station computer within 5 minutes after the record is taken. Other gauges use satellite telemetry to transmit the data on an hourly basis. The data is rapidly processed and can be accessed on the USGS website at `https://www2.usgs.gov/water/southatlantic/nc/projects/char/`. For the case of study of this research, data were collected for a period from 2001 to 2015 with a temporal resolution of 15 min.

3.3. DATA PROCESSING

3.3.1. PRECIPITATION AND DISCHARGE

Precipitation and discharge data were analysed to avoid missing values, negative values, or any other possible error in the recording of the measurements. The negative and missing values were substituted by zero values. This treatment was recorded as a percentage of missing values and kept for further analysis.

Another process that was executed for the original time series was to make sure that the whole time series had the same temporal resolution, as some years have a 5-minute and others a 1-minute temporal resolution. Measurements with a 1-minute and a 5-minute temporal resolution were resampled into 15-minute temporal resolution measurements to be consistent with the rest of the data.

Thereafter, another processing activity carried out for the precipitation radar observations time series was to generate a basin average time series based on values corresponding to each radar pixel within the catchment. This activity was carried out by importing the coordinates of radar pixels into the QGIS® environment. Once all the pixels are displayed using the same coordinate reference system WGS 84 as when setting the boundaries of each the catchment, all pixels being above the area of each catchment are selected and a table with the id of each pixel is created for each case.

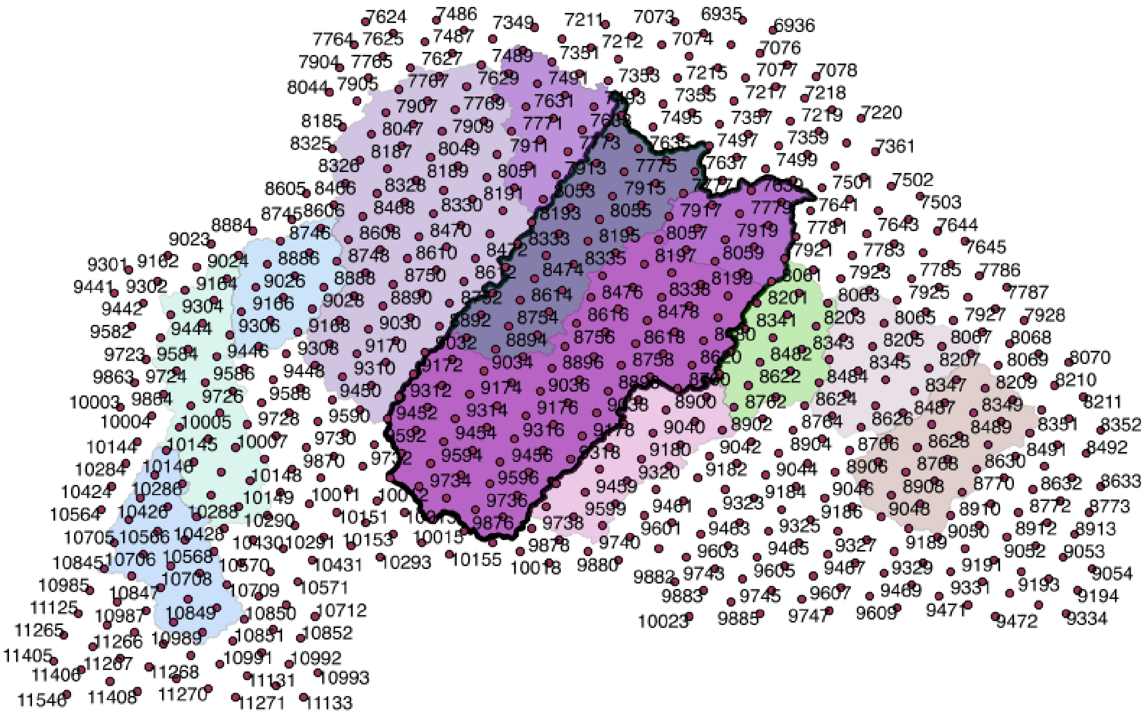


Figure 3.2: Radar pixels above the metropolitan area.

The generated lists are used for computing precipitation average values using the pixels that correspond to each case based on the tables. The result is a new precipitation time series for each sub-catchment with the average value of the precipitation measurements. This new average precipitation time series per sub-catchment was the time series used as starting point by this research. Subsequently resampling activities were carie out to also generate precipitation and discharge time series with a temporal resolution of 30 and 60 minutes, in addition to the original 15 minutes.

These resampling resolutions of 30 and 60 minutes are selected for a comparative analysis due the fact that this research covers urban basins in which runoff processes are expected to be quick, in particular for small basins. It is true that big basins, even if they are highly urbanised, may experience lag times of several hours as presented in the analysis done by Zhou, J. A. Smith, et al. (2017). Nevertheless, 60 minutes is selected as the lower resolution to be studied in order to allow for a more meaningful comparison.

In the case of discharge time series, the same resampling activity for measurements with a 1-minute and a 5-minute temporal resolution were carried out, as those performed for the precipitation time series to produce 15-minute temporal resolution records to be consistent with the rest of the data. Finally, the time index of all discharge time series was adjusted from its original UTC-5 to UTC.

3.4. SELECTION OF EVENTS

The purpose of this research is to focus on the most common events (events that occur with the highest frequency), which means that extreme events, either those that are extremely large or extremely low, are not of interest for this research. The selection of the events that are going to be used in the study was made using a visual identification as a first step.
By using graphical displays of cumulative discharge curves and precipitation time series together, it was possible to identify which precipitation events generated any response in the discharge curve as first approach to identify relevant events.

After the first observations of the precipitation events causing a response in the discharge curve, it was observed that base flow accounted for around 95% of the flow; thus, all the discharge measurements above the 95^{th} percentile on an annual basis, were targeted as relevant, meaning that for each year the 95^{th} percentile would be different. The intention of having a different value as threshold each year, rather than a same value valid for the length of the study, is based on the idea that stationarity applied to selecting a threshold may result in the selection of events that may not be of interest for a given year. The resulting new time series that only includes values above the previously indicated percentile includes events that need to be validated. In order to call these events valid, an inspection of the precipitation time series over the same time spam is carried out. This inspection seeks to establish the start and end time of the corresponding pre-selected discharge event. The start time is fixed at the first immediate moment with precipitation different to zero and with precedent zero precipitation values for at least 6 hours. The start time will be indicated until both conditions are fulfilled. Similarly, precipitation end time is found at the point immediately after the discharge end time and when the following six hours have zero precipitation.

Once the procedure described above was applied, the results were a discharge and a precipitation time series with a certain amount of pairing events. As precipitation generates discharge, one precipitation event is paired to a discharge event. Intermittent events were those that have several peaks that occurred within the 6-hour time period. No differentiation in the selection of events is made between single and multi peak events. Nevertheless, further classifications of single and multi peak events were made for analysis purposes.

As mentioned at the beginning of this section, the focus of this research is on using the events that are more likely to occur; in order to achieve this, 2 selection criteria are applied to the already pre-selected events, which are maximum discharge and maximum precipitation. These 2 indicators were established with the aim of arranging the entirety of the events based on each one of the 2 criteria. This is intended to have a more diverse and complete vision of the nature of the different events that are in the universe of interest. All the events were sorted based on the criteria described above and the events between quantile 1 and 3 were selected. The result of this selection is a universe of events that presents more than 100 events for the catchment.

In order to have just a few events that are representative of this new universe of events, a new second selection based on just the events closest to the values of quantile 1, 2 and 3 for each of the 2 selecting criteria, maximum discharge and maximum precipitation, is applied. The resulting final total number per year is 6 events.

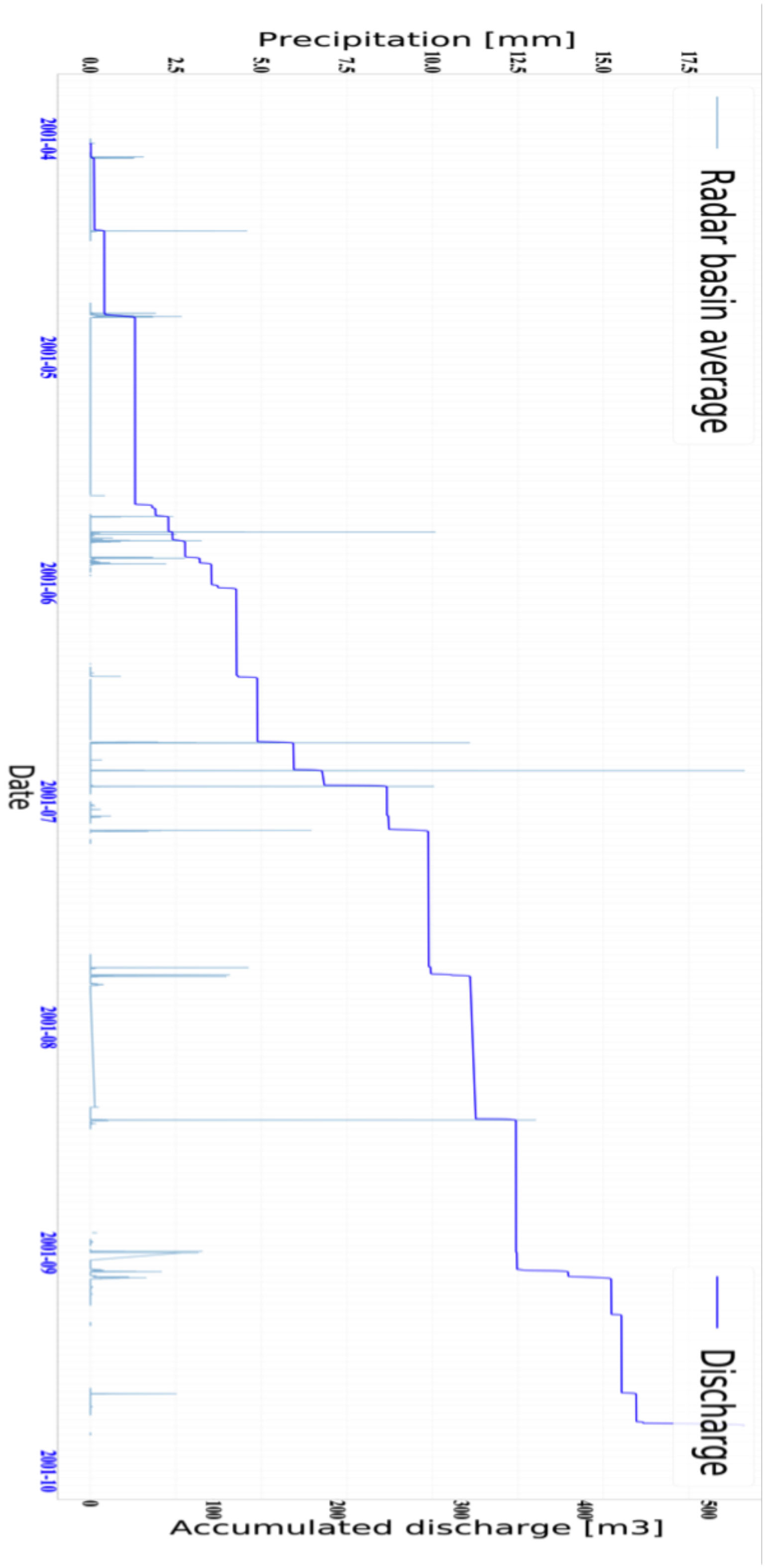


Figure 3.3: Discharge cumulative curve with precipitation curve.

3.5. IAT

3.5.1. IAT TIME SERIES COMPUTATION

Based on the previously presented theory of IAT, the computation of time series for both precipitation and discharge, was done by implementing a script for the Python environment with the following considerations:

Temporal resolution was set at 900 sec, 1800 sec and 3600 sec for the cases of 15 min, 30 min and 60 min resolution, respectively. In each of the 3 cases, temporal resolution represented the only possible value that could be given as input in terms of temporal resolution measurements. The maximum observable scale was also limited to correspond to each of the temporal resolutions. With the file containing the different events, the total amount of flow or precipitation and the total duration of each event is computed for each event.

To make sure that the same number of passage times exist for both precipitation and discharge events, and due the fact that significant differences between volumes and duration of events for precipitation or discharge may generate differences in the number of passage times, a first run of the script is executed to establish the number of passage time that each event generates for precipitation and discharge. The resulting number of passages times for each one is compared and the minimum number of passage time is set as the one to be used for the event in study. A second run is done with a now exact number of passage time for both time series.

The resulting mean inter amount time is then computed as the difference in passages times and stored in a vector with the series of values of IAT for each event in hours.

3.5.2. IAT TIME INDEXATION

As mentioned previously, the values computed as mean IAT are expressed in terms of hours, or fractions thereof, but are not associated to a given moment of time. In order to visualise these results as proper measurements linked to a certain moment of time, an indexation procedure is performed. This procedure is carried out by selecting the starting time index for the corresponding precipitation or discharge event. Once this first point is set, the values of the corresponding IAT vector are transformed into time objects and added to the previous time index each IAT measurement.

3.5.3. IAT LAG TIME

It is important to reckon that in order to talk about proposing a lag time definition based on the values obtained using the IAT approach, the IAT results could be seen as an alternative time series but with the same start and end points, i.e. no unique values are obtained from it. The measurements recorded are distributed along the whole duration of the precipitation or discharge event with a clear accumulation of measurements around the points of interest marked as those moments of time corresponding to high values of discharge or precipitation.

The first step was to generate a simple difference between the IAT measurements of precipitation and discharge. This was performed by subtracting the value of the precipitation IAT from the discharge IAT.

$$IATlag_{1...n} = IATd_{1...n} - IATp_{1...n}$$

(3.3)

Where:
IAT_{lag}: Inter amount time point lag time $[hr]$.
$IATd_n$: Discharge IAT point value at position n $[hr]$.
$IATp_n$: Precipitation IAT point value at position n $[hr]$.

The result of this operation is a list with several different values of the differences between precipitation and discharge points of the IAT time series. The statistical median value of the IAT lag time series is selected to obtain a unique value that could be representative of a specific event. The reason to use the median value rather than the mean value is that the latter is more susceptible to be influenced by outliers.

3.6. STATISTICAL ANALYSIS

3.6.1. DISTRIBUTION ANALYSIS

For the statistical analysis, the approach was to generate histograms of the lag time of the 84 events. The histograms were computed for the IAT technique, Peak-to-Peak and Centroid-to-Centroid methodologies for the 3 time resolutions. This situation would allow to compare the distribution of results corresponding to the three methodologies through the different time scales. Besides the use of histogram for graphical analysis, coefficient of variation (CV), skewness and medcouple values were generated to analyse and compare the results coming from each of the three methods.

3.6.2. LAG TIME COMPARISON

The proposal of a lag time definition using IAT uses the results of the IAT methodology to compute a characteristic lag time value that later was compared with the values obtained by applying the known definitions of lag time based on peak-to-peak observations and centroid-to-centroid observations.

The latter comparison studied the results using the above-mentioned resolution for the precipitation and discharge time series, which are 15, 30 and 60 minutes.

3.6.3. CORRELATION ANALYSIS

In order to compare the evolution of the methods over the 3 time resolutions, scatter plots along with correlation coefficients were plotted. This was done to evaluate the strength of the first order correlation between different lag time methods and temporal resolution combinations. The resulting series of combinations are listed hereunder:

1. IAT lag time 15 minutes Vs IAT lag time 30 minutes.
   IAT lag time 15 minutes Vs IAT lag time 60 minutes.
   IAT lag time 30 minutes Vs IAT lag time 60 minutes.

2. P-to-P lag time 15 minutes Vs P-to-P lag time 30 minutes.
   P-to-P lag time 15 minutes Vs P-to-P lag time 60 minutes.
   P-to-P lag time 30 minutes Vs P-to-P lag time 60 minutes.

3. C-to-C lag time 15 minutes Vs C-to-C lag time 30 minutes.
   C-to-C lag time 15 minutes Vs C-to-C lag time 60 minutes.
   C-to-C lag time 30 minutes Vs C-to-C lag time 60 minutes.

4. IAT lag time 15 minutes Vs P-to-P lag time 15 minutes.
   IAT lag time 15 minutes Vs C-to-C lag time 15 minutes.

5. IAT lag time 30 minutes Vs P-to-P lag time 30 minutes.
   IAT lag time 30 minutes Vs C-to-C lag time 30 minutes.

6. IAT lag time 60 minutes Vs P-to-P lag time 60 minutes.
   IAT lag time 60 minutes Vs C-to-C lag time 60 minutes.

3.6.4. SENSITIVITY ANALYSIS

Using the results coming from the correlation analysis, the twelve cases with the highest and lowest correlation for each combination were selected to evaluate if there was a explanation causing the high or low correlation. The main objective of this analysis is to identify the kind of events within the IAT lag time method that behave in a different manner.

These events were evaluated by means of maximum discharge, maximum precipitation and duration of the precipitation and discharge event. This procedure was performed by using interquartile analysis identifying the location of those events with the lowest and highest correlation within the whole universe of events. The aim of this procedure was to identify patterns of behaviour of these relevant events that may give indications about certain properties(i.e. Maximum precipitation, Maximum discharge, Event duration) of the events that led to a low or high correlation.

The results coming form this analysis were used to identify two situations. First, identify those values corresponding to maximum discharge, maximum precipitation and duration of the precipitation and discharge event that consistently yielded low or high correlation. Second, based on the correlation between the IAT Lag time method and the classical methods used in this research, identify the events for which the lag time results were very similar regardless the lag time method used for their calculation. This will allow further analysis about the correct use of a certain lag time definition based on the observed local events.

4

Results

4.1. Urban catchment characterisation

Land use characterisation

Table 4.1 shows the different land uses in the Little Sugar creek for 2001 and 2011.

	Little Sugar Creek Land Cover comparison				
	2001		2011		2011 Vs 2001
Land cover	Area/LC[m^2]	Percentage [%]	Area/LC [m2]	Percentage [%]	Percentage [%]
Open Water	13541	0.012%	6888	0.010%	-0.002%
Developed, Open Space	43426215	39.1%	42314990	38.1%	-1.00%
Developed, Low Intensity	35901893	32.3%	35550068	32.0%	-0.31%
Developed, Medium Intensity	15169611	13.6%	16446071	14.8%	1.15%
Developed High Intensity	11193049	10.1%	12040305	10.8%	0.76%
Barren Land (Rock/Sand/Clay)	2708	0.0%	0	2.4%	2.38%
Deciduous Forest	2892373	2.6%	2648454	0.3%	-2.29%
Evergreen Forest	416162	0.4%	341819	0.1%	-0.28%
Mixed Forest	143535	0.1%	105043	0.0%	-0.09%
Shrub/Scrub	0	0.0%	41328	0.1%	0.14%
Grassland/Herbaceous	188672	0.2%	159286	0.1%	-0.06%
Pasture/Hay-areas of grasses, legumes	378247	0.3%	123124	0.2%	-0.12%
Cultivated Crops	30693	0.0%	0	0.0%	-0.03%
Woody Wetlands	259989	0.2%	249692	0.0%	-0.23%
Emergent Herbaceous Wetlands	3611	0.003%	3444	0.000%	-0.003%
	Total Area [m^2]	**111138000.00**			

Table 4.1: Little Sugar Creek land use comparison 2001 - 2010.

In 2001, around of 56% of the 111.138.000 m^2 of the surface of the Little Sugar Creek had urban characteristics. Among this percentage, 39,1% corresponded to low intensity developed areas that had between 20% and 49% of the total area with impervious characteristics. Medium intensity developed areas accounted for 13% of the total area with areas with impervious characteristics between 50% and 79%. The remaining 10,1 % had high intensity developed characteristics, which are defined by areas in which impervious surfaces account for 80% up to 100% of the total area.

Open bodies areas are almost nonexistent with a surface area of less that 1% of the total Little Sugar Creek; and, green, woody or pervious areas accounted for less that 4%. Most of the pervious surfaces were encountered in the 39.1% of the total area corresponding to the developed open space land use classification. Less than 20% of the 39.1% of the total area that was classified as open space presented impervious characteristic.

As seen in figure4.1, after ten years the main changes corresponded to an increase in 1.15% of medium intensity developed area and a 2.29% decrease of the area with characteristics of deciduous forest.
Another important aspect of the land cover classification is the interception capacity related to each of the different land covers. The main actors in interception are canopies. In this case, canopies accounted for a very small part of the total area of the Little Sugar Creek. Some roof areas could generate interception, but its contribution is not well identified at this point.

WATER BODIES AND HYDRAULIC INFRASTRUCTURE

The water bodies found in the Little Sugar Creek were 63 ponds with a total area of 238251.14 m^2.

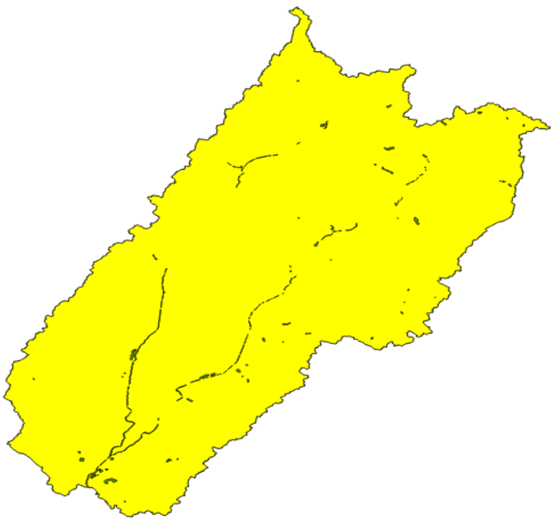
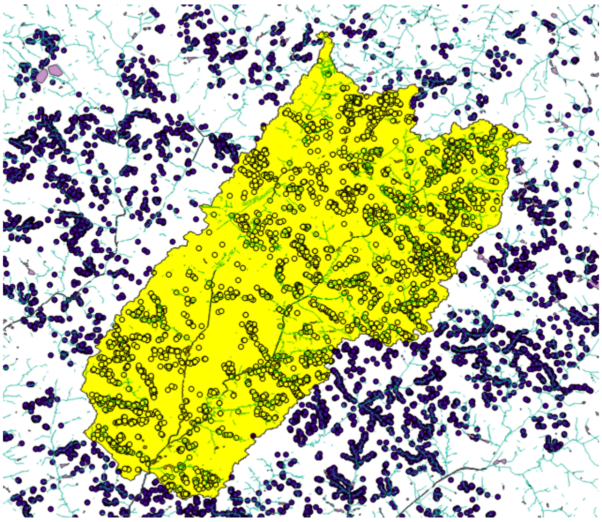


Figure 4.1: Little Sugar Creek ponds and water bodies.

With respect to the hydraulic infrastructures within the catchment, 4413 registers of storm drainage easement were found. This amount of storm drainage infrastructure translated into a total length of the storm drainage infrastructure of 198.67 km, which represents a storage capacity of approximately 1302571.5 m^3.


(a) Little Sugar Creek storm infrastructure easements.

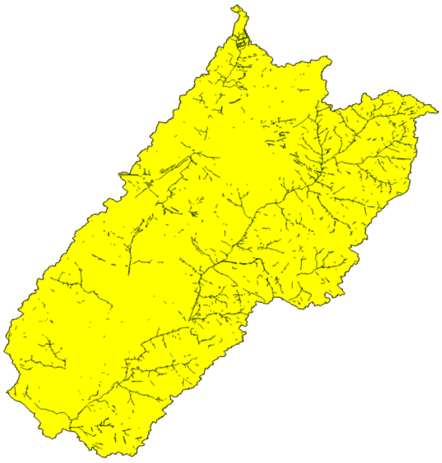

(b) Little Sugar Creek streams.

Figure 4.2: Little Sugar Creek storm drainage infrastructure.

4.2. HYDROLOGICAL DATA

4.2.1. PRECIPITATION

QUALITY CONTROL OF PRECIPITATION DATA

Little sugar creek has ten rain gauges that are part of the already mentioned network of 72 rain gauges maintained by the USGS within its boundaries. Image 4.3 shows the location and identification number for each of the ground observation points.

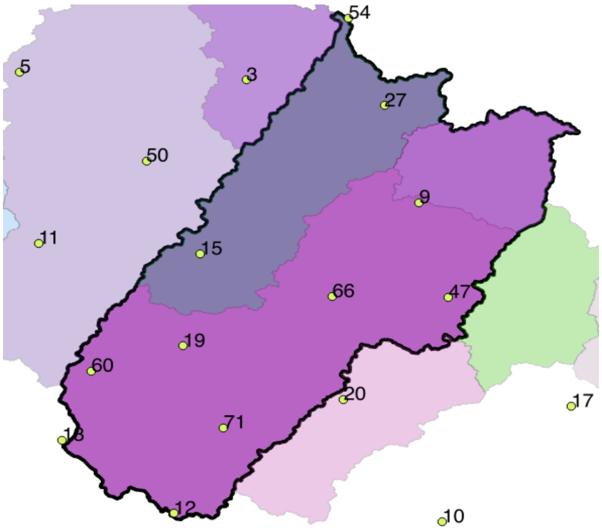


Figure 4.3: Rain gauges within Little Sugar Creek.

	Additive bias summary													
	2001	2002	2003	2004	2005	2006	2008	2009	2010	2011	2012	2013	2014	2015
Max [mm]	18.84	15.71	17.90	19.89	26.35	23.18	27.89	20.54	23.75	20.44	29.40	27.92	30.99	23.50
Min [mm]	-8.06	-10.54	-13.61	-6.45	-11.05	-12.76	-32.50	-12.65	-11.43	-15.48	-10.58	-8.91	-11.43	-8.43
Mean [mm]	-0.01	0.00	-0.01	0.01	0.00	-0.01	-0.01	0.00	0.00	0.02	-0.01	0.01	0.00	0.00
#id RG Max value	15	54	47	60	12	54	27	27	47	60	71	47	71	54
#id RG Min value	60	71	71	71	71	12	54	12	60	12	54	54	47	12

Table 4.2: Additive bias analysis summary.

	Multiplicative bias summary													
	2001	2002	2003	2004	2005	2006	2008	2009	2010	2011	2012	2013	2014	2015
Max [mm]	31.10	33.64	35.80	22.03	32.61	31.57	126.46	31.71	31.73	34.52	29.14	33.04	26.61	28.96
Mean [mm]	0.02	0.02	0.04	0.02	0.02	0.04	0.04	0.03	0.03	0.04	0.03	0.03	0.03	0.02
#id RG Max value	12	54	12	15	9	27	54	15	54	54	9	9	66	54

Table 4.3: Multiplicative bias analysis summary.

Tables 4.2 and 4.3 serve as summary for results corresponding to the additive bias and to the multiplicative bias. With respect to the additive bias, rain gauges 54 and 71 had the biggest differences. For the case of the multiplicative bias, rain gauge 54 was the one with the biggest differences. This value is not surprising since it is located at one of the locations that are farthest away. In general, mean values in both cases were close to zero, which validates the use of the radar basin average time series as precipitation input for this research.

4.3. SELECTION OF EVENTS

Events - Little Sugar creek				
Event	Prec Duration[hr]	Disch Duration [hr]	Max Prec [mm/ 15 min]	Max Disch [m^3/15 min]
0	17.25	22.75	4.03	26.96
1	17.50	29.25	3.40	16.31
2	27.00	30.50	3.06	14.10
3	9.75	18.00	4.29	16.20
4	17.50	29.25	3.40	16.31
5	27.00	30.50	3.06	14.10
6	42.25	48.75	1.60	22.91
7	26.00	29.50	1.23	14.61
8	4.75	7.75	0.84	12.63
9	5.50	10.25	4.48	9.34
10	15.75	20.25	3.45	10.59
11	16.75	20.50	1.84	13.34
12	44.00	44.00	1.23	66.54
13	12.50	15.75	1.70	64.00
14	21.50	21.50	5.23	41.91
15	8.50	10.50	7.55	63.43
16	9.50	17.50	3.82	102.79
17	12.25	17.00	2.48	37.38
18	28.25	15.00	4.49	86.37
19	15.25	17.75	3.55	39.93
20	6.50	14.00	1.09	32.28
21	6.00	7.00	4.78	11.13
22	29.25	26.75	3.55	155.74
23	23.75	26.75	2.11	35.11
24	9.00	15.50	9.51	94.30
25	10.75	15.00	1.69	37.38
26	1.75	9.90	3.95	13.22
27	3.50	14.25	4.51	143.85
28	1.25	10.75	4.04	10.70
29	9.00	10.00	2.78	9.54
30	23.50	32.25	2.85	85.52
31	13.75	13.50	5.33	21.80
32	9.50	11.50	0.91	12.15
33	4.00	8.33	7.27	8.38
34	10.75	17.50	4.76	33.70
35	12.75	12.25	3.06	20.76
36	13.50	12.50	9.86	53.52
37	3.00	13.25	6.46	20.50
38	6.00	9.75	3.37	10.70
39	8.00	15.25	6.87	7.59
40	3.75	12.12	5.81	26.79
41	18.00	21.00	3.15	8.01
42	24.00	27.25	5.42	54.65
43	12.00	18.25	1.60	17.02
44	5.50	10.75	5.64	12.35
45	24.00	27.25	5.42	54.65
46	20.25	20.75	3.73	33.41
47	17.50	25.75	2.27	13.68
48	7.25	12.75	4.01	135.92
49	15.50	15.75	5.62	47.37
50	33.50	41.00	2.88	28.15
51	32.25	36.25	7.49	416.54
52	9.00	14.75	3.31	95.99
53	14.75	8.25	2.04	38.03
54	12.75	19.00	1.50	191.42
55	11.75	19.25	4.07	83.19
56	9.25	12.00	3.39	32.62
57	10.75	15.75	8.77	100.81
58	4.25	10.75	5.73	91.46
59	11.75	19.25	4.07	83.19
60	16.25	22.25	6.34	139.32
61	17.50	20.25	7.40	66.01
62	24.50	24.50	1.09	36.67
63	9.75	15.25	5.93	43.07
64	3.75	9.00	4.00	16.37
65	12.50	18.50	2.66	29.45
66	26.00	29.75	8.62	158.01
67	15.25	18.50	1.79	95.99
68	12.75	17.00	1.50	46.84
69	13.50	16.75	5.56	148.95
70	27.00	31.50	2.49	154.89
71	15.75	23.75	1.72	112.70
72	28.00	31.75	2.61	210.39
73	15.50	22.00	2.72	91.18
74	12.50	16.50	5.08	57.17
75	13.25	19.50	4.64	65.30
76	11.25	13.25	3.46	62.84
77	15.50	22.00	2.72	91.18
78	7.25	10.50	2.67	58.02
79	10.00	12.00	2.74	27.30
80	2.25	12.00	1.60	17.44
81	9.00	12.75	4.81	234.75
82	13.25	23.00	3.00	117.51
83	4.00	13.00	1.62	17.44

Table 4.4: List of selected events in the original 15 minutes time resolution.

4.4. IAT

4.4.1. IAT TIME SERIES COMPUTATION

Event # 16 15 minutes		
Index	Precipitation IAT	Discharge IAT
1	0.00	1.34
2	0.28	1.01
3	0.20	1.33
4	0.19	1.30
5	0.33	1.52
6	5.10	0.44
7	0.08	0.14
8	0.08	0.11
9	0.07	0.10
10	0.03	0.09
11	0.03	0.09
12	0.03	0.07
13	0.03	0.07
14	0.03	0.07
15	0.03	0.07
16	0.03	0.06
17	0.03	0.06
18	0.03	0.06
19	0.02	0.06
20	0.02	0.05
21	0.02	0.05
22	0.02	0.05
23	0.02	0.05
24	0.02	0.05
25	0.02	0.05
26	0.02	0.05
27	0.02	0.05
28	0.03	0.05
29	0.05	0.05
30	0.05	0.06
31	0.05	0.06
32	0.05	0.06
33	0.05	0.06
34	0.11	0.07
35	0.12	0.07

Event # 16 30 minutes		
Index	Precipitation IAT	Discharge IAT
1	0.00	2.49
2	0.37	2.44
3	5.25	2.28
4	0.25	0.40
5	0.22	0.19
6	0.05	0.19
7	0.05	0.12
8	0.05	0.12
9	0.05	0.12
10	0.05	0.12
11	0.05	0.10
12	0.05	0.10
13	0.05	0.10
14	0.05	0.10
15	0.05	0.10
16	0.10	0.12
17	0.12	0.12
18	0.12	0.12

Event # 16 60 minutes		
Index	Precipitation IAT	Discharge IAT
1	1.56	4.42
2	5.03	2.51
3	0.58	0.60
4	0.13	0.24
5	0.13	0.21
6	0.13	0.21
7	0.13	0.21
8	0.13	0.23

Table 4.5: IAT time series for 15, 30 and 60 minutes resolution.

Example of resulting IAT time series are given in table 4.5. These examples correspond to event 16 with time resolutions of 15, 30 and 60-minute for both precipitation and discharge IAT time series, respectively.

Results of the indexation process can be found in tables 4.6 and 4.7 for each of the three time resolutions.

Event # 16 15 minutes	
Time index	Precipitation IAT
17/6/03 19:30:00	0.00
17/6/03 19:46:52	0.28
17/6/03 19:58:43	0.20
17/6/03 20:10:18	0.19
17/6/03 20:29:53	0.33
18/6/03 1:35:39	5.10
18/6/03 1:40:10	0.08
18/6/03 1:44:41	0.08
18/6/03 1:48:43	0.07
18/6/03 1:50:27	0.03
18/6/03 1:52:10	0.03
18/6/03 1:53:53	0.03
18/6/03 1:55:37	0.03
18/6/03 1:57:20	0.03
18/6/03 1:59:04	0.03
18/6/03 2:00:47	0.03
18/6/03 2:02:30	0.03
18/6/03 2:04:06	0.03
18/6/03 2:05:34	0.02
18/6/03 2:07:02	0.02
18/6/03 2:08:30	0.02
18/6/03 2:09:58	0.02
18/6/03 2:11:26	0.02
18/6/03 2:12:54	0.02
18/6/03 2:14:22	0.02
18/6/03 2:15:50	0.02
18/6/03 2:17:18	0.02
18/6/03 2:19:05	0.03
18/6/03 2:21:56	0.05
18/6/03 2:24:47	0.05
18/6/03 2:27:38	0.05
18/6/03 2:30:28	0.05
18/6/03 2:33:19	0.05
18/6/03 2:40:10	0.11
18/6/03 2:47:10	0.12

Event # 16 30 minutes	
Time index	Precipitation IAT
17/6/03 19:30:00	0.00
17/6/03 19:52:26	0.37
18/6/03 1:07:11	5.25
18/6/03 1:21:54	0.25
18/6/03 1:35:10	0.22
18/6/03 1:38:02	0.05
18/6/03 1:40:54	0.05
18/6/03 1:43:46	0.05
18/6/03 1:46:38	0.05
18/6/03 1:49:30	0.05
18/6/03 1:52:22	0.05
18/6/03 1:55:14	0.05
18/6/03 1:58:06	0.05
18/6/03 2:00:58	0.05
18/6/03 2:03:50	0.05
18/6/03 2:09:37	0.10
18/6/03 2:16:56	0.12
18/6/03 2:24:16	0.12

Event # 16 60 minutes	
Time index	Precipitation IAT
17/6/03 19:33:36	1.56
18/6/03 0:35:21	5.03
18/6/03 1:09:55	0.58
18/6/03 1:17:47	0.13
18/6/03 1:25:39	0.13
18/6/03 1:33:31	0.13
18/6/03 1:41:22	0.13
18/6/03 1:49:14	0.13

Table 4.7: IAT Precipitation time series with time index 15, 30 and 60-minute resolution.

Figure 4.4 provides a graphical visualisation of the same event 16 for both IAT time series along with precipitation and discharge time series. As can be appreciated in the graph, most of the concentration of observations are around the zones of the curve with bigger values. At these points, IAT observations are very close to minimum values, while at other locations IAT observations values are significantly higher. This behaviour was expected as IAT techniques attach more weight to these zones of interest, such as peaks of either precipitation or discharge.

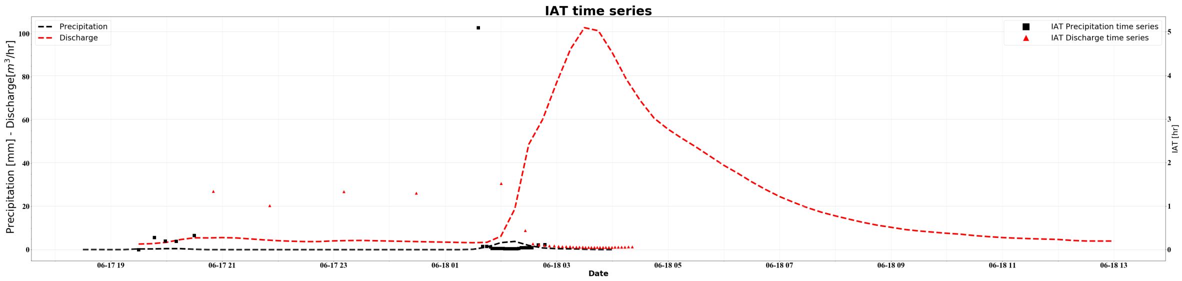


Figure 4.4: IAT Precipitation and discharge time series for event 16

Further examples of the results of the the IAT time series computation for a multi-peak event are provided in figures 4.5 and 4.6. Both graphs show how the IAT technique addresses multi-peak events. It is important to identify how a multi-peak event could have steady IAT observations all along the curve or how it could follow the dynamic observed in the IAT precipitation time series, where a cluster-type behaviour is observed, even though a certain presence of sparsely distributed measurements are also visible in the case of intermittent precipitation.

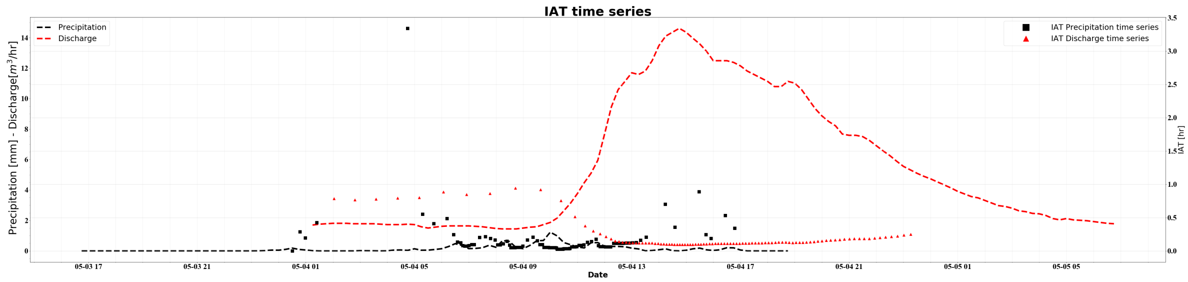


Figure 4.5: IAT time series along with precipitation and discharge time series for event 7 with 15 minutes resolution.

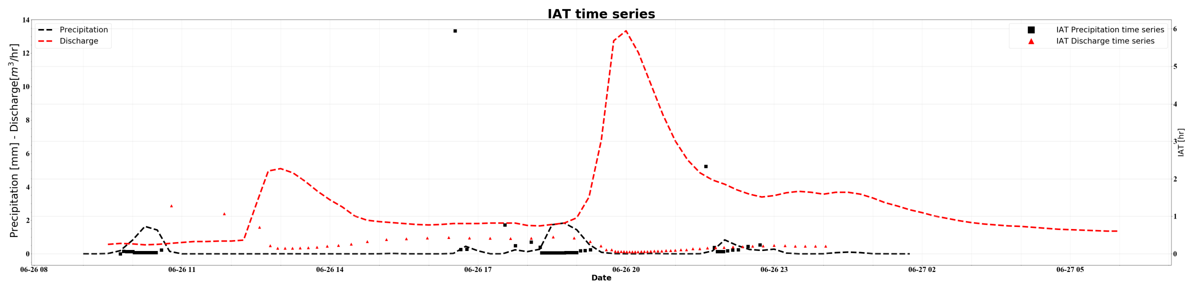


Figure 4.6: IAT time series along with precipitation and discharge time series for event 11 with 15 minutes resolution.

4.4.2. IAT Lag time

The process used for the computation of IAT lag time is shown in figure 4.7 of the aforementioned event 16. The top graph displays the IAT time series for both precipitation and discharge together with the corresponding precipitation and discharge events. The graph in the center represents how the difference between the IAT Discharge time series and the IAT Precipitation time series is computed to generate the IAT Lag time series. The black and bold line serve as a visual guide to identify the points of the IAT discharge and precipitation time series corresponding to the IAT lag time median value. Finally, the graph at bottom corresponds to the IAT lag time series.

For this particular event, the IAT Lag time was computed from values located almost at the peaks of the two curves. Figure 4.8 shows the procedure above mentioned for a multi-peak event. In this case, the values of those points corresponding to the median values are located in a zone that does not correspond to any particular peaks.

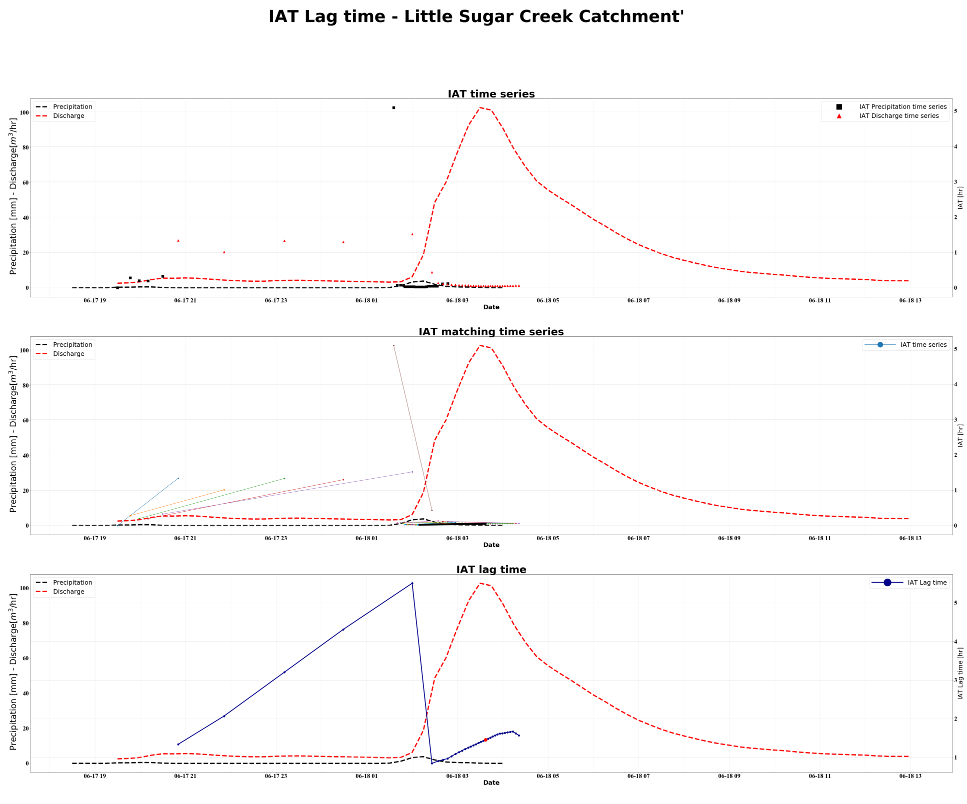


Figure 4.7: IAT Lag time computation procedure for event 16 with 15 minutes resolution.

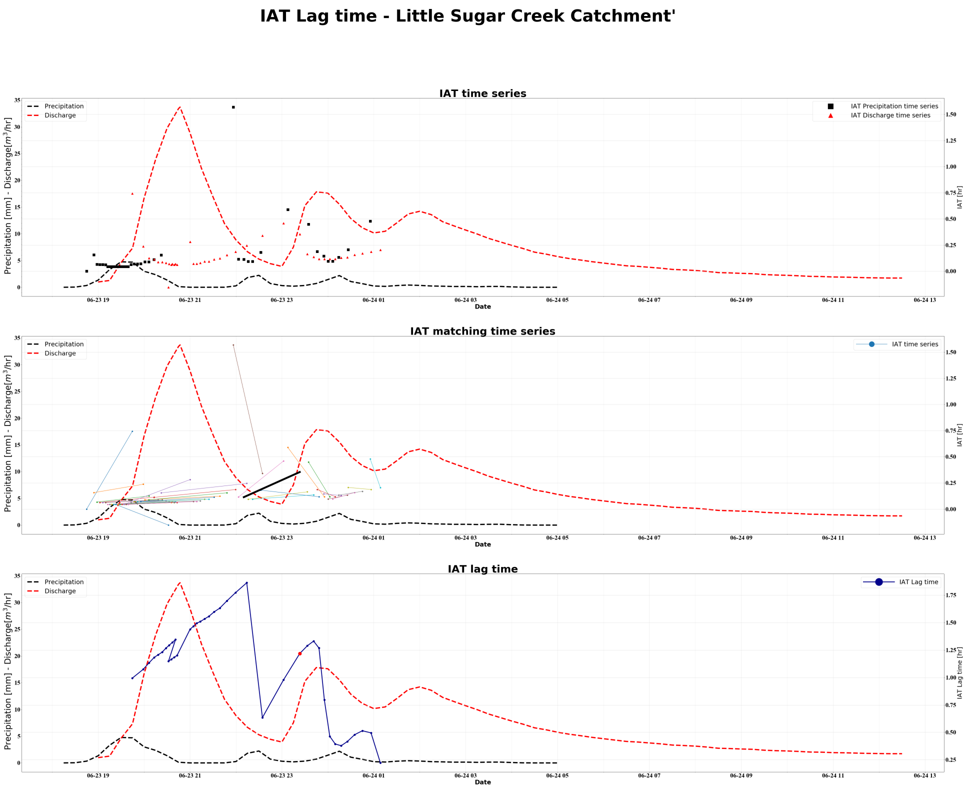


Figure 4.8: IAT Lag time computation procedure for event 34 with 15 minutes resolution.

4.4.3. Lag time comparison

IAT Lag time comparison			
Event	15 min	30 min	60 min
0	2.37	2.45	2.85
1	2.63	2.72	3.58
2	4.74	4.96	5.92
3	2.45	1.84	2.02
4	2.63	2.72	3.58
5	4.74	4.96	5.92
7	5.71	5.94	6.70
8	2.81	3.02	2.76
9	5.00	5.08	5.38
10	3.91	4.43	4.65
11	1.86	1.88	2.87
12	8.44	8.46	9.36
13	2.23	2.41	3.26
14	4.72	4.88	5.41
15	2.37	2.25	1.60
16	1.46	1.72	1.59
17	4.35	4.73	4.87
18	4.14	3.98	4.05
19	3.94	4.26	4.77
20	2.30	2.38	4.15
21	4.04	3.64	4.03
22	7.02	7.15	6.83
23	5.78	5.78	6.77
24	2.17	2.34	3.01
25	3.03	3.50	3.86
27	1.29	1.44	1.75
29	3.85	3.96	4.15
30	2.27	2.79	2.58
31	4.96	4.87	5.26
32	1.60	1.31	2.02
33	3.43	3.16	2.89
34	1.21	1.24	1.20
35	4.66	4.49	4.95
36	3.34	3.48	3.36
37	1.29	1.69	2.13
38	3.05	3.02	4.24
39	1.50	1.34	1.36
40	1.46	1.63	1.12
41	3.34	3.77	4.19
42	1.68	1.81	2.81
43	2.20	2.22	2.44
44	3.74	4.02	4.32
45	1.68	1.81	2.81
46	4.41	4.56	4.53
47	2.60	2.59	3.42
48	3.31	3.08	2.72
49	6.25	6.23	6.33
50	7.83	7.92	9.26
51	4.24	4.29	4.37
52	1.99	2.17	2.89
53	4.15	3.83	4.09
54	2.16	2.51	3.55
55	3.37	3.74	4.89
56	1.85	2.07	1.53
57	2.01	2.08	2.75
58	0.94	1.04	1.82
59	3.37	3.74	4.89
60	1.60	1.99	1.61
61	2.81	2.52	2.63
62	2.98	2.57	3.69
63	2.58	2.70	3.71
64	3.75	3.41	4.10
65	3.31	3.60	0.70
66	2.86	3.19	2.87
67	2.71	3.10	4.21
68	4.25	4.43	4.87
69	2.74	2.68	3.27
70	2.89	3.36	4.14
71	5.47	6.34	6.35
72	4.73	5.10	6.67
74	3.66	3.53	3.50
75	2.89	3.37	3.90
76	1.77	1.69	1.96
78	1.73	1.32	2.00
79	3.07	3.41	3.83
81	2.07	2.01	1.61
82	2.32	2.53	2.95

Table 4.8: IAT Lag time comparison.

Figure 4.8 resulted from the comparison of the values corresponding to IAT Lag time for 15 minutes, 30 minutes, and 60 minutes time resolutions.

Based on the results of figure 4.8, 14% of the higher values are found in the 15-minute time resolution, 16% in the 30-minute time resolution, and 70% in the 60-minute time resolution. Box plots of the IAT lag time values for each of the three time resolutions are shown in figure 4.9.

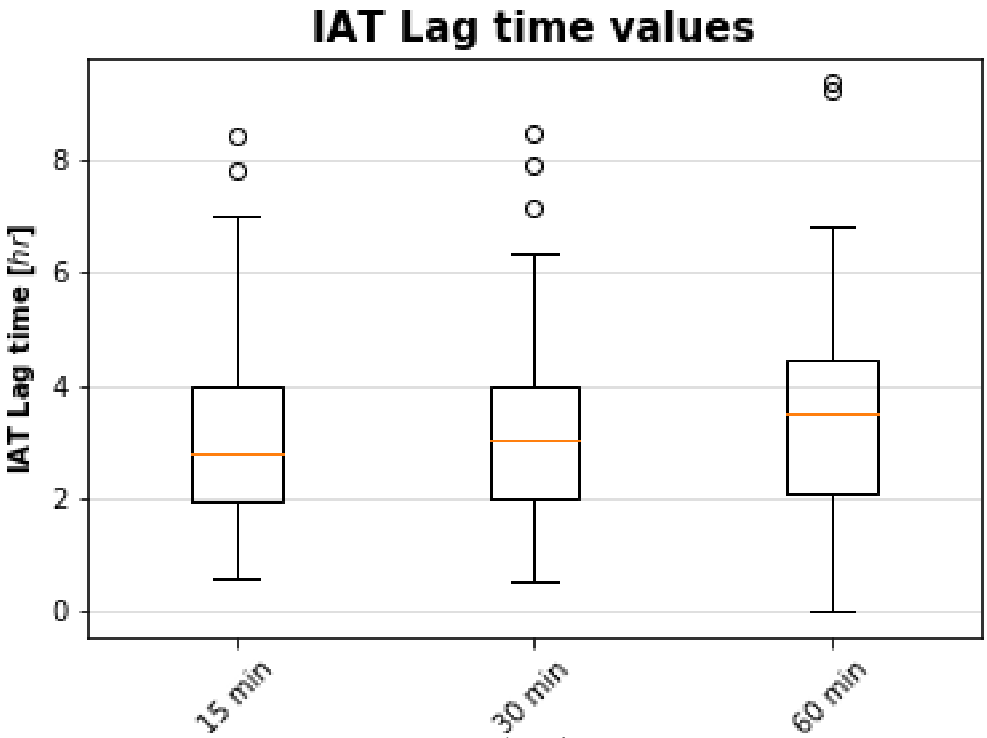


Figure 4.9: Box plots of IAT Lag time.

4.5. STATISTIC ANALYSIS

4.5.1. DISTRIBUTION ANALYSIS

Histograms resulting from the analysis are shown in figure 4.10. The first row of the figure corresponds to the IAT lag time method, for 15-, 30- and 60-minute resolutions from the left to the right. Following the same logic, the second row corresponds to the P-to-P method and the third row to the C-to-C method.

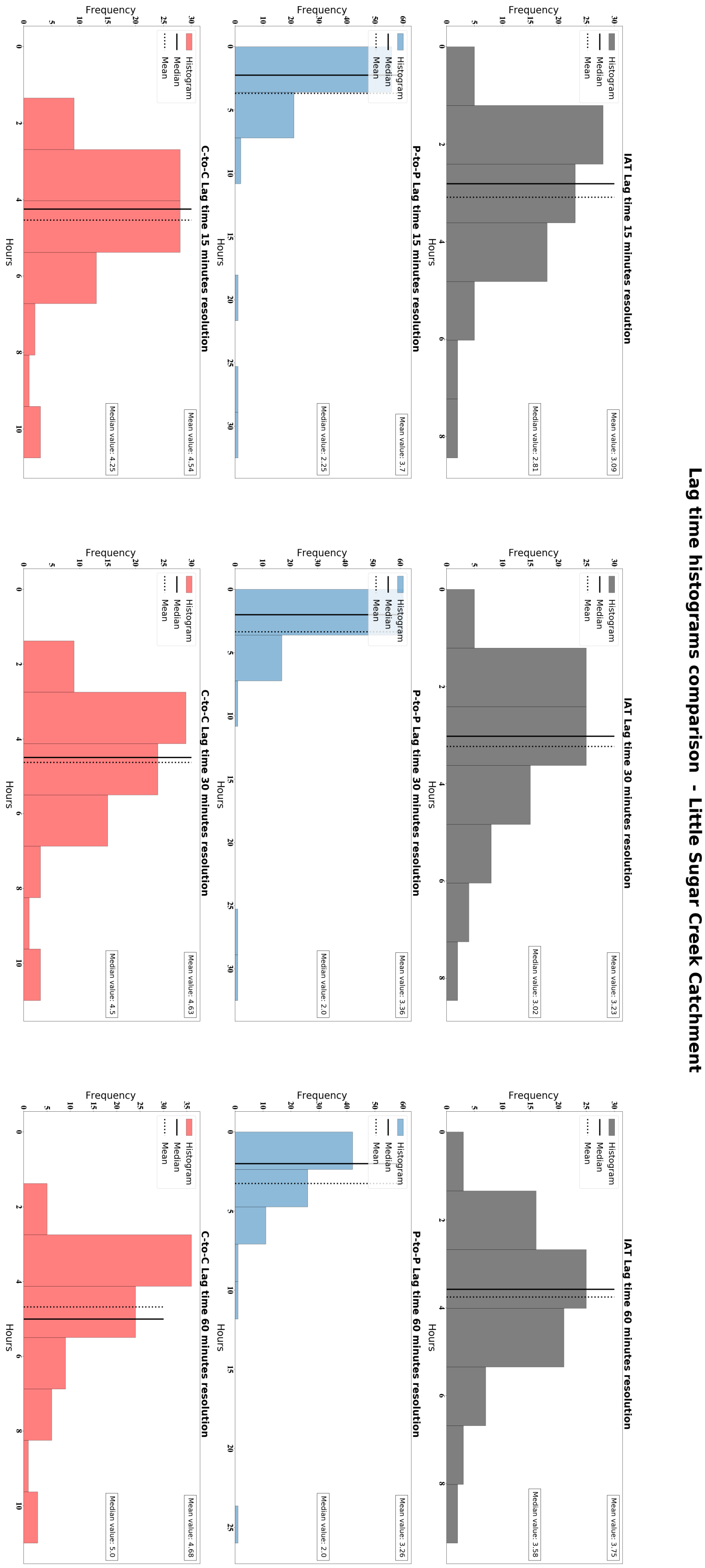
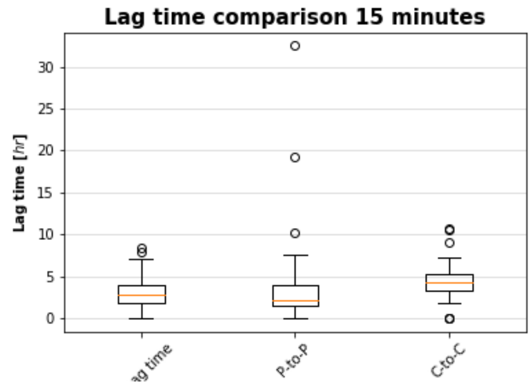
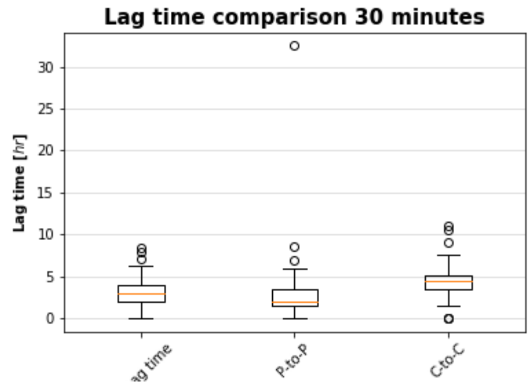


Figure 4.10: Three-Method Histogram Comparison.

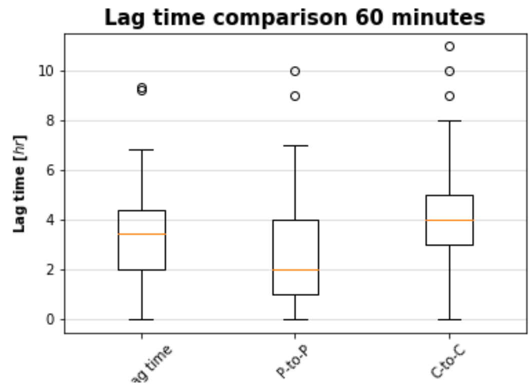
In general, the histograms for IAT tended to follow a normal distribution as the time resolution decreased. The P-to-P histograms remain largely positively skewed. The C-to-C histograms also are positively skewed with very little changes between the three time resolutions. One important aspect to observe is the range of values that each of the three methods had. The lowest values for the IAT lag time method were 0.52 hours,0.5 hours for P-to-P and 1.5 hours for C-to-C technique. This is an important difference in terms of the capability to calculate small events or flash-type events. Another way to look at the distribution of the values is through box plots.



(a) 15 minutes lag time values comparison.



(b) 30 minutes lag time values comparison.



(c) 60 minutes lag time values comparison.

Figure 4.11: Box plot of lag time values for the three time resolutions comparison.

In terms of location, the median values for the P-to-P technique were lower than those of the C-to-C and IAT lag time techniques. As shown in table 4.10, the value at the 15-minute resolution is 2.25 and 2.0 for the 30 and 60-minute resolutions. The C-to-C and IAT lag time techniques had median values that would increase as the resolution increased from 15 minutes to 30 minutes and then to 60 minutes. As seen in table 4.10, median values were lower for the IAT lag time than for the C-to-C technique.

	Median		
Resolution[min]	IAT	C-to-C	P-to-P
15	2.81	4.25	2.25
30	3.02	4.50	2.00
60	3.58	5.00	2.00

(a) Median values for the three lag time techniques.

	Mean		
Resolution[min]	IAT	C-to-C	P-to-P
15	3.09	4.54	3.70
30	3.23	4.63	3.36
60	3.75	4.68	3.26

(b) Mean values for the three lag time techniques.

Table 4.9: Mean and median values for the three methods.

Regarding the other measure of location, mean values are shown in table 4.10 for the C-to-C method, and the IAT lag time increased from 15 minutes to 30 minutes and then to 60 minutes. For the P-to-P technique, the mean values increased in an opposite direction to those of the two other techniques ranging from 3.26 at the 60-minute resolution to 3.36 at 30-minute resolution, and 3.70 at the 15-minute resolution.

For measures of spread, the coefficients of variation (CV) shown in table 4.11a had different behaviours for each of the three methods. The C-to-C method has the same CV for each of the three resolutions while the IAT technique had the same value for the 15-minute resolution and for the 30-minute resolution, and a lower value for the 60-minute resolution. The P-to-P method CV values first increased from 1.32 for the 15-minute resolution to 1.34 for the 30-minute resolution and then decreased to 0.97. The lower value was observed in the C-to-C method.

	Median		
Resolution[min]	IAT	C-to-C	P-to-P
15	2.81	4.25	2.25
30	3.02	4.50	2.00
60	3.58	5.00	2.00

(a) Median values for the three lag time techniques.

	Mean		
Resolution[min]	IAT	C-to-C	P-to-P
15	3.09	4.54	3.70
30	3.23	4.63	3.36
60	3.75	4.68	3.26

(b) Mean values for the three lag time techniques.

Table 4.10: Mean and median values for the three methods.

With respect to measures of shape for the statistical distributions, values of skewness and medcouples are shown in table 4.11b and table 4.12. Unlike what was observed for the median values, the results of skewness for the IAT lag time and C-to-C methods decreased as the time resolution also decreases. In contrast, the skewness values for the P-to-P method had the lowest value for the 15-minute resolution, increased for the 30-minute resolution, and decreased for the 60-minute resolution. The minimum values observed were those corresponding to the IAT lag time method.

	CV		
Resolution[min]	IAT	C-to-C	P-to-P
15	0.51	0.38	1.32
30	0.51	0.38	1.34
60	0.46	0.38	0.97

(a) Coefficients of variation values for the three lag time techniques.

	Skewness		
Resolution[min]	IAT	C-to-C	P-to-P
15	1.01	1.36	4.24
30	0.91	1.35	5.11
60	0.87	1.20	4.79

(b) Skewness values for the three lag time techniques.

Table 4.11: skewness and medcouples values for the three methods.

The other measure of shape used was the meadcouple parameter. The results displayed in table 4.12 show a different behaviour for each one of the techniques. For the IAT lag time method, the values decreased as the time resolution also decreased, and for each of the three time resolutions the values were the lowest compared to those of the other two methods. Similarly to the values of the IAT Lag time technique, values corresponding to the C-to-C method also decreased as the time resolution decreased. In a different manner, values for the peak-to-peak method first increased as the time resolution went from 15 minutes to 30 minutes, and the values from 4.24 to 5.11; then, the value related to the 60-minute resolution decreased from 5.11 to 4.79

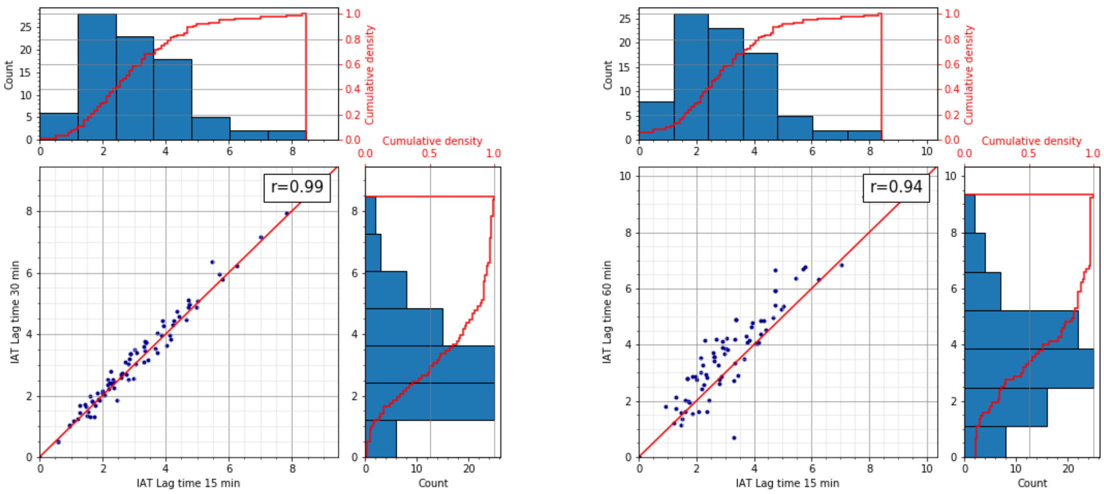
	medcouple		
Resolution[min]	IAT	C-to-C	P-to-P
15	0.17	0.07	0.47
30	0.08	0.00	0.50
60	0.02	0.00	0.33

Table 4.12: Medcouple values for the 3 lag time techniques.

The left tail corresponding to IAT Lag time suggested the ability of this method to also compute lag time for shorter events and for flash events. In comparison, the C-to-C method had its left tail closer to the mean than the previously mentioned method. The P-to-P method was very right skewed and had an almost nonexistent left tail.

4.5.2. CORRELATION ANALYSIS

Figure 4.12a and figure 4.12b show the correlation between IAT Lag time 15 minutes and IAT Lag time 30 minutes and between IAT Lag time 15 minutes and IAT Lag time 60 minutes. For these pairs of data sets, Pearson´s correlation is 0.99 and 0.94, respectively.



(a) Correlation IAT lag time 15 minutes Vs IAT lag time 30 minutes.

(b) Correlation IAT lag time 15 minutes Vs IAT lag time 60 minutes.

Figure 4.12: IAT lag time correlation throughout the three time resolutions.

For the same data sets comparisons, Spearman´s rank correlation were computed and the results were 0.98 and 0.88, respectively.

	IAT Lag time comparison 15 min Vs 30 min Max/Min values		
	Minimum correlation		
Event id	IAT Lag time 15 min [hr]	IAT Lag time 30 min [hr]	Difference [hr]
71	5.47	6.34	0.87
3	2.45	1.84	0.60
30	2.27	2.79	0.53
10	3.91	4.43	0.52
70	2.89	3.36	0.47
75	2.89	3.37	0.47
25	3.03	3.50	0.47
41	3.34	3.77	0.43
62	2.98	2.57	0.41
78	1.73	1.32	0.40
21	4.04	3.64	0.40
37	1.29	1.69	0.40
	Maximum correlation		
Event id	IAT Lag time 15 min [hr]	IAT Lag time 30 min [hr]	Difference [hr]
77	0.58	0.52	0.06
51	4.24	4.29	0.05
26	1.52	1.48	0.04
80	1.89	1.85	0.04
34	1.21	1.24	0.03
38	3.05	3.02	0.03
11	1.86	1.88	0.02
12	8.44	8.46	0.02
43	2.20	2.22	0.02
49	6.25	6.23	0.02
47	2.60	2.59	0.01
23	5.78	5.78	0.00

(a) IAT lag time Max/min correlation 15 and 30 minutes.

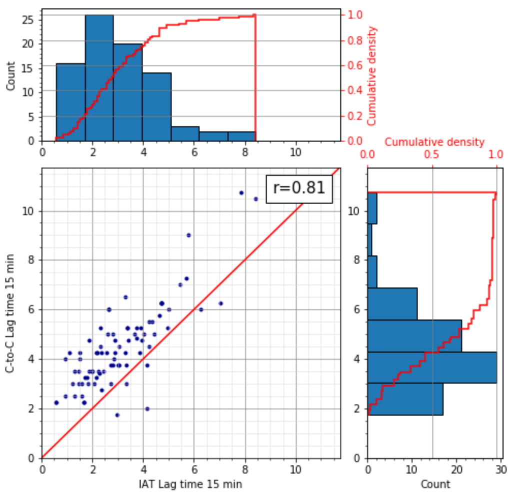
	IAT Lag time comparison 15 min Vs 60 min Max/Min values		
	Minimum correlation		
Event id	IAT Lag time 15 min [hr]	IAT Lag time 60min [hr]	Difference [hr]
65	3.31	0.70	2.61
72	4.73	6.67	1.94
20	2.30	4.15	1.85
55	3.37	4.89	1.53
59	3.37	4.89	1.53
67	2.71	4.21	1.50
50	7.83	9.26	1.43
54	2.16	3.55	1.38
70	2.89	4.14	1.25
38	3.05	4.24	1.20
2	4.74	5.92	1.18
5	4.74	5.92	1.18
	Maximum correlation		
Event id	IAT Lag time 15min [hr]	IAT Lag time 60 min [hr]	Difference [hr]
16	1.46	1.59	0.13
51	4.24	4.37	0.13
46	4.41	4.53	0.12
18	4.14	4.05	0.10
49	6.25	6.33	0.09
53	4.15	4.09	0.07
8	2.81	2.76	0.04
36	3.34	3.36	0.02
60	1.60	1.61	0.01
66	2.86	2.87	0.01
21	4.04	4.03	0.01
34	1.21	1.20	0.01

(b) IAT lag time Max/min correlation 15 and 60 minutes.

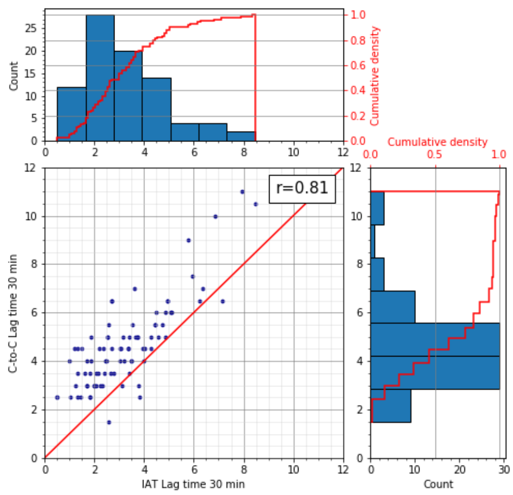
Table 4.13: IAT lag time Max/min correlation.

Table 4.13 shows the identification number of the events identified as those with the highest and lowest correlation. Surprising, only events 49 and 51 appeared repeatedly among those with maximum correlation in both comparisons, and only event 70 for the minimum correlation comparison.

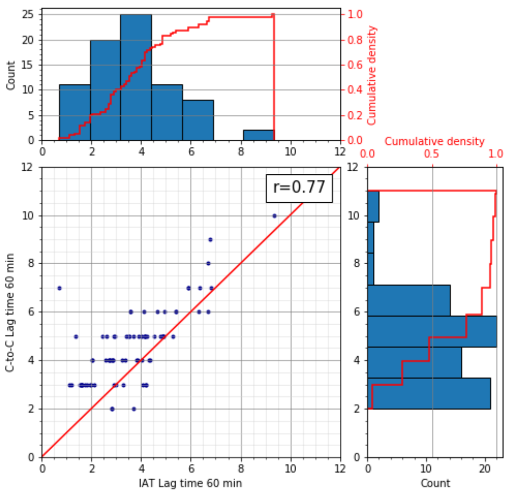
Figure 4.13 shows the correlation between the IAT lag time method values and the C-to-C lag time method values for each of the three time resolutions. Similar to this, correlation between the IAT lag time method values and the P-to-P lag time method values are shown in figure 4.14.



(a) Correlation IAT lag time 15 minutes Vs C-to-C l5 minutes.

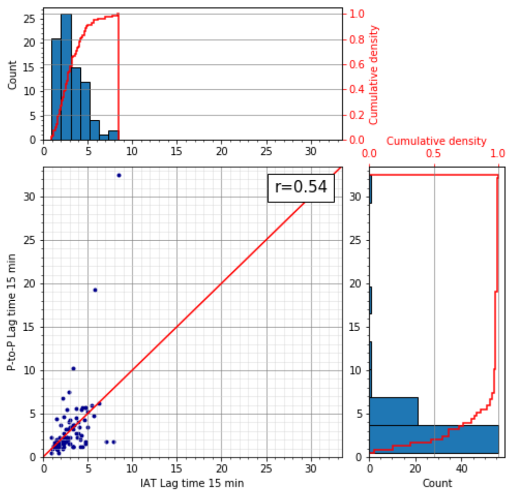


(b) Correlation IAT lag time 30 minutes Vs C-to-C 30 minutes.

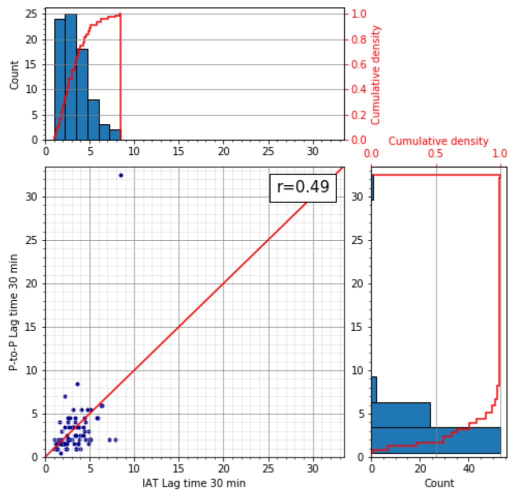


(c) Correlation IAT lag time 60 minutes Vs C-to-C 60 minutes.

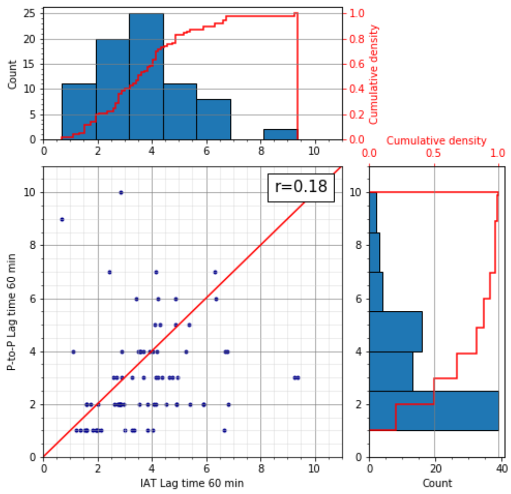
Figure 4.13: Correlation IAT lag time Vs C-to-C for the three time resolutions.



(a) Correlation IAT lag time 15 minutes Vs P-to-P l5 minutes.



(b) Correlation IAT lag time 30 minutes Vs P-to-P 30 minutes.



(c) Correlation IAT lag time 60 minutes Vs P-to-P 60 minutes.

Figure 4.14: Correlation IAT lag time Vs P-to-P for the three time resolutions.

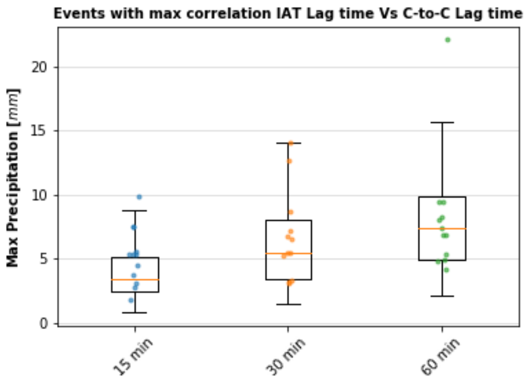
Values of the corresponding Spearman´s rank correlation are shown in table 4.14.

	Spearman´s rank correlation		
	15 Minutes	30 Minutes	60 Minutes
IAT VS C-to-C	0.74	0.74	0.68
IAT VS P-to-P	0.53	0.53	0.37

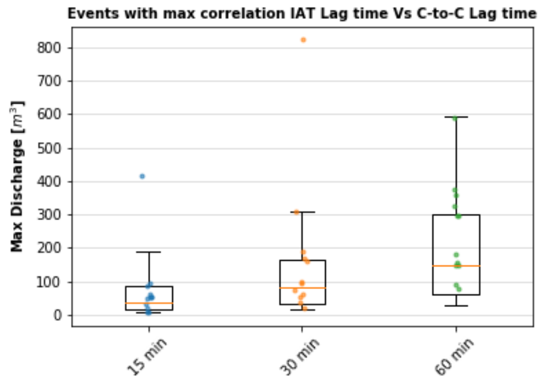
Table 4.14: Spearman´s rank correlation.

4.5.3. SENSITIVITY ANALYSIS

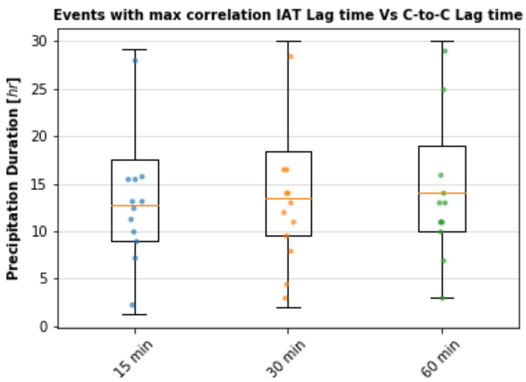
Figures 4.15, 4.16,4.17 and 4.18 display box plots of the comparison between methods previously mentioned in the three time resolution based on maximum precipitation per event, maximum discharge per event, event precipitation duration and event discharge duration with the twelve events with the highest and lowest correlation being shown as points within the box plot.



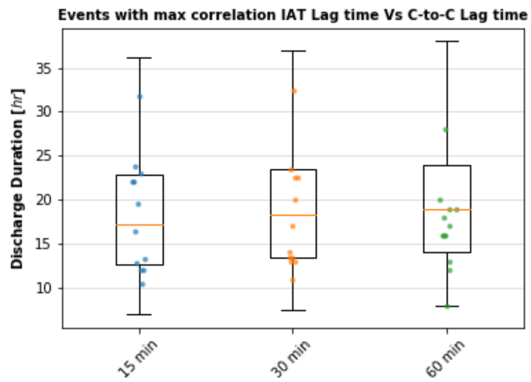
(a) Max correlation box plot - Max precipitation.



(b) Max correlation box plot - Max discharge.



(c) Max correlation box plot - Max event precipitation duration.

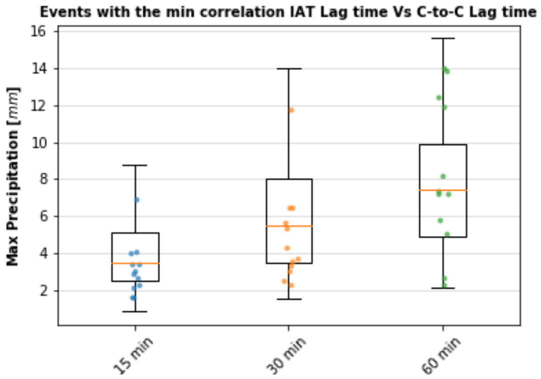


(d) Max correlation box plot - Max event discharge duration.

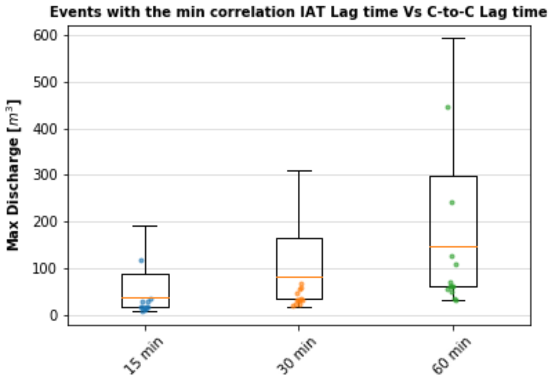
Figure 4.15: IAT lag time and C-to-C max correlation box plots.

Results from the box plots of maximum correlation for IAT lag time compared to C-to-C method suggested that maximum precipitation values are majorly located above quartile three. Only 25% of the values where located within Q1 and Q3 in the case of 15 minutes resolution. As the time resolution decreased more number of observations were within Q1 and Q3. The presence of one outlier was observed in the three time resolutions. Alike this behaviour, maximum discharge observations exhibited a tendency to move out of the boundaries of Q1 and Q3 as the time resolution decreased. The presence of a couple of very big outliers was observed in the case of 15 and 30 minutes resolution. In both cases, the upper whisker is considerably bigger than the lower one, especially in the case of maximum discharge.

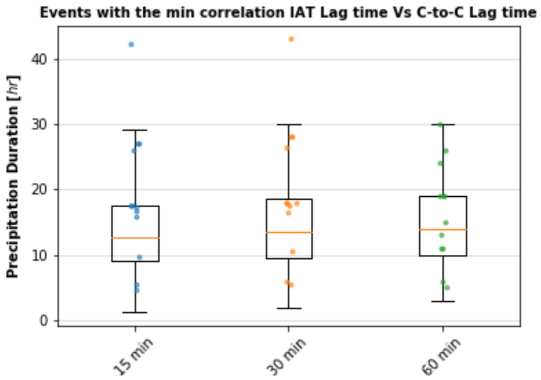
Precipitation event duration and discharge event duration values were mostly within or close to the boundaries of Q1 and Q3. The box plots were very similiar in both cases, with similar median values also.



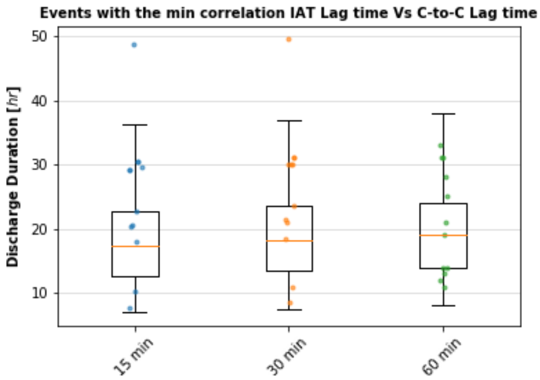
(a) Min correlation box plot - Max precipitation.



(b) Min correlation box plot - Max discharge.



(c) Min correlation box plot - Max event precipitation duration.

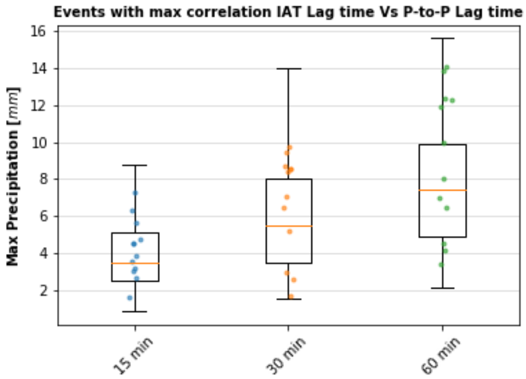


(d) Min correlation box plot - Max event discharge duration.

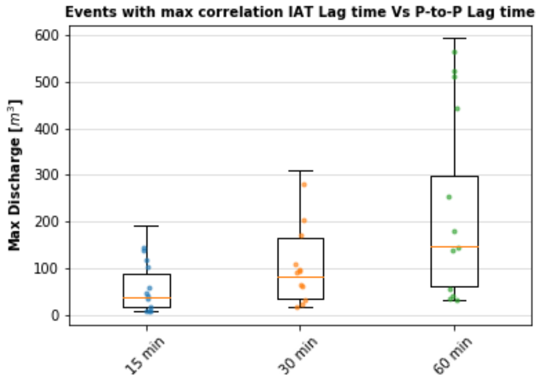
Figure 4.16: IAT lag time and C-to-C min correlation box plots.

Results from the box plots of minimum correlation for the same comparison for IAT lag time compared to C-to-C method suggested that maximum precipitation values are majorly located above quartile three. Only 25% of the values where located within Q1 and Q3 in the case of 15 minutes resolution. As the time resolution decreased more number of observations were within Q1 and Q3. The presence of one outlier was observed in the three time resolutions. Alike this behaviour, maximum discharge observations exhibited a tendency to move out of the boundaries of Q1 and Q3 as the time resolution decreased. The presence of a couple of very big outliers was observed in the case of 15 and 30 minutes resolution. In both cases, the upper whisker is considerably bigger than the lower one, especially in the case of maximum discharge.

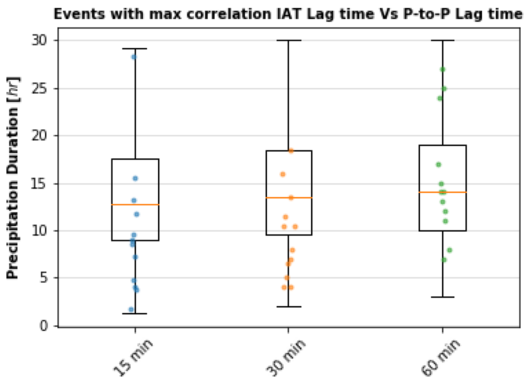
Precipitation event duration values were mainly located outside or close to the boundaries defined by Q1 and Q3 for the 15 and 30 minutes resolution. For the 60 minutes resolution, values were mainly above Q3 but more values were within Q1 and Q3 than in the previous two cases. For discharge event duration values, most of the vales were above Q2 and none value were within Q2 and Q1 in all the three cases.



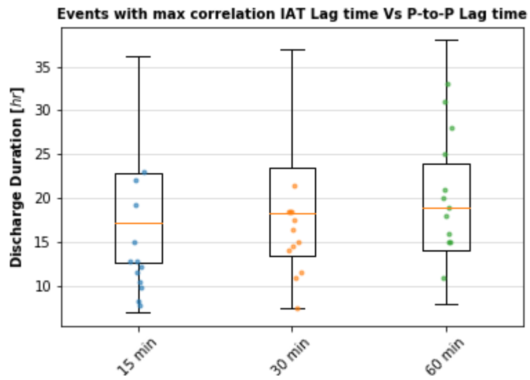
(a) Max correlation box plot - Max precipitation.



(b) Max correlation box plot - Max discharge.

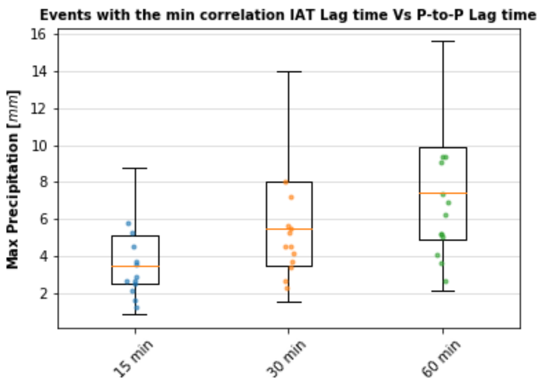


(c) Max correlation box plot - Max event precipitation duration.

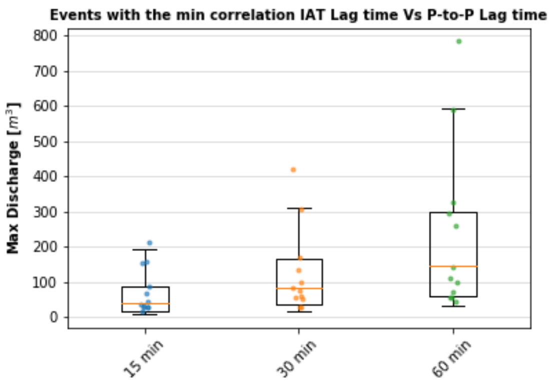


(d) Max correlation box plot - Max event discharge duration.

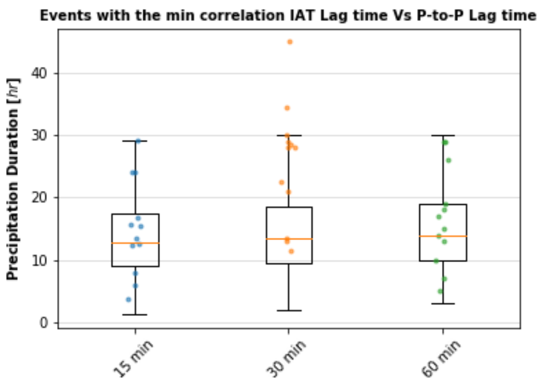
Figure 4.17: IAT lag time and P-to-P max correlation box plots.



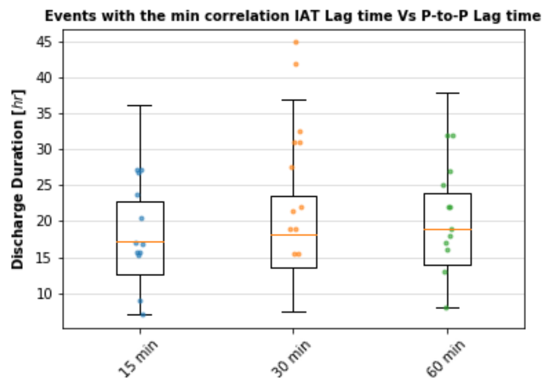
(a) Min correlation box plot - Max precipitation.



(b) Max correlation box plot - Max discharge.



(c) Min correlation box plot - Max event precipitation duration.



(d) Min correlation box plot - Max event discharge duration.

Figure 4.18: IAT lag time and P-to-P min correlation box plots.

Event # 16 15 minutes	
Time index	Discharge IAT
17/6/03 20:50:18	1.34
17/6/03 21:50:56	1.01
17/6/03 23:11:01	1.33
18/6/03 0:28:59	1.30
18/6/03 2:00:09	1.52
18/6/03 2:26:21	0.44
18/6/03 2:34:29	0.14
18/6/03 2:41:02	0.11
18/6/03 2:46:53	0.10
18/6/03 2:52:11	0.09
18/6/03 2:57:28	0.09
18/6/03 3:01:55	0.07
18/6/03 3:06:03	0.07
18/6/03 3:10:11	0.07
18/6/03 3:14:15	0.07
18/6/03 3:17:41	0.06
18/6/03 3:21:07	0.06
18/6/03 3:24:33	0.06
18/6/03 3:27:59	0.06
18/6/03 3:31:11	0.05
18/6/03 3:34:17	0.05
18/6/03 3:37:24	0.05
18/6/03 3:40:30	0.05
18/6/03 3:43:36	0.05
18/6/03 3:46:45	0.05
18/6/03 3:49:54	0.05
18/6/03 3:53:03	0.05
18/6/03 3:56:11	0.05
18/6/03 3:59:23	0.05
18/6/03 4:02:53	0.06
18/6/03 4:06:23	0.06
18/6/03 4:09:53	0.06
18/6/03 4:13:23	0.06
18/6/03 4:17:20	0.07
18/6/03 4:21:23	0.07

Event # 16 30 minutes	
Time index	Discharge IAT
17/6/03 21:29:08	2.49
17/6/03 23:55:18	2.44
18/6/03 2:12:17	2.28
18/6/03 2:36:25	0.40
18/6/03 2:47:37	0.19
18/6/03 2:58:49	0.19
18/6/03 3:06:05	0.12
18/6/03 3:13:16	0.12
18/6/03 3:20:26	0.12
18/6/03 3:27:37	0.12
18/6/03 3:33:50	0.10
18/6/03 3:39:49	0.10
18/6/03 3:45:48	0.10
18/6/03 3:51:47	0.10
18/6/03 3:57:46	0.10
18/6/03 4:04:42	0.12
18/6/03 4:11:52	0.12
18/6/03 4:19:03	0.12

Event # 16 60 minutes	
Time index	Discharge IAT
17/6/03 23:25:07	4.42
18/6/03 1:55:36	2.51
18/6/03 2:31:28	0.60
18/6/03 2:45:41	0.24
18/6/03 2:58:32	0.21
18/6/03 3:11:22	0.21
18/6/03 3:24:13	0.21
18/6/03 3:37:54	0.23

Table 4.6: IAT Discharge time series with time index 15, 30 and 60-minute resolution.

5

Discussions

5.1. Land use characterisation

Water bodies and hydraulic infrastructure

As expected, the Little Sugar Creek had characteristics of a highly urbanised area with an important amount of storm infrastructure. The water management approach that has been followed within the boundaries of the catchment was evidently focused on draining the excess of water rather than delaying or storing it. This was evidenced by the inequality in terms of a relative small number of land use classified as water bodies or green areas against the high amount of storm water channels present in the area. This situation is important when assessing the validity of any lag time results stemming from different methods. The aim of the lag time is to provide a representation of characteristics such as velocity and storage of the runoff along a certain water path in a specific context (Watt and Chow, 1985). This implies that the lag time definition should be able to correctly identify the process that is most likely to occur in the area of study. For the Little Sugar Creek case, it is advised to use a lag time definition able to compute with certainty fast lag time.

5.2. Quality control of precipitation data

The generated average basin precipitation time series was compared against the ten ground observation gauges installed in the catchment. Results from the bias analysis of the radar precipitation data should be taken as proxy, in the understanding that basin area could be too big to be represented by average values. Even if bias mean values were small, questions about the real differences in specific locations at specific periods of the rain event are an important point of analysis when trying to correctly capture flash hydrological response.

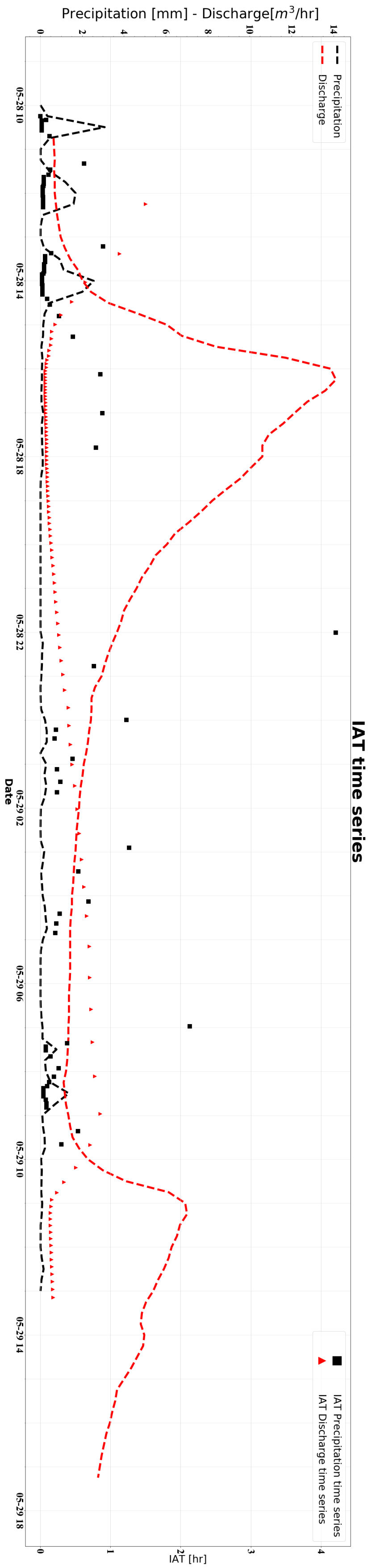
5.3. Selection of events

The event selection was one of the most challenging activities of this research. The procedure followed in this research involved the transformation of a continuous time series into a discrete time series as a general idea. Dilmi (2017) proposed analysing precipitation in terms of events rather than in specific periods of time as an adequate way to define some features of the precipitation process with greater success. For this research, not all the events were subject of study: only precipitation that generated a response on the discharge curve was of interest.

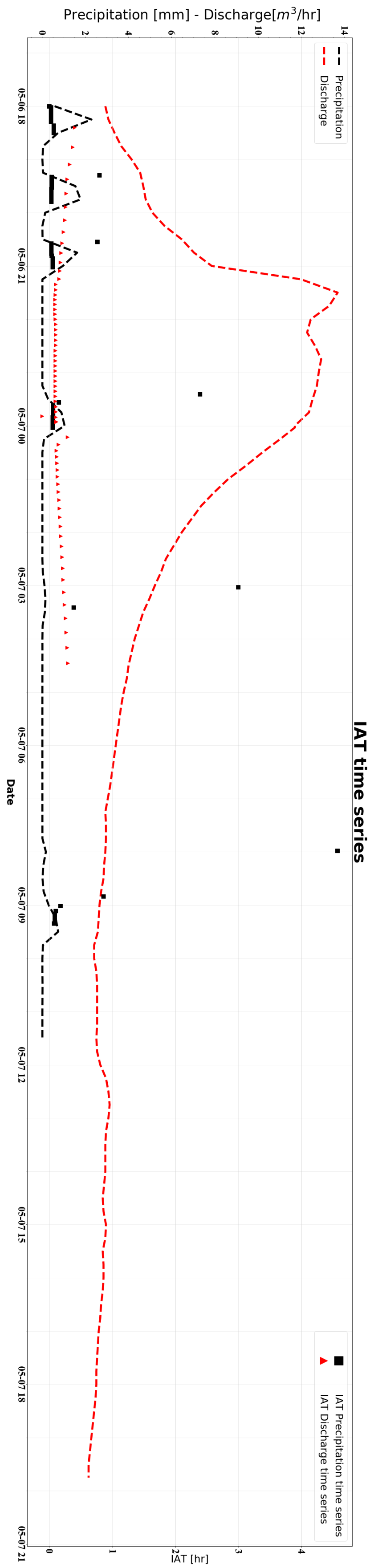
At this point, the requirement was not only to define and identify a precipitation event but to identify paired precipitation-discharge events. To achieve this requirement, the first criteria that was used replicated the idea of peak-over-threshold (POT), using an educated estimation of a significant threshold that may allow focusing solely on those parts of the discharge time series that would have experienced increments due to a precipitation event. As previously described, the threshold used for this research was set at the $95^t h$ percentile of the annual flow. Different thresholds are expected to be chosen for studies in different areas, in particular in areas in which flows have intermittent behaviours. After that first filter was imposed, the definition of the criteria that dealt with intermittency were fundamental. This criteria has being used by different authors as a way to study runoff process (De Vos and Rientjes, 2008; Zhang et al., 2005) and different values have been used to establish a maximum time between dry or zero precipitation periods and wet periods. Values ranging from 24 hours (Dunkerley, 2008) to three hours (Lloyd, 1990) have been used in different environments.

After selecting the events used in this research, using a 6-hour minimum inttermittency criteria to call a new event, questions regarding the validity of this procedure are still open to discussion in order to evaluate whether it was an appropriate value or not. Selecting a different minimum inttermittency value will change the number of events.

Figure 5.1a and 5.1b shows event 2 and 47. These two events could have been split into two 2 events each if the minimum inttermittency would have been set at 5 hours. Both graphs shows how prior wetness developed different behaviours in the discharge curves. Event 5 indicates how certain accumulation of precipitation was required to have a peak in the discharge rather than a bare increment. In a different manner, event 47 had a similar precipitation curve but the discharge curve did not develop a second peak even though some important precipitation peaks were observable. If these two events would have been split, the analysis may suggest that the new event will generate runoff even if the precipitation was not high. The reality showed that that was not the case. On the other hand, two different events rather than only one would provide some advantage when computing lag times later in this research. Another possibility could have been to increase the minimum inttermittency time aiming to capture hydrological response under very long precipitation periods. This could be specially valid for precipitation generated by warm fronts.



(a) Event 2



(b) Event 47

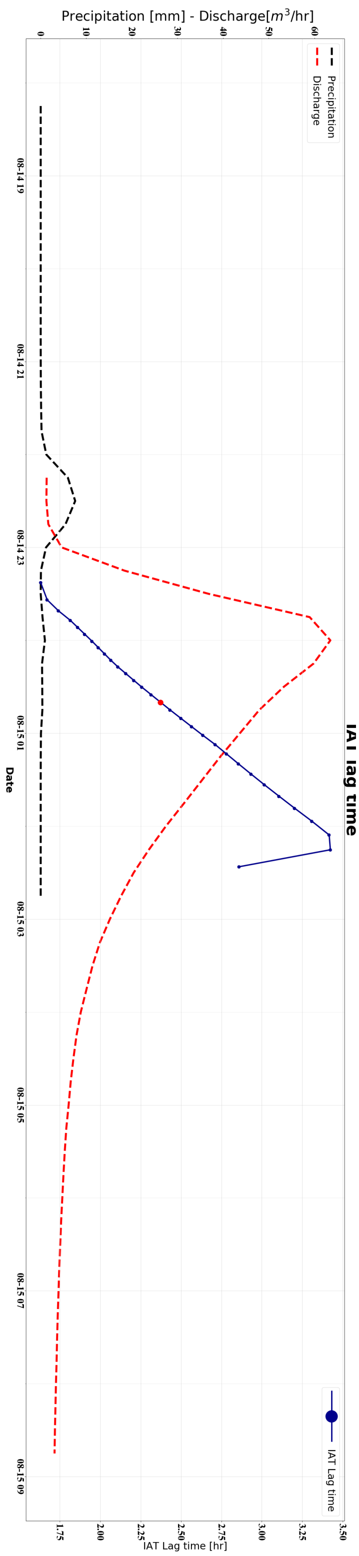
With the aim of investigating the hydrological response of the catchment, a new focus to select the minimum intermittency defining a precipitation event could be implemented to design the selection in a more dynamic and data driven manner rather than with the use of usual assumptions of estimated time required for the soil or canopy to dry (Bracken, Cox, and Shannon, 2008; Lloyd, 1990). This dynamic selection of the required time to call a new event could be based on the statistics of the observed minimum time to accumulate certain amount of precipitation that does have a response in the discharge curve.

5.4. IAT TIME SERIES COMPUTATION

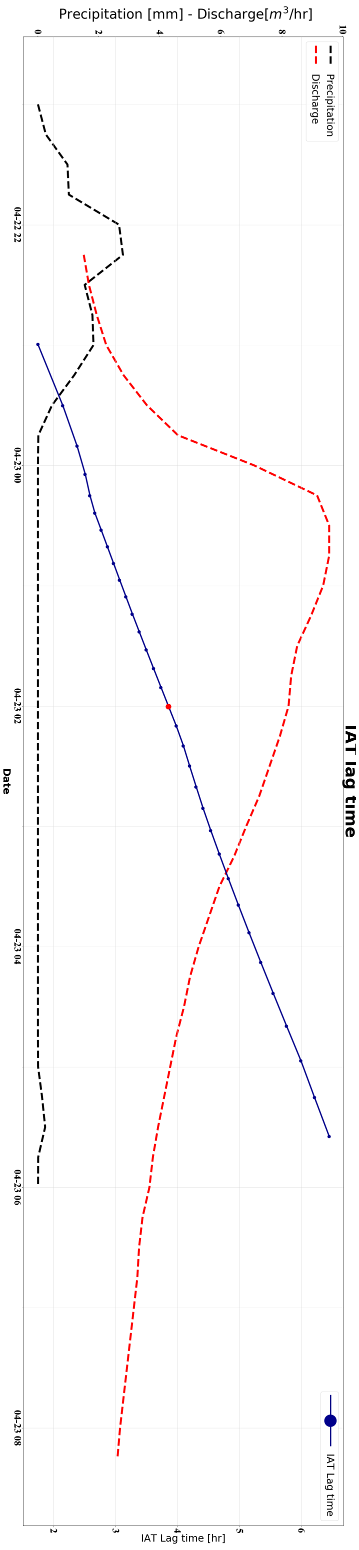
The IAT technique was applied to the eighty-four events to generate new time series for precipitation and discharge. The results showed how more observations were generated in parts where peaks or high values of either precipitation or discharge were recorded. As expected, the base flow in the discharge time series barely generated any sample under the IAT technique. This is again particularly important for the base flow representation because all the flow above this flow value will be identified, allowing for a causal analysis with respect to the IAT precipitation time series. Marie-Claire ten Veldhuis and Schleiss (2017) mentioned that IAT can provide complementary insights into flow properties. This was true, and, for instance, it is worth to look at the distribution of samples after peaks, where discharge started to slow down. This situation is important to analyse because the velocity at which discharge values decreased gives important information that may be used to study flashiness, storage capacity and runoff delay. Using a fixed sample method, this example would be limited to the fixed (low) temporal sampling rate but with the IAT discharge time series it is possible to have much more information of the changes in discharge.

5.5. IAT LAG TIME

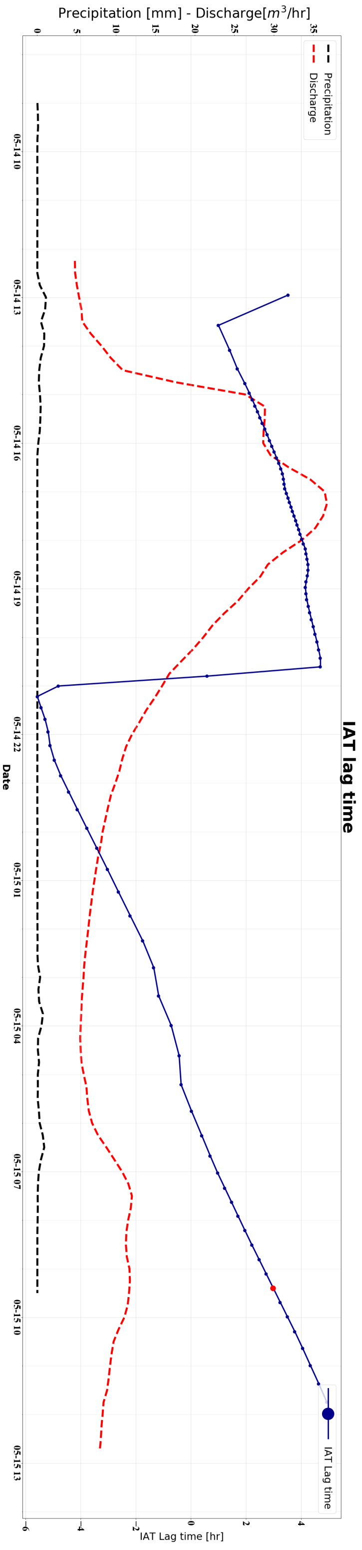
The lag time based on the IAT time series was defined as the median value of differences between the IAT Discharge time series and the IAT Precipitation time series. These differences for each of the events resulted in curves with different behaviours. Two different kind of behaviours were observed for the curves. One was a constant and steady behaviour of the values, which increased as shown in figure 5.2b and 5.2a. The second was a phase-type behaviour. This kind of behaviour was mainly observed in long events in which intermittency occurred as is observable in figure 5.2c for example. This phase-type curves show how different responses are generated by the intermittent presence of precipitation. This is particularly interesting for further analysis because it shows how the second response is generated given the first phase response.



(a) Event 15



(b) Event 29



(c) Event 62

Even if only one value is extracted from these kind of curves, their behaviour remains an important area of analysis due the information that they provide about the response over time. This ability of showing how the lag time evolves over time through the event was lost as the time resolution went lower. Compared to the 15-minute resolution curves for precipitation and discharge, 30 and 60-minute resolution time series smoothed the peaks or created new ones. Thus, few IAT samples were generated in some zones, leaving only tendencies observable, while small changes were lost.

If the aim of other research is to investigate specific characteristics of the hydrological response, IAT lag time time series could be a powerful tool to look at the hydrological behaviour.

5.6. DISTRIBUTION ANALYSIS

Histograms of the values of the IAT lag time method, the P-to-P method and the C-to-C method presented in the results section showed how results of the three methodologies evolved as the time resolution decreased. As previously mentioned, the three methodologies are positively skewed but not in the same way. The P-to-P method method was by far more skewed than the other two methods. The IAT Lag time method has lower skewness compared to the C-to-C method. Skewness for these two methods decreased as the resolution decreased. This did not happened in the case of the P-to-P method, whose values increased and also decreased for the 60-minute resolution. This behaviour was induced due the fact that the P-to-P method is very susceptible to intermitency. The peaks used to compute the lag time values were mainly the first peaks of the events that lead to higher numbers of small lag time values. On the other hand, the left tail of the IAT Lag time method remained almost unaltered because this methodology was able to compute most of the small lag time values through each of the three time resolutions. The same happened with the C-to-C method but with bigger changes that those of the IAT Lag time method. The left tail of the distributions provided information about the minimum values of lag times that can be computed using one of the above-mentioned methods. In the case of the P-to-P method, those small values were most of the values presented in the histogram. The IAT Lag time method showed a constant ability to capture small values that may correspond to flash responses. The C-to-C method proved to have an important limit regarding performance as it could not compute lag time lower than 1.7 hours in any of the three time resolutions. An analysis of the minimum values observed in the left tail is particularly important for urban catchments that are expected to have flash hydrological response; therefore, a method able to identify small values is critical.

The coefficient of variation (CV) results also evidenced how the P-to-P method was less sensitive to small peaks as the curves were becoming single peaks curves. The IAT Lag time method also had a lower CV value at the lowest time resolution, due the fact that the precipitation and discharge curves got simplified by merging variabilities into big peaks and the methodology was more straightforward applied in such conditions. The C-to-C method had the same CV in all three time resolutions because the mass of the events did not change.

5.7. CORRELATION ANALYSIS

The results from the correlation analysis comparing the IAT lag time for the 15-minute resolution to the 30 and 60-minute time resolutions suggested a high linear correlation with a small decrease as the time resolution went to 60 minutes. The Rank correlation coefficients were also high. High Pearson´s and Spearman´s values imply linearity and monotonic behaviour. When analysing those values with the highest and lowest linear correlation values, it was discovered that only two events (Events 49 and 51) were among those with the highest correlation values in both comparisons and only one (Event 70) was among the ones with the lowest correlation in both comparisons. Nevertheless, this analysis may not be very informative for the purpose of finding characteristics of the events with low correlation since the range of values between the time difference with the highest correlation and the lowest correlation is less than one hour for the case of the comparison against IAT Lag time for the 30-minute time resolution.

In the case of the the comparison against the 60-minute resolution, the range of values with the lowest correlation goes up to 2.61 hours, as shown in figure **??**. This difference is important for the case of urban catchments since it may suggest that the ability of computing hydrological response could be biased by a couple of hours, due to low resolution.

Values from the IAT Lag method time with a 15-minute resolution were used as proxy due the fact that they are based on the highest time resolution available for this research. Based on this and looking at the IAT Lag time method calculation process for the three cases, one situation should be stated as a potential drawback of the IAT Lag time method: As the time resolution decreased for both precipitation and discharge time series, peaks of both time series increased or smoothed out. When the peaks increased, these zones got more IAT samples. When the peaks becoming smoother, some samples disappear or move to the surrounding areas of the curve. In both cases, the final result of such situation is to move the IAT samples along the curves from its original locations. This displacement will translate into a higher or lower difference between samples of the IAT Precipitation and discharge time series.

5.8. SENSITIVITY ANALYSIS

The discussion of this correlation analysis between the IAT lag time method and the other two methods should focus on those events with the highest and lowest correlation. Analysing the events with the highest correlation will enable the identification and evaluation of those characteristics of the events that generate similar results for both methods. On the other hand, events with the lowest correlation will facilitate the identification of the events and their characteristics that could have generated this varying result. This discussion would serve as starting point for the discussion about whether a certain lag time method is valid or not depending on the specific situation of the area in which it will be applied.

An analysis of the twelve events with the highest correlation is shown in figure 4.15. The four variables of study - maximum precipitation, maximum discharge, precipitation event duration, and discharge event duration - did not provide any conclusive information about the possible reasons for such high correlation. With regards to those events with the lowest correlation, the box plots gave an interesting insight of how most of the events with low correlation had maximum precipitation values below Q2 and also some outside Q1. This behaviour became less evident as the time resolution decreased. For the case of maximum discharge, most of the values were located near Q1 and only for the 60-minute resolution this behaviour was less drastic. Looking at the event duration box plots, most of the values were close to or greater than Q2. Similarly, for the 60-minute resolution this was not entirely true.
An inverse relationship between maximum discharge and event duration may be pointed as an indicator of the low correlation. This relationship caused the center of mass of the discharge event to be farther from the center of mass of the rain event. The effect of the event duration is related to the selection methodology of the event and should be taken into account for further studies which may establish ranges for the event duration that may allow the C-to-C method to perform in a less constrained way.

Based on the correlation analysis for the P-to-P method, box plots of events with maximum correlation showed that for the maximum precipitation criteria values exhibited a slight tendency to be located above Q2. The maximum discharge criteria had certain pattern, which had clusters of values around the lower whisker, around Q2 and outside Q3. Regarding the event duration criteria, precipitation duration values for the 15-minute resolution were mainly located between the bottom whisker and Q1. Some values were located almost evenly distributed Within Q1 and Q3. The 30-minute resolution box plot had the same pattern but slightly moved up. The 60-minute box plot showed values throughout the bottom and top whiskers. The same behaviour was observed in the discharge box plots.

Relations for the events with the highest correlation based on precipitation and event duration can be observed and defined as a tendency to have maximum precipitation values among the highest values of the time series paired with discharge duration values among the lowest possible values from the observations. In general, the IAT lag time and the P-to-P methods had the most similar results as the event was short and had high maximum precipitation. Regarding discharge related box plots, a similar but less strict pattern was found.

Similar analysis were performed for the minimum correlation case. The results showed that for the maximum precipitation criteria most of the values were located below Q2. In the case of maximum discharge, values were located mainly within Q1 and Q with the presence of some outliers. Regarding the duration of the events, the box plot corresponding to the 15-minute time resolution for both discharge and precipitation duration had around of 50% of their values within Q1 and Q3, 25% above Q3 and 25% below Q1. In line with the above, the box plot for the 30-minute resolution had 50% or more of its values outside Q3. The values of the 60-minute box plot were similarly distributed as in the 15-minute case. Events with minimum correlation had a clear relation between maximum discharge and precipitation with the event duration. In general, this relation suggests that events with low correlation had as common characteristics low values of maximum precipitation and discharge along with a high event duration.

5.9. LIMITATIONS

This research has shown that most of the results and their validity are defined by the event definition criteria. This implies that a substantiated and tailored criteria for the definition of hydrological event is crucial. It is important to realise that there is not a unique way to perform a hydrological response analysis, therefore its validity depends on the ability of the method to correctly identify and use $relevant information$.

The IAT lag time method is limited to a correct implementation of the adaptive sampling technique. If the technique is not well implemented, the results will be meaningless. Even if correctly implemented, some adjustments should be made to the implementation with respect to the minimum values of precipitation/discharge and the minimum duration time of the events.

6
Conclusions

The study of the hydrological response in urban areas requires a very complex analysis. Most of the complexities are related to the lack of information or the inability to capture relevant information. This situation could result in a biased analysis mainly due to the use of several assumptions that are not suitable for the area of interest.

The quality of the hydrological data is improving, and thus, making it possible to work with higher resolution products. Nevertheless, some hydrological definitions do not take advantage of this situation since they were defined based on low resolution time series or assumptions. The IAT lag time method seemed to take advantage of these new products. The results suggested that the performance of this technique is enhanced as the temporal resolution increases. This improved behaviour was not found in the other two methods, particularly in the case of the C-to-C method. More information could be derived from the IAT Lag time series if further work is undertaken in that field. For that reason, field and model based tests are required to calibrate the proposed IAT Lag time method. Finally, to fully understand the hydrological behaviour of any urban environment, very detailed characterisations of the urban area and high resolution products are essential to enable the identification of water processes and to trace their generating factor in order to have information to support decisions.

6.1. Answers to the research questions

6.1.1. How can we estimate lag time based on IAT?

Through a correct implementation of the IAT technique, it was possible to derive IAT precipitation and discharge time series. Subsequently, the methodology explained in section 3.5.3 was applied to compute lag time. A comparison of the results from said proposed technique in contrast to the classical methods (i.e. the C-to-C and P-to-P methods), indicated that the results of this new method were similar in many cases. Even if the IAT lag time method should be further tested and improved, initial results suggest that the method could be relevant for the study of hydrological response in urban areas.

6.1.2. How do the different lag time methods represent the hydrological response in urban areas defined by the interaction of the urban basin´s characteristics and rainfall events at different scales?

The results from the characterisation of the urban area of the Little Sugar Creek showed that the area is highly urbanised. The presence of a large hydraulic infrastructure was also noticed. This infrastructure was mainly observed as stormwater channels. This situation suggests that the hydraulic system was engineered to collect water and immediately discharge it, which enables a fast discharge. Besides that, the land use characterisation showed a high percentage of impervious areas that cause runoff generation. Zhou, J. A. Smith, et al. (2017) reported 1.5 hours as median lag time value for the events studied by their research. With this information as background, the lag time methods applied to investigate the hydrological response of this area should be able to identify a fast hydrological response, particularly when the hydrological data has high temporal resolution.

The results obtained by applying the IAT lag time, C-to-C and P-to-C methods are shown in figure 4.10. Based on these results, the C-to-C method was not able to compute low lag times. This limitation could be more or less important depending on the definition of the hydrological event applied to select events. The longer the event is, the lower the ability to compute short lag times.

Unsurprisingly, the P-to-P method proved to be very suitable for the computation of lag time of single peak events. On the other hand, lag time for multi peak events was very often largely over- or underestimated even at high time resolutions.

The IAT lag time method proved to be flexible and less susceptible to the event selection methodology if correctly implemented. The reason for that is its ability to deal with inttermitency, which is particularly important for long events, and due to its ability to sample flash-type events. This flexibility becomes more visible when working with high temporal resolution.

6.2. FUTURE WORK

To confirm the flexibility and suitability of the IAT Lag time method further work is required. Researches focused on testing the validity of using median values as lag time definition should be undertaken. These researches should test the method in different catchments with very distinct urban characteristics in order to identify potential sensitivities to certain types of urban environments. Furthermore, the method should be tested in order to provide some indication of its validity as the temporal resolution of the hydrological data increases or decreases.

Another important aspect to further investigate is the event selection methodology. Much of the meaning of the lag time results using any of the methods relies on the way hydrological events were selected. Based on this research, a more statistical approach should be taken in order to identify inttermitency patterns of the data that may suggest characteristic rain events.

Finally, further research on the behaviour of the IAT Lag time time series is suggested. Such research could provide a very promising new way to investigate the hydrological response in a dynamic and data-driven manner. The IAT Lag time time series may provide information about the actual state of the storage capacity in the catchment by understanding the changes in IAT values during the observation periods.

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