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# Evidence of the impact of urbanization on the hydrological regime of a medium-sized periurban catchment in France

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**Abstract**

In this paper we explore several indicators to evidence the impact of land use change, and particularly of urbanization/artificialization on discharge series of periurban catchments. A first set of indicators is derived from the literature and describes the monthly and annual hydrological regime, low flows and high flows, and flow components. Statistical tests are also applied to assess the existence of trends/ruptures on the longest time series. In addition, new indicators, especially built to show the impact of Sewer Overflow Devices (SODs) and infiltration into sewer networks are proposed. The method is applied to the Yzeron (150 $km^2$) catchment, located close to Lyon city (France) where various discharge gauges with a variable time step are available on sub-catchments ranging from a few to 130 $km^2$ (some of them nested), with a large variety of land uses (forest, agricultural land, artificialized areas). In addition, discharge is also measured in a SOD and a combined sewer network so that the relevance of the new proposed indicators can be assessed. In the largest sub-catchments, the results show a decrease of specific discharge from upstream to downstream corresponding to an increase of artificialized areas, except for high flows. When a SOD is present, the specific discharge is increased for frequencies larger than 50%, and the frequency of zero daily discharge is decreased. Waste water can be the only source of water in autumn month in a 4.1 $km^2$ sub-catchment. Base flow is also decreased for the most urbanized catchments. Our results confirm the impact of SODs on the modification of the flood regime, with an increase of frequent floods, but a marginal impact on the largest floods, mainly governed by saturation of the rural parts of the catchments. The decomposition of the sewer discharge shows that, on an annual basis, infiltration in the sewer network accounts for 30% of the total discharge and runoff due to rainwater to about 40% (the remaining being composed of the waste water discharge). It can explain the decrease of base flow. Our analysis shows that, for periurban catchments, a long term monitoring of nested sub-catchments and infrastructures (SODs, sewer networks) with a small time step, is very valuable and provides data allowing a quantitative assessment of the impact of urbanization on the whole hydrological regime.

Keywords: Suburban/periurban rivers, hydrological regime, high flow, low flow, impact of urbanization

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# 1. Introduction

Projections of population growth states that about 60% of the worldwide population is expected to live in towns in 2030 (Paul and Meyer, 2001). Around big cities, periurban areas are often the most affected by the corresponding urbanization (e.g. Meija and Moglen., 2010). In this paper, the word periurban, used in Europe and Australia, will refer to catchments made of a mixture of natural or agricultural lands, and urbanized areas. In the US, the word suburban is most often used, but it refers generally to residential areas with houses and gardens. Urbanization increases imperviousness of previously natural or agricultural areas. Construction of built-up areas is generally associated with the building of artificial structures such as road networks, drinkable, rainwater or sewer networks. These changes have an impact on the water cycle and aquatic ecosystems, due to the increase and acceleration of surface runoff, decrease of groundwater recharge and a modification of natural water pathways due to the artificial networks (e.g. Bras and Perkins, 1975; Chocat et al., 2001; Booth et al., 2002; Randhir, 2003; Matteo et al., 2006; Marsalek et al., 2007). This can lead to flooding, pollution and erosion problems within periurban rivers. In some areas, equipped with Combined Sewer Systems (CSSs), Sewer Overflow Devices (SODs) are introduced. When the sewer network is overflowed, it delivers polluted water to the river. This can lead to incision and erosion problems, which perturb the ecological status of the rivers (e.g. Hatt et al., 2004; Walsh et al., 2005; Lafont et al., 2006). In addition, periurban catchments have a complex structure, made of a mixture of natural, agricultural and urbanized areas, and are evolving very quickly (e.g. Beighley et al., 2003; Radojevic et al., 2010; Jankowfsky, 2011).

Studies of land use change impact on the hydrological regime generally analyse long term time series or long term simulations, and not only events. The objective is not to reproduce some historical events for sizing hydraulic works, but to get an appraisal of the change of the whole river regime. Appropriate criteria and indicators relevant to reveal the impact of land use change on this river regime must therefore be defined. In the following, the discussion will be restricted to indicators related to quantitative hydrology. Lots of other indicators have been defined to quantify the ecological status of receiving waters, based on chemistry, biology, etc (e.g. Walsh et al., 2005), in particular in Europe with the Water Framework Directive. But they are beyond the scope of this paper. In the remaining of the paper, the word indicator will be used in a broad sense and will include both hydrological variables and quantities derived from discharge data analysis.

The literature dealing with the impact of climate change, land use/ land cover change on the water cycle and hydrological model evaluation was reviewed. The objective was to identify the hydrological indicators used by their authors to quantify the impact on discharge data. A review of climate change studies is provided by Praskievicz and Chang (2009). Examples of land use change studies, mainly related to the impact of deforestation/aforestation on the water cycle can be found in Ott and Uhlenbrook (2004), Wang et al. (2007), Archer (2007) and Bathurst et al. (2011). These studies are either based on model results or on data analysis (Table 1). A large number of the experimental studies are based on paired catchments, where natural and preserved catchments are compared to disturbed catchments (Table 1). Vazquez et al. (2008) and Willems (2009) introduced several criteria which provide information on the performance of a model for several ranges of discharges. These indicators include the components of stream flow: base flow, inter flow and quick flow, as well a Peak Over Threshold (POT) analysis (Stedinger et al., 1992) both for low flows and high flows. From this literature review we have extracted 5 classes of indicators used to examine the impact of land use/land cover change on discharge time series. They are summarized in Table 1, which also presents the corresponding references.

The first class of indicators in Table 1 is related to the hydrological regime where the indicators are the mean annual runoff, its seasonal components, discharge quantiles and flow duration curves.

The second class of indicators is related to high flows: value and/or date of the annual maximum discharge, peak over threshold (POT) analysis which studies peak flow. The QdF – Discharge – duration – frequency analysis (Galéa and Prudhomme, 1994, 1997; Javelle et al., 1999), an extension of POT analysis to different characteristic durations and not only to the instantaneous maximum, is also used to study high flows.

Low flow indicators form the third class of indicators. They include value and date of minimum annual discharge, frequency of zero discharge, base flow index defined as the ratio between annual base flow and total annual flow, POT analysis for low flow (Willems, 2009).

The fourth class of indicators is based on hydrograph analysis. It includes the study of event characteristics (runoff coefficient, rising and falling limbs of hydrographs), the quantification of flow components based on the separation into base flow, interflow and quick flow (Blume et al., 2007; Willems, 2009). Archer (2007) and Archer et al. (2010) introduce more sophisticated indicators based on the analysis of rising and falling limbs of discharge series,

or their rate of change. These indicators are the number and duration of exceedance of multiple of the annual discharge. These indicators are relevant to identify quick disturbances in hydrographs.

Finally the fifth class of indicators is based on statistical analyses of discharge time series, mainly relevant when long time series are available. This includes the results of statistical tests, comparing if differences between various periods are significant (e.g. Tong, 1990; Wang et al.,2007; Radojevic et al., 2010), the results of trend analysis (e.g. Claessens et al., 2006). The results of regression analysis or neural network models, proposed by some authors to relate hydrological characteristics to climate or landscape variables such as imperviousness (Tetzlaff et al., 2005; Dow, 2007; Wang et al., 2007; Arrigoni et al., 2010) can also be included in this fifth class.

In urbanized areas, as can be seen from Table 1, the analysis is often restricted to mean annual runoff (Beighley et al., 2003; Claessens et al., 2006); high flow with indicators such as annual peak discharge (Beighley et al., 2003; Burns et al., 2005), QdF analysis (Radojevic et al., 2010) and/or to the study of selected events (Ott and Uhlenbrook, 2004; Chormanski et al., 2008; Meierdiercks et al., 2010). But this may not be sufficient for all applications, in particular when addressing the quality of receiving waters. For ecological problems, the whole hydrological regime, and in particular low flows are also important. Walsh et al. (2005) suggest that a good target for the rehabilitation of rivers affected by urbanization would be to go back to “near natural” surface flow conditions. This requires the characterization of the whole range of discharges. Indicators of Hydrological Alteration (IHA) spanning all the hydrological regime to compare pre and post river flow management with an emphasis to stream ecology are proposed by Richter et al. (1996, 1997, 2003). It includes timing of annual extreme water conditions; frequency and duration of high/low pulses; rate/frequency of water condition changes. Jacobson (2011) also provides a review of the impact of imperviousness in urban catchments.

Response times of impervious areas are much shorter than those of natural areas. For small periurban catchments, with response time of less than one day, indicators based on daily discharge may not be fully relevant. In addition, given the very short functioning time of SODs, specific analyses are required to fully evidence the impact of the urban areas on the river flow, especially for small catchments (a few $km^2$). Therefore the analysis of indicators based on smaller time steps should be contemplated. Some authors also suggest that periurbanization mainly affect frequent floods (e.g. Radojevic et al., 2010) like observed

when studying the impact of forest or deforestation on floods (Bathurst et al., 2011). Therefore indicators based only on peak discharge or extreme events may not be relevant for assessing the impact of urbanization on the water regime, and the whole range of floods must be investigated. Another specificity of periurban catchments is the impact of sewer networks, installed to manage both waste water and rainwater. In general those networks are not watertight and infiltration of clear water in the sewer system is very common (e.g. Breil et al, 1993; Berthier et al., 2004; Rodriguez et al., 2008). This may have an impact on the low flow within the rivers (e.g. Gufstafsson et al., 1997) and should also be considered.

In order to characterize the impact of urbanization on periurban rivers discharge, paired catchments studies, comparing a natural and an urbanized catchments would be the best way to get the answer. When trying to assess land use change impacts on discharge, it is also sometimes difficult to distinguish between climate variability and land use impact (e.g. Ashagrie et al., 2006). Sub-periods comparison for instance may be affected by climate variability which can lower the significance of the results. Some authors have proposed methods to filter climate variability and highlight the impact of land use by removing climate variability using regressions from a reference period, in general considered as undisturbed (e.g. Dow, 2007; Wang et al., 2007; Arrigoni et al., 2010). However, those methods may be of limited use when recorded data have started as the same time as urbanization (i.e. in the 1970s, as it is the case in France). And it is not obvious to find “natural” catchments other things being equal. Therefore, there is a need to develop specific methods which cope with existing data series and try to separate the impact of land use change/ urbanization/ management structures from the natural variability of discharge time series. This direction is explored in this paper for small to medium-sized periurban catchments, that range from some hectares to some tenth/hundreds of squared kilometres. This analysis is complementary to the set of indicators identified in the previous literature review.

The objectives of the paper can therefore be stated as follows: are we able to define indicators revealing and possibly quantifying the impact of land use change and in particular artificialization on the hydrological regime of small to medium size periurban catchments? The study is conducted in two steps. First some indicators characterizing the discharge time series, derived from the above cited literature, are assessed. Then, given their identified limitations, essentially in taking into account the effect of sewer systems and SODs, specific approaches, adapted to periurban catchments are introduced and discussed. The methods are applied to the Yzeron catchment, located close to the city of Lyon, France where quite long

time series of both rainfall and discharge are available for nested sub-catchments encompassing various ranges of urbanization and sizes. The results are discussed in order to define the advantages/limitations of the retained indicators.

# 2. Case study

## *2.1. Context of the study and presentation of the catchment*

The Yzeron catchment (150 km$^2$) is located to the south-west of Lyon city (Figure 1). It forms part of the Observatoire de Terrain en Hydrologie Urbaine (OTHU, 2011) long term observatory. It is representative of French periurban areas and is characterized by a marked topography (Figure 1). The outlet reaches the Rhône river at the elevation of 162 m and the highest points culminates at 917 m above see level. The slope map calculated from a 25 m resolution Digital Elevation Model (DEM), derived from IGN BDTopo® shows that more than 50% of the catchment has slopes larger than 10% (Gnouma, 2006). The geology is contrasted with crystalline formations (granite, gneiss ) in the western part of the catchment and more alluvial and glacier formations in the eastern part. This led to a complex soil types map with 22 cartographic units identified in the soil map (SIRA, 2011). The land use is heterogeneous. The upstream and western part of the basin is limited by a range of hills covered with forests. The intermediate part is mainly covered with grassland and cultivated lands, mixed with urban nucleus. Thin green corridors remain along rivers, covered with deciduous trees. The downstream part is mainly covered with densely urbanized areas (Figure 2c).

A fast progression of urbanization is observed since the eighties (Cottet, 2005; Gnouma, 2006, Radojevic et al., 2010). This evolution generally develops in the form of small urban centres that expand from old villages, along road networks, following topographic constraints that are imposed by the river networks. A recent analysis was conducted to quantify the increase of urbanization in this catchment (Jacqueminet et al., 2011; Kermadi et al., submitted for publication). A manual digitalization of aerial photographs allowed the identification of artificialized surfaces including the urban parcels, parkings, industries and their green fraction (gardens, parks) (Figure 3). The percentage of artificialized surfaces was 22% of the catchment area in 1970, 33% in 1990 and 36% in 2008 (Figure 2), showing a slight decrease in the rate of urbanization between 1990 and 2008, as compared to the period 1970-1990. A similar analysis based on SPOT images analysis allowed the quantification of impervious areas which were found to cover 15% of the catchment area in 1990, 18% in 1999 and 23% in

2008. The difference between both image treatments can be seen by comparing Figure 1 2which shows the impervious areas and Figure 2c, which shows the artificialized areas for year 32008.

4The area is prone to sharp Mediterranean-type flood events due to its steep topography in the 5upstream part and limited soil water storage capacity overall. The response time of the 6catchment is about 12 hours at 130 $km^2$, causing sometimes flooding in the downstream town 7of Oullins. An increase in the frequency of flooding has been observed in the recent years 8(Radojevic et al., 2010). The water responsible from these flooding mainly comes from the 9rural part of the catchment, but its effect can be enhanced by the fast contribution of urbanized 10zones. The water coming from combined sewer overflow devices is rich of sediments and 11pollutions, causing quality problems in the rivers, especially during summer storms, where 12most of the water reaching the river comes from urbanized areas via SODs (Lafont et al., 132006). Increased erosion of the river banks has also been evidenced with impact on the 14ecosystems (Schmitt et al., 2008).

15The Yzeron catchment was recently studied within the framework of the AVuPUR (Assessing 16the Vulnerability of Peri-Urban Rivers) project (Braud et al., 2010). The aim of the project 17was to increase the knowledge of the functioning and behaviour of periurban catchment 18hydrology and to propose modelling tools, adapted to those catchments. The study presented 19in this paper is a contribution to this project. The indicators discussed here are also relevant 20for model evaluation.

21

## 22*2.2. Available data*

23Rainfall and climate data: A network of rain gauges was set up over the Grand Lyon area in 241985. It includes 28 rain gauges, 4 of which are located within the Yzeron catchment, but 25mainly in the eastern part of the catchment (Figure 1). The rainfall is recorded continuously 26with a 6 minutes time step and all the data set is available until 2010. In order to better 27document the research catchment and the mountainous area, Cemagref has also installed 28complementary rain gauges with a variable time step. The oldest ones were installed in 1997 29(Pollionnay and Grézieu) and the network is continuously upgraded since then. The daily data 30(1921-2009) from the synoptic Bron station, located about 20 km east of the catchment, were 31also used.

32The SAFRAN reanalysis data set (Quintana-Segui et al., 2008; Vidal et al., 2010), which 33provides the climate variables over a 8 x 8 $km^2$ grid is also available for the grid points

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covering the Yzeron catchment over the 1970-2010 period with an hourly time step. This data set is the only one available to document the climate (air temperature and humidity, wind speed, long and short wave radiation). The SAFRAN data were used to compute the reference evapotranspiration, PET, following the FAO (1998) method.

Stream flow data: Two gauges from the national HYDRO data base, maintained by DREAL Rhône-Alpes are available on the catchment: the Craponne station (48 $km^2$) since 1969, and the Taffignon station (130 $km^2$) since 1988 (Figure 1). These two stations are nested. The data are available with a variable time step. Three other stations from Cemagref are also available. They sample the Mercier (7 $km^2$), Chaudanne upstream a sewer overflow device (Upstream_SOD1) (2.19 $km^2$), Chaudanne at La Léchère (2.9-4.1 $km^2$) experimental sub-catchments (Figure 1). The last two stations are nested. The data are registered with a variable time step. In addition, in the Chaudanne catchment, data are collected at the outlet of the sewer overflow device (SOD1) since 2001. Discharge is also measured since 2001 in the combined sewer system (CSS) which is directed to the WWTP but sometimes overflows in the SOD1 (Figure 3). The main characteristics of the gauging stations are summarized in Table 2 and Figure 4 provides the land use encountered within the sub-catchments, using three main classes: wooded areas, agricultural land and artificialized areas. We must also mention the existence of additional SODs just upstream the gauging stations of La Léchère (SOD2) (Figure 3) and Craponne. The methodology presented in section 3.2 will be used to assess the impact of these SODs on the discharge measured at the downstream gauging stations.

The discharge gauging stations network is quite original due to the range of scales and variety of land uses which are sampled (Table 2 and Figure 4). The length of the series is also very valuable to evidence the impact of land use change on river discharge.

### *2.3. Summary of previous researches*

The Yzeron catchment is studied for about 20 years. In the following, we only summarize the studies directly related with hydrology and water fluxes. Radojevic (2002) and Radojevich et al. (2010) analysed the rainfall and stream flow data (Craponne and Taffignon stations) over the 1969-1978 and 1988-1997 decades. The rainfall series showed significant differences between both decades, with an increase of maximum daily rainfall in the 1988-1997 period. This analysis was updated using the climatic data presented above (Bron rainfall daily time

series and SAFRAN daily climatic data) in order to detect possible changes in the climate/rainfall forcing (Kermadi et al., 2011; Braud, 2011). On the rainfall data, a significant increase (Mann Kendall test (Mann and Whitney, 1947) at the 5% level) of the annual maximum of 5, 10, 15-day cumulative rainfall was found for the Bron station in the 1920-2010 period, with a rupture detected in 1974 by the Pettitt test (1976). No significant trends/ruptures were found when the period was restricted to the 1970-2009 period. The analysis of the daily SAFRAN data on the 1970-2009 period showed a significant increase (at the 1% level) of the annual mean temperature of 0.52 °C every 10 years. But no significant trend in annual PET was found. On the other hand, the Pettitt test show a significant (at the 5% level) rupture of the annual PET in 2002, which will have to be confirmed in the future. From all the results obtained on the daily rainfall, temperature and PET data, we concluded that it was unlikely that change in the rainfall and climate could have affected the hydrological regime on the 1970-2010 study period. However, in the context of urban catchments with short response times, such an analysis should also be conducted with shorter time steps. It will be done when longer short time step rainfall series will be available (they are presently only 25 years long).

In the study by Radojevic et al. (2010), the stream flow series showed an increase of frequent floods, whereas large floods were not so affected. The change in frequent floods was attributed to the impact of urbanization. Radojevic et al. (2010) also used a modelling approach to asses the possible impact of urbanization on the hydrological regime, through the impact on the discharge – duration – frequency (QdF) curves. But their analysis is restricted to two short periods of about 10 years, and more than 10 years additional data are now available. Gnouma (2006) analysed the data from the Craponne, Mercier and Chaudanne sub-catchments, and tried to propose monthly water balance. The analysis was restricted to the 1997-2004 period.

In the present study, the discharge data analysis will be extended to include the whole available period (until 2010) and all stream flow gauges will be considered. The aim is the assessment of indicators, relevant to evidence the impact of land use change on the discharge time series. These indicators include annual and monthly discharge, base flow index, peak over threshold (POT), QdF analysis and flow components deduced from hydrographs decomposition. The analysis provides elements for a better understanding of the catchment behaviour, both for its rural and urban components. The derived data and synthesis are also useful for the evaluation/validation of the models developed within the AVuPUR project.

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# 3. Methodology

In section 3.1, we first assess indicators taken from the five classes that were identified in the literature review, as our objective was to qualify the impact of land use change and urbanization on the whole hydrological regime: flow duration curves, low flows, high flows. The flow components derived from the hydrograph decomposition were also considered as urbanization is suspected to increase quick flow and decrease base flow. Finally, as one of the discharge series was long enough, statistical tests (trends/ruptures) were also applied to this time series.

In section 3.2, we present methods specifically developed to evidence the impact of sewer systems and sewer overflow devices (SODs) on the river discharge time series.

## *3.1. Indicators derived from the literature*

The objective of this analysis is to describe and characterize the discharges time series at a given location. Whenever possible the indicators will be adapted/normalized so that comparison between different catchments of various sizes and/or various land use become possible.

Hydrological regime:

For the characterization of the hydrological regime (annual, monthly and daily time step), the variable time step stream flow data were first interpolated to a 30 (respectively 60) minutes time step for the Pollionnay, Upstream_SOD1, La Léchère stations (respectively Craponne and Taffignon stations) and then aggregated to daily, monthly and annual time step from which the hydrological regime was calculated (Sauquet et al., 2000, 2008). Missing daily values were replaced by the interannual monthly average corresponding to the month of the missing data.

From the daily discharges we also derived the flow duration curves (FDCs). They are obtained by ordering all the daily discharge values in decreasing order. Each ordered discharge value $Q_f$ is associated with an empirical frequency which is the probability of finding a value $Y$, larger or equal to $Q_f$.

$$\Pr ob\left(Y \geq Q_f\right) = \frac{r}{N} \qquad (1)$$

where $N$ is the total number of observations and $r$ is the rank of observation $Q_f$.

In order to compare data from catchments of different sizes and identify the possible impact of land use on the discharge, it is convenient to normalize the discharge data before calculating the flow duration curves. The most obvious choice is to compute specific discharges by dividing all the data by the catchment area. The advantage is that this method provides water heights comparable to rainfall heights, which can be directly used to compute the water balance or runoff coefficients. However, in periurban catchments, especially equipped with combined sewer systems, this is not so obvious (Jankowfsky, 2011). Jankowfsky (2011) shows that, in such catchments, the boundary is not only dependent on topography, but is influenced by the sewer systems. The areas connected to the river via sewer overflow devices are only contributing to the streamflow when the sewer systems overflows. In addition, only part of this runoff drains into the river, because part of it continues to reach the Waste Water Treatement Plant (WWTP). For the Chaudanne at La Léchère catchment, Jankowfsky (2011) shows that under dry conditions, the area of the catchment is 2.9 $km^2$, whereas it reaches 4.1 $km^2$ when all the SODs are activated. This result shows that using the specific discharge in periurban watersheds may lead to some problems and that this quantity, as well as runoff height and runoff coefficients must be used with caution.

The second option is to normalize discharge data with the average annual discharge (e.g. Sauquet et al., 2008). This indicator is independent of the catchment area estimation. However, if the mean annual discharge changes with time due to land use modifications, this may bias the results. Comparison between catchments is therefore more difficult and only normalisation based on specific discharges will be discussed in the remaining of the paper.

Low flows:

The base flow was estimated using the Tallaksen and Van Lanen (2004) algorithm on the daily data. The base flow was estimated by linear interpolation between $n$ points corresponding to the local minima of $n$ periods of 5-days duration without intersection. The BFI (Base Flow Index), which is defined as the average of the base flow divided by the mean interannual discharge of the time series, was selected in this study. It is a non-dimensional index which allows comparison between catchments. Low flow were also characterized with the frequency of zero daily discharge (Richter et al., 1996).

High flows:

Variable time step discharge time series were used for the discharge- duration- frequency analysis (QdF). The method provides a theoretical description of floods for several durations. The studied variable was the maximum discharge continuously exceeded during the duration $d$, $QCX_d$ (Figure 5a) The analysis was performed in several steps.

- A characteristic flood duration was estimated for each gauge. The analysis was performed using data from which the base flow (calculated as described above) had been removed. As the base flow data were available at the daily time step, an interpolation of base flow at the variable time step was performed before removing it from the variable time step time series. An automatic program has been developed which selects the hydrographs around major floods. A discharge threshold, determined from the POT analysis (see below) is prescribed for the events selection and all the floods higher than this threshold are retained. Each hydrograph is scaled by its maximum peak discharge $Q_{max}$. Therefore all the hydrographs have a maximum value of 1 (and can be compared amongst catchments). From all the hydrographs, we compute the median hydrograph. The characteristic flood duration $\theta$ is then calculated as the duration where $Q/Q_{max}$ =0.5 in this median hydrograph (Figure 5b). An iteration with the next step may be required to properly fix the discharge threshold.
- The next step is the extraction of independent values of floods for various durations $d$. One value per year (annual maximum) can be extracted, but in order to increase the sample size, the Peak Over Threshold approach was used. We tested extractions with an average of 2 and 4 floods per year in the analysis. As we are interested not only in extreme floods but also in frequent floods and given the shortness of some of the time series, the extraction with 4 floods per year was finally used and will be presented below. The corresponding threshold was automatically determined so that the target average flood number per year was obtained (Lang et al., 1999). The procedure also ensures independence of the selected events. The analysis was performed on the hydrological years (from September 1 to August 31) for the instantaneous flood peak ($d$ =0) and for $d/8$, $d/4$, $d/2$., $d$, 3$d$. For the various gauges, the duration $d$ was chosen close to the characteristic flood duration $\theta$ determined in the previous step. Next, the empirical probability of non-exceedance of the value $x$

$$\Pr ob(QCX_d \le x) = F(x) \qquad (2)$$

was calculated on the sampled variable $QCX_d$. From this relation, it is possible to calculate the quantile $x(T)$ of return period $T$, associated with the $F$ law.

Hydrograph separation:

In this study, we used the WETSPRO tool proposed by Willems (2009) to compute base flow, inter flow (sub-surface flow) and quick flow. This method is an extension of the recursive digital filter of Chapman (1991). It assumes that the recession curve can be adjusted with an exponential model. The recession constant, $k$, of the exponential model corresponds to the time in which the flow is reduced by a factor exp(-1)=0.37 during dry weather periods. The

method of Willems (2009) includes a second parameter *w*, which corresponds to the average fraction of the sum of the quick and inter flow volume over the total flow volume. The filtering procedure is first applied to extract the base flow. It is then repeated to extract the interflow on the (total – base flow) time series. The values of the *k* and *w* parameters were determined manually by trials and errors so that the base flow fraction was close to the BFI determined previously. The analysis was performed for the Craponne and Taffignon data using daily data, and the Pollionnay, Upstream_SOD1 and La Léchère gauges, using two-hours time step data in order to capture the inter flow.

Statistical tests:

The Craponne gauging station was the only station with a long enough (40 years) time series to perform trend/rupture statistical tests. The Mann Kendall (Mann and Whitney, 1947) and Pettitt (1979) tests were used for trend and rupture analyses respectively. The analysed variables were the mean annual discharge, BFI, components of the flow as derived from the hydrograph separation, the POT values (using an extraction of two and four floods per year on variable time step time series), following the methodology proposed by Renard et al. (2006) and Lang et al. (2006).

### *3.2. Methods specific to the existence of sewer overflow devices and sewer networks*

As said before, given the quick response time of the urban parts and the very short functioning time of SODs, the indicators proposed in the previous section are not sufficient to fully evidence the impact of the urban areas on the river flow, especially for small catchments (a few $km^2$). Therefore, we propose specific methods, particularly adapted to these conditions. These methods rely on filtering techniques of the discharge time series. Two types of applications were developed (Table 3):

Filtering of SODs discharge to derive "pseudo-natural" discharge series. In order to get a clear signature of the SOD on the river discharge time series, the SOD must be located upstream and close to the discharge gauging station (10 to 100 m). The filtering method is applicable to variable time steps time series as it takes benefit of the fact that, in case of SOD overflows, the discharge will increase rapidly and the measurement points will be more frequent. The filtering is based on a moving average with a *constant* number of points. Therefore the time step of the filtering will be much shorter when the response is quicker (activation of the SOD) than when the response is slower. The method was applied to the La

Lèchere and Craponne stations where a SOD is present less than 100m upstream, with a 4 points moving average. This leads to two additional time series corresponding to the SOD discharge (indexed SOD in Table 3) and the river discharge if the SOD was absent (indexed Rural in Table 3).

Filtering of the combined sewer systems discharge (CSS) series. In this case, the method allows the separation of the measured discharge between waste water (WW), parasite clear groundwater infiltration in the sewer network (GW) and the runoff component (RW). Its application combines times series of Combined Sewer System (CSS) discharge, rainfall data, SOD discharge (when a SOD is present). Contrarily to the previous case, the filtering method is applied to fixed time step time series (in our case 6 min time step given the size of the catchment and the response time) in order to process simultaneously the various time series. The fixed time step time series are obtained from linear interpolation of the variable time step times series.

The principles underlying the method are summarized in Figure 6 and detailed below.

- Step 1: determination of the WW fraction. This step is conducted in two phases. Step1a: During the night, as the catchment is quite small, it is assumed that the waster water (WW) is zero. In dry period conditions, the discharge measured in the sewer system during the night can therefore be assumed to be clear parasite groundwater infiltration (GW). This GW water is obtained by using a moving average tracking the daily minimum discharge (in our case a moving average calculated using 240 points, corresponding to 24h of 6 min time step data). Step 1b: This clear parasite water infiltration is subtracted from the CSS discharge, leading to a residual time series (CSS – GW). To estimate the waste water discharge, it is assumed that, during dry weather periods, the CSS-GW discharge is equal to the waste discharge (WW). A weekly averaged cycle is calculated from the 6 min time step data during dry weather. This weekly cycle takes into account week and week-end days that have specific patterns.
- Step 2: The WW series is substracted from the CSS data. This leads to a time series of runoff + infiltrated groundwater data (RW + GW). The same moving average tracking the daily minimum discharge is applied once again to separate the RW and GW discharges.
- Step 3: If a SOD exists, its contribution is added to the runoff because the water which overflows the SOD is also generated by runoff. This leads to the final value of the runoff series (RW + SOD).

Table 3 presents a synthesis of the various time series, derived using the two filtering methods and the name they will be referred to in the paper. The same indicators as those presented in section 3.1 were applied to the filtered time series, when relevant.

# 4. Results

The results section contains two sub-sections. First we present the results of the observed data analysis, based on the methods described in section 3.1. Second we present the result of the filtering methods presented in section 3.2

## *4.1. Analysis of observed discharge time series*

### 4.1.1. Hydrological regime

Table 4 provides the values of the mean annual discharge (and specific discharge when relevant) and 50% quantile of the FDC. Figure 7 shows the average monthly specific discharge for the 5 gauged stations for the 2005-2010 common measurement period. Table 4 and Figure 7 show that the "rural" catchments have an average annual specific discharge ranging between 5.5 and 6.9 l $s^{-1}$ $km^2$. They also exhibit similar monthly patterns with higher values in spring and winter and low discharge in summer and autumn (Craponne, Pollionnay, Upstream_SOD1). On the other hand, the Taffignon station exhibits systematically lower monthly specific discharge than its upstream gauging station Craponne. This is also reflected in the average annual specific discharge which is only 5.1 l $s^{-1}$ $km^2$ as compared to 6.9 l $s^{-1}$ $km^2$ for Craponne. An analysis of the annual runoff coefficient (not shown) confirms that the Taffignon values are systematically lower than those of Craponne and the difference in mean (0.26 for Craponne and 0.21 for Taffignon) is significant at the 5% level ($p$=0.02 for the t-test). Figure 7 shows that the La Léchère station (when considering the most favourable case with a 2.9 $km^2$ catchment area) has larger values of average monthly discharge than its upstream station (Upstream_SOD1) in summer and autumn (May to October ). It can be explained by a larger contribution of artificialized areas in summer (see section 4.2.3).

Figure 8a shows the flow duration curve of the daily specific discharge for the gauged catchments: Taffignon, Craponne, Pollionnay, Upstream_SOD1, La_Léchère. It shows that the Craponne station has larger specific discharge than the downstream Taffignon station for almost all the range of frequencies. The lowest runoff production is therefore generalised for

the whole range of discharges (except high flows – see section 4.1.3). The downstream La_Léchère station has significantly higher values than the Upstream_SOD1, which is much less urbanized than the La_Léchère station (Figure 4), for the frequencies larger than 40%.

4.1.2. Low flows and hydrograph separation

Low flows are characterized using the % of zero daily discharge and the BFI (Table 4). For the gauged catchments, the % of zero daily discharge ranges between 0.25% (Craponne) to 31% (Upstream_SOD1). Note that the Taffignon gauge has a larger frequency of zero discharge (5.4%) than the upstream gauging station Craponne. This confirms the decrease in runoff production, already observed on the annual specific discharge and the FDC, from upstream to downstream. On the other hand, the % of zero daily discharge decrease from 31.2% Upstream_SOD1 to 11.1% at the downstream La Lèchère station (see also Figure 8a). This increase can be attributed to the impact of urbanization as the additional area is mainly composed of artificialized areas (Table 4).

The BFI values of the observed time series range between 0.26 and 0.54. Those values are quite low and are characteristic of catchments with a low storage capacity. For the catchments with the lowest % of artificialized areas (Upstream_SOD1 (24%), Pollionnay (11%), Craponne (18%)), the BFI increase with the catchment area, consistently with a decrease of the % of days with zero discharge (Table 4). The behaviour of the Taffignon station is, once again, inverse to what is expected: the BFI decreases between the upstream Craponne and downstream Taffignon stations. The lowest specific annual discharge could therefore be explained by a lower base flow.

Table 5 shows the results of the discharge decomposition into base flow, inter flow, quick flow using the WETSPRO tool. The two small rural catchments (Pollionnay and Upstream_SOD1) have similar values of the $k$ recession constant (5 days). The quick flow represents 43.5% of the total flow for the Pollionnay station and 49% for the Upstream_SOD1 catchment. This can be explained by the difference in land use (mainly forest and crops for Pollionnay and crops for Upstream_SOD1), and because crop land has been shown to have a lower infiltration capacity than forest (Gonzalez-Sosa et al., 2010). The recession constant of the La_Léchère station is smaller than that of the upstream station Upstream_SOD1, and the % of quick flow is higher (54.4% against 49%), with a lower base flow. This shows the impact of the SODs and the urbanized areas which is the dominant land use in the additional

area between the two gauges. When comparing the Craponne and Taffignon stations, we can see that the $k$ recession constant increase between the upstream and downstream gauge (28 and 35 days respectively). However, the downstream Taffignon gauge has a smaller base flow (39.3% against 49.8%), as said before, and a higher portion of quick flow (37.6% against 25.6%). This corresponds to an increase of the artificialized surfaces (from 18% of the total catchment area at Craponne to 31% of the total catchment area at Taffignon – see Figure 4). This analysis confirms the expected impact of urbanization: an increase of quick flow at the expense of base flow, but this effect has been quantified here.

4.1.3. High flows

The characteristic flood durations appear in Table 4. Figure 9a shows the normalised median hydrographs for the various observed time series. We remind that the base flow has been removed before performing the extraction. For all the catchments, Figure 9a shows that the rising limb of the characteristic hydrographs is very sharp (a few hours). On the other hand, the catchments with the lowest artificialized area (Craponne, Pollionnay, Upstream_SOD1) have a quite heavy and long recession, although the characteristic duration, corresponding to $Q/Q_{max}$=0.5 is short (between 3 and 7 hours, Table 4), except for Upstream_SOD1 where it reaches 10 hours. The most artificialized catchments (La Léchère and to a lesser extend Taffignon) present characteristic hydrographs with the sharpest rising limbs (less than 5 hours) and a very quick recession (about 5 hours). Urbanization has therefore a significant impact on the hydrograph shape.

The maximum daily discharge and their corresponding specific values are provided in Table 4. Figure 10 shows the result of the QdF analysis in terms of specific discharge, for durations $d$=0 (maximum instantaneous peak discharge) and 12h for the 5 gauged stations. For all the stations, the flood discharge decreases sharply between the two durations, which is consistent with the peaky shape of the characteristic flood hydrographs (Figure 9a). For the duration $d$=0 and for a return period of less than ten years, the highest floods are encountered for the Pollionnay, Upstream_SOD, Taffignon and Craponne stations, in decreasing order. The most rural and natural catchment (Pollionnay) appears the most productive in terms of high floods. Contrarily to what is observed for the monthly regime and the low flow, the downstream Taffignon station is most productive than the upstream Craponne one for high flows. Urbanization may be responsible for this larger runoff for the highest floods. These features also hold for the $d$= 12 h duration. The results for the La Léchère station are shown using the two extreme catchments areas. For the most frequent floods, the specific discharge for $d$=0, is

significantly larger than that of the Upstream_SOD1 station, whatever the choice of the catchment area. We can deduce that the urbanization of the downstream part of the catchment increase the magnitude of the most frequent floods.

4.1.4. Statistical tests for the Craponne gauging station

The results of the trend and rupture statistical tests performed on the Craponne time series (1970-2010) are summarized in Table 6. They show a significant decrease of the % of base flow and inter flow at the 5% and 1% level respectively, whereas the quick flow increase significantly at the 1% level. The increase in maximum annual discharge is not significant, nor the increase in maximum peak discharge. On the other hand, the POT analysis reveals a significant increase (at the 5 or 10% level) of the magnitude of floods for all the durations except $d$=0, when sampling the floods with two floods per year. If the sampling is performed to retain four floods per year, i.e to include less intense floods, none of the trend/rupture remains significant (not shown). These results show that a trend is only evidenced for the largest floods.

## *4.2. Application of the filtering methods*

4.2.1 Evaluation of the SOD discharge filtering method

The result of the filtering of SOD discharge is illustrated in Figure 11 for the La Lèchere station. This figure shows the initial time series, the calculated La_Léchère_SOD2 and La_Léchere_Rural time series. We have also added the SOD1 time series on the graph, in order to assess the relevance of the method. Although the La_Léchère_SOD2 seems to react much more frequently than the SOD1 (the frequency of zero daily discharge are 22.9 and 87% respectively, see Table 4), we can assume that when SOD1 is active, SOD2 should also be active. This can allow the validation of the timing of the filtering method. Figure 11 shows that the agreement is reasonable and similar results were obtained on the whole period. The total volume discharged by SOD2 represents 5.3% of the total discharge at La Lèchère gauging station.

For the Craponne_SOD time series, no data were available for validation. The area drained by the SOD is estimated to be about 10% of the total catchment surface (Table 3). The total volume of the SOD discharge represents 7% of the total Craponne discharge. This figure is reasonable and comparable to that of the La Léchère catchment. In the near future, it will be possible to fully validate them, as the La Léchère and Craponne SODs are gauged since 2010.

In the remaining of the paper, we will assume that the filtering method is accurate enough so that the corresponding data series can be analysed similarly to the truly gauged time series.

### 4.2.2. Hydrological regime

When considering the reconstructed "rural" time series for the Craponne and La Léchère time series, the average annual specific discharge of the rural time series is 13% lower for the Craponne station and 5% for the La Léchère station (Table 4).

This is confirmed (both for the Craponne and La Léchère station) by Figure 12 (top), which shows the fraction of the total average monthly discharge coming from the SODs. This contribution of the SODs to the monthly regime ranges from 2-3 to about 15% with a clear annual cycle. The highest values occur in summer and autumn, when the natural discharge is the smaller. In this period, the contribution of SODs to the discharge is therefore important in a period where the river can be dry (see next section). This can increase pollution problems, all the more than discharge is low and dilution effects cannot occur.

### 4.2.3. Low flows and high flows

The frequency of zero daily discharge for the total, rural and SOD components of the Craponne and La Léchère stations (Figure 12, bottom), show very different behaviours between the two gauges. Whereas the frequency of zero discharge in the Craponne_SOD is quite constant throughout the year, it presents a clear annual cycle at La_Lèchère_SOD2. Values are higher in summer than in winter, which shows that the SOD2 is more frequently activated in winter, when the soil conditions are humid, than in summer when they are drier. For the two gauges, the % of zero daily discharge of the "rural" time series is systematically lower than that of the total discharge. For the La Léchère station, the difference can reach 20% in September and October. It means that the discharge in the river only comes from the SOD2 during this period.

We also see that, when the SODs contribution are filtered, the BFI values are larger than for the total discharge (Table 4), showing, as expected that SODs mainly contribute to quick flow.

### 4.2.3. Low flows and high flows

Figure 9b and 9c show the normalized hydrographs for the total, rural and SOD components of the Craponne and La Léchère stations respectively. As expected the SOD hydrographs are very peaky with characteristics flood durations of about 1h. Although the total and rural hydrographs are very close for the La Léchère station, the rural Craponne series shows a

much slower recession than the total curve with a doubling of the characteristic flood duration for the rural component. On this gauge, the impact of the SOD seems to be much influential on the hydrographs shapes than for the La Léchère catchment.

Figure 13 shows the QdF analysis for the total, rural and SOD components of both the Craponne and La Léchère stations. This figure shows that, for the largest floods, the rural and total curves are very close. It suggests that the largest floods are mainly associated with a large contribution of the rural area. On the other hand, the impact of SODs is significant for frequent floods, with return period of less than 2 years.

4.2.4. Analysis of the sewer system components

The mean annual values of the sewer discharge components are provided in Table 4. The waste water accounts for 33% of the total discharge, the rainwater runoff for 38% and the infiltration of groundwater into the sewer for 30%. The results of the filtering of the sewer discharge time series is illustrated in Figure 14 at the monthly time scale for the whole measurement period (2001-2010). It shows that the groundwater infiltration exhibits a clear annual cycle. It is almost zero in summer when the soil is dry and increases in winter and spring when the soil moisture is higher. The monthly pattern of rainwater runoff follows that of the monthly rainfall. Figure 8b shows the FDC of the CSS discharge and its various components. The FDC of the waster water (WW) is very flat as expected from its building. Values of CSS_RW+SOD1 below 0.001 $m^3 s^{-1}$ can be considered as noise, which explain the low value of zero daily discharge (about 10% in Table 4). The average fraction of rainy days is about 50% and the CSS_RW+SOD component of the CSS discharge is only not null when it rains. For the values larger than 0.001 $m^3 s^{-1}$, Figure 8b shows that the ranges of infiltrated groundwater and runoff discharges are very similar. Groundwater infiltration into the network is therefore a major problem for the efficiency of the sewer network. It may explain the larger activation of SOD2 in winter when the groundwater table is high (see Figure 12, bottom).

# 5. Discussion

*The importance of data collection*. The analysis presented in this paper relies on a nested and complete network of gauging stations, monitoring discharges in sub-catchments with various land uses but also on some infrastructures such as SODs and sewer networks. The set up in the Chaudanne sub-catchment is very valuable, as it allows the quantification of the impact of SODs and infiltration into the sewer network. However, although lots of efforts were dedicated to monitor the various branches, it is still impossible to close the water balance of

the catchment (uncertainty of the partition of water between SODs and the Waste Water Treatment Plant, partial measurements of the SODs).

For the type of analysis presented in the paper, the data quality and length of the series is of prime importance. The data availability period is very variable (between 5 and 40 years). Except Figure 7, all the indicators are calculated using the largest available time series. Due to internanual climate variability, which is large in this catchment (the CV of average annual rainfall is 241 mm at Pollionnay for an average of 746 mm on the 1997-2009 period), this may induce sampling fluctuations of the indicators. We verified that the conclusions were similar when the indicators were calculated on the same period (2005-2010). Another important point is the accuracy of the discharge data. A diagnostic of the gauging stations showed that low flows are generally quite uncertain due to very large sections and a small water height (Pollionnay, Upstream_SOD). This problem is being solved by adding a triangular device to get a higher accuracy for small discharges. The Craponne and Taffignon stations are considered reliable by their manager (DREAL) and therefore the decrease of runoff from upstream to downstream cannot be attributed to measurement problems. The La Lèchère station is the most accurate as it is equipped with a calibrated canal, but it may be overflooded for the largest discharges. This can explain the decrease in specific discharge for high flows (Figure 10). Branger et al. (2011) proposed a method to assess the accuracy of stage-discharge relationship and provide an error bound for each discharge measurement. The use of this information was beyond the scope of this paper, but will be useful to better assess the significant changes/trends. In terms of monitoring, progress is under way as new SODs are now monitored in the context of the quantification of rejected water in the receiving rivers (Water Framework Directive). These new data offer an opportunity to better understand the response of urbanized areas in periurban catchments and further validate the filtering method leading to the decomposition of total discharge into rural and SOD components. The Craponne subcatchment has a quite large area and it may be difficult to discriminate between the influence of the various infrastructures impacting the flow. The new discharges measurements in the SOD will be very valuable as they will allow a better assessment of the limits of applicability of the SOD filtering method.

*Impact of artificialization on the regime and the flow components. Impact on low flows and the importance of the sewer network*. Two results of this study are particularly striking: the decrease of specific discharge from upstream to downstream between the Craponne and Taffignon gauges, and the large fraction (30% of the total discharge) of infiltration into the

sewer system calculated for the Chaudanne subcatchment. This figure is high but consistent with independent estimation conducted using punctual measurements during the night by the services in charge of the network management. Recently Prigiobbe and Guilianelli (2009) reported an infiltration of about 50% in the old Rome sewer network and 14% in a recently constructed area. Berthier et al. (2004) found that the contribution of soil water infiltration to runoff in sewer pipes was about 15% in a small residential periurban catchment. On the same catchment, Rodriguez et al. (2008) simulate 11% of infiltration into the rainwater sewer system and 18% in the wastewater sewer system. In the Yzeron catchment, the main pipes network was built along the valley bottom in the seventies to collect waters from the surroundings. Breil et al. (2010) analysed one year of discharge monitoring in the main sewer collector close to the Taffignon station. They estimated the infiltration into the network to be 27% of the annual discharge. There is therefore a consistency in the results and infiltration into the sewer network can be considered as responsible for the decrease of base flow and average monthly discharge between Craponne and Taffignon. The impact of the SODs is also significant on low flows. They significantly impact the frequency of zero discharge and, for the smallest sub-catchments where the natural river regime is seasonal, water coming from the SODs is the only source of water during a significant part of the year. The impact in terms of water quality is of course important (Lafont et al., 2006). However, in order to conform to the water framework directive, the management of rainwater is being reconsidered: where possible rain waters are diverted to new separate sewers flowing to retention/detention basins. This process is under way in the Chaudanne catchment and should be monitored to quantify its future impact on the river discharge. Another lesson of this study is the importance of knowing precisely the catchments areas. This task is quite simple for natural catchments but is much more complicated for periurban catchments (Jankowfsky, 2011). However, such determination is essential to compare various catchments based on specific discharge. A normalisation with the mean annual discharge was attempted, but the interpretation of the results was not found relevant. This question of catchment area is therefore a major challenge for data interpretation and comparison in periurban catchments.

*Impact on high flows*. The results obtained in this paper confirm that for the highest floods, the impact of urbanization (via the SODs) is limited. In this case, the rural part of the catchment is the major contributor to floods, which can be explained by saturation of the soil due to long rainfall events. It may be counter-intuitive to see that the most productive catchment for high flows is the less urbanized one (Pollionnay). However, other studies (Sarrazin, 2012) have shown that the whole catchment is saturated during the largest floods

(corresponding to long lasting events of at least 70-80 mm). The whole catchment area is therefore contributing to the flow, whereas a part of the rainwater is diverted towards the WWTP in the artificialized catchments, even if all the SODs are activated. Our results also confirm that SODs mainly impact frequent floods, as already shown by Radojevic et al. (2010) using model simulations. Urbanization and catchment artificialization have also an impact on the hydrographs dynamics as shown by Figure 9. The most urbanized catchments have more peaky flood hydrographs. In order to refine this type of analysis, approaches such as those proposed by Archer (2007), Archer et al. (2010) should be investigated in the future, as they allow a full exploration of the whole discharge series, by analysing the frequency and duration of exceedance of various threshold discharges. In the Yzeron catchment, it has been shown that these variables were very relevant to quantify the impact of SODs on the incision and bank erosion risk (Grosprêtre, 2011). In the case of a upstream-downstream gradient of urbanization, like in the Yzeron basin, urban generated floods are flowing before the rural floods, avoiding peak flood accumulation. The effect of urbanization could be more sensitive and may be dramatic if impervious areas extension takes place upstream, increasing the probability of concomitancy between urban and rural floods (Ostrowski, 2000; Ostrowki et Bras, 2000.). Such an explanation may be invoked to explain the largest specific discharge of the downstream Taffingon station, as compared to its upstream Craponne one for high flows. Indeed, the Yzeron rivers receives a tributary flowing through a quite densely urbanized area before the Taffignon station.

*Statistical tests*. Statistical tests were only applied to the longest Craponne time series. They highlighted a modification of the components of the flow, with a decrease of base and inter flow, and an increase of quick flow. The SODs in this catchment were installed between 1970 and 1980 and therefore impact most of the available time series (1970-2010). There is also a significant increase of POT discharge (sampling with an average of two floods per year) for all the durations, except peak discharge. This can be put in parallel to the increase of artificialized surfaces in this catchment between 1970 (9%) and 2008 (18%), all the more than no significant change of maximum annual cumulated (1 to 15 days) daily rainfall can be evidenced. For the analysis of floods, an analysis of rainfall with a shorter time step (typically hourly) would be necessary but the available time series are too short up to now for such an analysis. In addition, those results on floods must be considered with caution as they are sensitive to the sampling strategy.

*Towards a perceptual model of the Yzeron catchment behaviour*. From the data analysis presented before, we can propose a perceptual model of the Yzeron catchment hydrological

functionning. The rural part of the catchment has a high infiltration capacity (Gonzalez-Sosa et al., 2010) but a small storage capacity. Therefore, for the small to medium events, the catchment response is mainly dominated by the quick response of urban areas for the formation of peak discharge and a delayed rural response mainly impacting the recession curve. Frequent floods are increased by the catchment urbanization. For the largest events (mainly long duration rainfall events), the catchment response is dominated by the rural response due to soil saturation. The river regime is also perturbed by the sewer systems through a high rate of infiltration of soil water which is diverted towards the WWTP and contributes to a decrease of base flow in the rivers. On the other hand, SODs have an antagonist impact as they provide a significant contribution to the river discharge in summer, especially for small catchments. But their impact is smaller than that of the sewer systems and the whole impact is mostly a base flow decrease. However, given the actions planned to improve the quality of the receiving waters (improvement of the tightness of the sewer systems, separation of rainwater and waste water, building of retention basin, etc), the discharge monitoring must be continued to see if those actions have a real impact on the discharge. The indicators presented in this study can help monitoring the system.

## 6. Conclusions and perspectives

The data analysis presented in this paper provides valuable insight into the periurban Yzeron catchment behaviour. We were able to highlight relevant indicators of the impact of urbanization/artificialization on the hydrological regime of periurban rivers. The results were obtained thanks to the availability of a long term and rich data set, sampling various aspects of the periurban water cycle. These series were relevant for our analysis. However, longer time series and sampling of more infrastructures would be necessary to fully close the water balance of such catchments. We have also seen that the determination of the periurban catchment area is also of importance for a correct data analysis. The filtering method proposed to decompose the measured discharge into rural and SOD component was found to be efficient in highlighting the major role of SODs on the whole hydrological regime, including, mean monthly regime, low flows and high flows. The application of the method requires the location of the SOD and gauging station to be very close, and data acquired with a variable time step. This findings provide guidelines for the setting of proper monitoring networks of those periurban catchments. Finally, the role of water infiltration within the sewer

system was highlighted. It was found to account for 30% of the total combined sewer system discharge. There are evidence that this infiltration has an impact on low flow and on a large part of the hydrological regime, by decreasing the water into the stream. This impact is important to consider due to its large impact on water quality and on ecosystems.

The indicators derived in this study are also very useful for the assessment of model results set up in the Yzeron catchment both at small scale (Chaudanne and Mercier catchments, Jankowfsky et al, 2011) and the Yzeron catchment (Branger et al., 2012).

Future work would be required to analyse more in depth the events characteristics, such as done in Sheeder et al. (2002) or Furusho et al. (2012) and characterize the impact of artificialization on the hydrograph shape using for instance methods derived from Archer (2007), Archer et al. (2010).

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Figure 2: Maps of land use of the Yzeron catchment in (a) 1970; (b) 1990; (c) 2008. The original maps were obtained by manual digitalization of aerial photographs by Jacqueminet et al. (2011), UMR EVS, 2010. They were reclassified in 3 classes: wooded areas (broad leaved and coniferous forests, moors), agricultural areas (crops, pastures, orchards, gardens) and artificialized areas (urban parcels including gardens and parks, roads, parkings).

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1Table 1: Indicators derived from discharge time series analysis found in the literature, and 2associated references. We distinguished studies based on model simulations and data analysis. 3In bold, we highlight references dealing with catchment urbanization. With a star, the study 4uses paired catchments

| Analysed indicators | Model simulation | Data analysis |
|---|---|---|
| **Hydrological regime** | | |
| Mean annual runoff, runoff coefficient | Ashagrie et al. (2006), **Beighley et al. (2003)**, Praskievicz and Chang (2009), | *Arrigoni et al. (2010), Bullock (1992), Wang et al. (2007) |
| Seasonal runoff | Praskievicz and Chang (2009) | Richter et al. (1996) |
| Quantiles | | *Arrigoni et al. (2010) |
| Flow duration curve | Gustard and Wesselink (1993) | *Bathurst et al. (2011), Wang et al. (2007) |
| Water balance components | **Claessens et al. (2006), Elfert and Bormann (2010)** | |
| **High flows** | | |
| Value and/or date of annual max peak discharge or max annual discharge other several durations | Ashagrie et al. (2006), **Beighley et al. (2003), Burns et al. (2005)**, Praskievicz and Chang (2009) | *Arrigoni et al. (2010), *Bathurst et al. (2011), Bullock (1992),Wang et al. (2007), Richter et al. (1996) |
| Peak over threshold (POT) | Vazquez et al. (2008), Willems (2009), Vazquez and Feyen (2010) | **Tong (1990)**, |
| QdF (discharge-duration-frequency) | Sauquet and Leblois (2001), **Radojevic et al. (2010)** | |
| **Low flows** | | |
| Value and/or date of annual min discharge (or minimum over a period of several days) | Ashagrie et al. (2006), **Burns et al. (2005)**, Praskievicz and Chang (2009) | *Arrigoni et al. (2010), Richter et al. (1996) |
| POT for low flow | Vazquez et al. (2008), Willems (2009), Vazquez and Feyen (2010) | |
| Base Flow Index (BFI) | | Bullock (1992), *Dow (2007), Wang et al. (2007) |
| Low flow frequency, $Q_{95\%}$ | Gustard and Wesselink (1993) | Bullock (1992) |
| **Indicators based on hydrographs analyses** | | |
| Indicators derived from events analysis: runoff coefficient, recession curves | **Chormanski et al. (2008)**, **Meierdiercks et al. (2010), Ott and Uhlenbrook (2004)** | *Buytaert et al. (2004) |
| Flow components based on flow separation | Vazquez et al. (2008), Willems (2009), Vazquez and Feyen (2010) | |
| Number and/or duration of discharge exceeding thresholds | | *Archer (2007), Richter et al. (1996) |
| Number and/or duration of rising and falling rate of discharge exceeding thresholds | | Archer et al. (2010), Richter et al. (1996), **Tetzlaff et al. (2005)** |
| **Results of statistical analyses** | | |
| Statistical comparison of sub-periods | **Radojevic et al. (2010)** | **Tong (1990)**, Wang et al. (2007) |
| Trend detection | **Claessens et al. (2006)** | Kliment and Matoušková (2009) |
| Regression with landscape characteristics | | *Arrigoni et al. (2010), *Dow(2007), **Tetzlaff et al. (2005),** Wang et al. (2007) |

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1Table 2: Characteristics of the gauged sub-catchments

| River | Name of the gauging station | Catchment area ($km^2$) | Data availability |
|---|---|---|---|
| Yzeron | Taffignon | 129.00 | 1988/09/16 – present |
| Yzeron | Craponne | 48.00 | 1969/10/27 – present |
| Mercier | Pollionnay | 6.77 | 1997/01/14 – present |
| Chaudanne | Upstream_SOD1 | 2.19 | 1997/06/21 – 2001/07/24; 2005/01/01 – present |
| Chaudanne | La_Léchère | 2.9 to 4.1(*) | 2005/01/01 – present |
| Chaudanne | SOD1 | ≈0.16 | 2001/06/26 – present |
| Chaudanne | CSS | ≈0.16 | 2000/11/15 – present |

2(*) The La Léchère area is minimum (2.9 $km^2$) under dry conditions, and can reach 4.1 $km^2$
3when all the SODs are activated (Jankowfsky, 2011)

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1 Table 3: Time series derived by the filtering methods
2

| River | Name of the time series | Discharge component | Method of derivation | Catchment area ($km^2$) |
|---|---|---|---|---|
| Yzeron | Craponne_SOD | Upstream SOD contribution | 4 points moving average on the variable time step series | ≈4.5 |
| Yzeron | Craponne_Rural | "Rural" discharge without the upstream SOD | 4 points moving average on the variable time step series | 48 |
| Chaudanne | La_Léchère_SOD2 | Upstream SOD2 contribution | 4 points moving average on the variable time step series | ≈1.1 |
| Chaudanne | La_Léchère_Rural | "Rural" discharge without the upstream SOD2 | 4 points moving average on the variable time step series | 2.9 |
| Chaudanne | CSS_RW+SOD1 | Rainwater runoff | Filtering of the 6mn Chaudanne_CSS series | ≈0.16 |
| Chaudanne | CSS_GW | Groundwater infiltration into the CSS | Filtering of the 6mn Chaudanne_CSS series | - |
| Chaudanne | CSS_WW | Waste water | Filtering of the 6mn Chaudanne_CSS series | - |

1Table 4: Mean annual discharge $Q_A$ ($m^3 s^{-1}$) and corresponding specific discharge $q_A$ ($l s^{-1} km^{-2}$), 50% quantile of the flow duration curves, $Q_{50\%}$; frequency of zero daily discharge and BFI; maximum daily discharge $Q_{max}$ ($m^3 s^{-1}$), and corresponding specific discharge $q_{max}$ ($l s^{-1} km^{-2}$); characteristic flood duration for an extraction of 4 floods per year, $\theta$ (h), and duration, $d$ (h), retained for the QdF analysis. Specific discharges are not provided for the SODs and CSS_RW+SOD components, due to the large uncertainty on their drained areas. For the La Léchère station, figures in parenthesis correspond to a 4.1 $km^2$ catchment area.

| Series | $Q_A$ | $q_A$ | $Q_{50\%}$ | % of zero daily discharge | BFI | $Q_{max}$ | $q_{max}$ | $\theta$ | $d$ |
|---|---|---|---|---|---|---|---|---|---|
| | $m^3 s^{-1}$ | $l s^{-1} km^2$ | $m^3 s^{-1}$ | - | - | $m^3 s^{-1}$ | $l s^{-1} km^2$ | h | h |
| Observed time series | | | | | | | | | |
| Taffignon | 0.664 | 5.15 | 0.275 | 5.44 | 0.388 | 46.25 | 358.5 | 6 | 12 |
| Craponne | 0.332 | 6.92 | 0.169 | 0.25 | 0.486 | 20.94 | 436.2 | 7 | 12 |
| Pollionnay | 0.045 | 6.65 | 0.129 | 13.96 | 0.336 | 5.95 | 878.9 | 3 | 12 |
| Upstream_SOD1 | 0.012 | 5.55 | 0.0028 | 31.25 | 0.307 | 0.67 | 305.9 | 10 | 12 |
| La_Léchère | 0.019 | 6.55 (4.63) | 0.0069 | 11.15 | 0.260 | 1.58 | 544.8 (385.4) | 1 | 4 |
| SOD1 | 0.00027 | - | 0.000 | 87.00 | - | 0.06 | - | 1 | 1 |
| CSS | 0.00545 | - | 0.0039 | 0.24 | - | 0.13 | - | - | - |
| Derived series using the filtering methods | | | | | | | | | |
| Craponne_Rural | 0.289 | 6.02 | 0153 | 0.53 | 0.536 | 14.79 | 308.1 | 16 | 12 |
| Craponne_SOD | 0.045 | - | 0.003 | 34.31 | - | 6.21 | - | 3 | 1 |
| La_Léchère_Rural | 0.018 | 6.20 | 0.0056 | 15.96 | 0.269 | 1.50 | 517.2 | 1 | 4 |
| La_Léchère_SOD2 | 0.001 | - | 0.0002 | 22.86 | - | 0.08 | - | 1 | 1 |
| CSS_RW+SOD1 | 0.002 | - | 0.0012 | *9.90* | - | 0.13 | - | 1 | 1 |
| CSS_GW | 0.002 | - | 0.0015 | 48.33 | - | 0.03 | - | - | - |
| CSS_DW | 0.002 | - | 0.0017 | 0.00 | - | 0.002 | - | - | - |

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1Table 5: Decomposition of the discharge into base flow, inter flow and quick flow (in % of 2the total volume) for the 5 gauged catchments. The values of the constant of the exponential 3recession model, *k* (days) and the *w* parameters are also given.
4

| Gauging station | Exponential parameter *k* for the base flow extraction (days) | Exponential parameter *k* for the inter flow extraction (days) | *w* (-) parameter | % base flow | % inter flow | % quick flow |
|---|---|---|---|---|---|---|
| Taffignon | 35 | 12 | 0.25 | 39.3 | 23.1 | 37.6 |
| Craponne | 28 | 7 | 0.20 | 49.8 | 24.6 | 25.6 |
| Pollionnay | 5 | 3 | 0.28 | 34.6 | 21.9 | 43.5 |
| Upstream_SOD1 | 5 | 3 | 0.32 | 30.2 | 20.8 | 49.0 |
| La_Léchère | 3.75 | 1.5 | 0.35 | 26.3 | 19.2 | 54.5 |

5

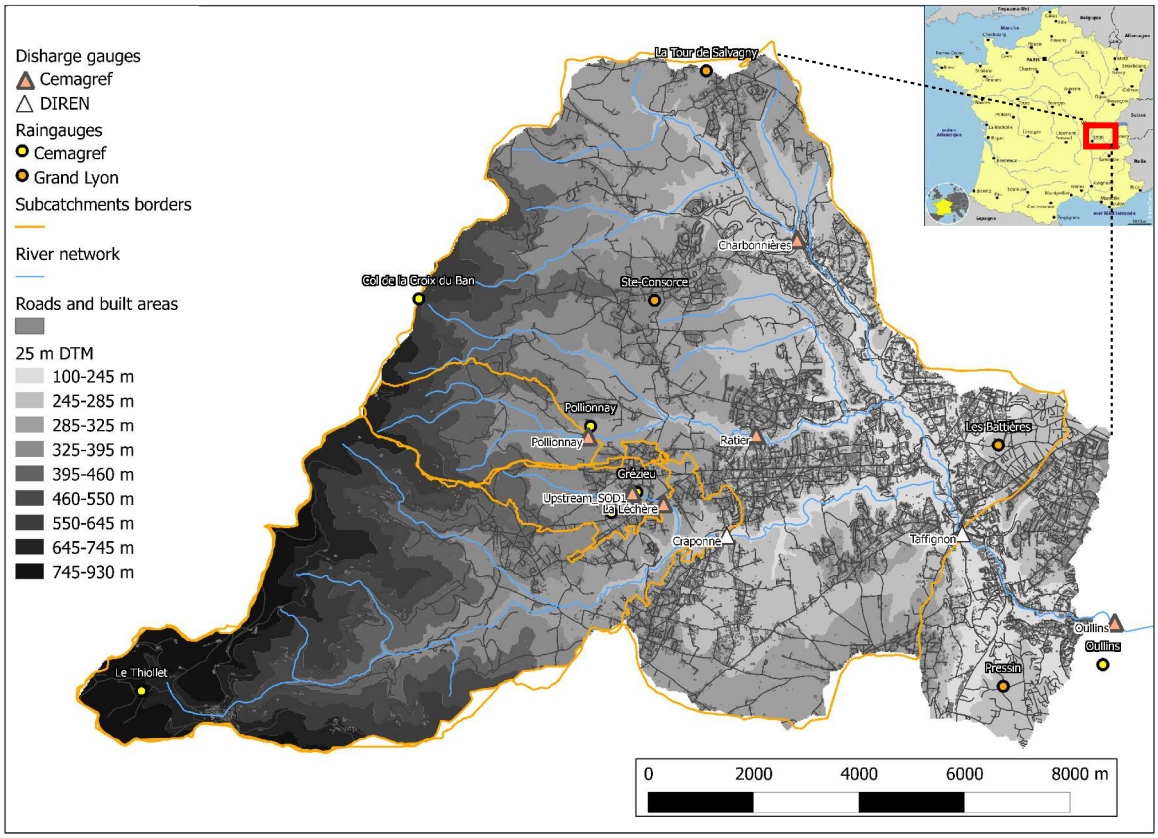
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Table 6: Results of statistical tests applied to the Craponne daily discharge time series. The *p*-values of the Mann-Kendall trend tests are provided in the first line and the direction of the trend (+ for an increase, - for a decrease) are given in parenthesis when significant. The second line contains the p-value of the Pettitt test and the date of the most probable rupture is given in parenthesis when significant. The *p*-value are followed with (*) when the test is significant at the 10% level, (**) at the 5% level and (***) at the 1% level. The POT analysis is applied on the $QCX_d$ data (maximum discharge continuously exceeded during the duration *d*) extracted with an average of two floods per year on the variable time step discharge time series.

| **Indicator calculated using the daily discharge at Craponne from 1970-2010** | ***p*** |
|---|---|
| BFI (calculated using the Tallaksen et al., 2004 algorithm) | 0.12 (-) |
| | 0.17 |
| % base flow (from WETSPRO) | **0.02** (-)** |
| | 0.13 |
| % inter flow (from WETSPRO) | **0.006*** (-)** |
| | 0.11 |
| % quick flow (from WETSPRO) | **0.001*** (+)** |
| | **0.02** (1988)** |
| Max annual discharge | 0.21 |
| | 0.63 |
| POT *QCX d*=0 (maximum peak discharge) | 0.35 |
| | 1.05 |
| POT *QCX* duration *d*=1h30 | **0.04** (+)** |
| | 0.17 |
| POT *QCX* duration *d*=3h | **0.06 * (+)** |
| | 0.13 |
| POT *QCX* duration *d*=6h | **0.07 * (+)** |
| | **0.08* (1979)** |
| POT *QCX* duration *d*=12h | **0.06 * (+)** |
| | 0.21 |
| POT *QCX* duration *d*=36h | **0.07* (+)** |
| | **0.07* (1977)** |

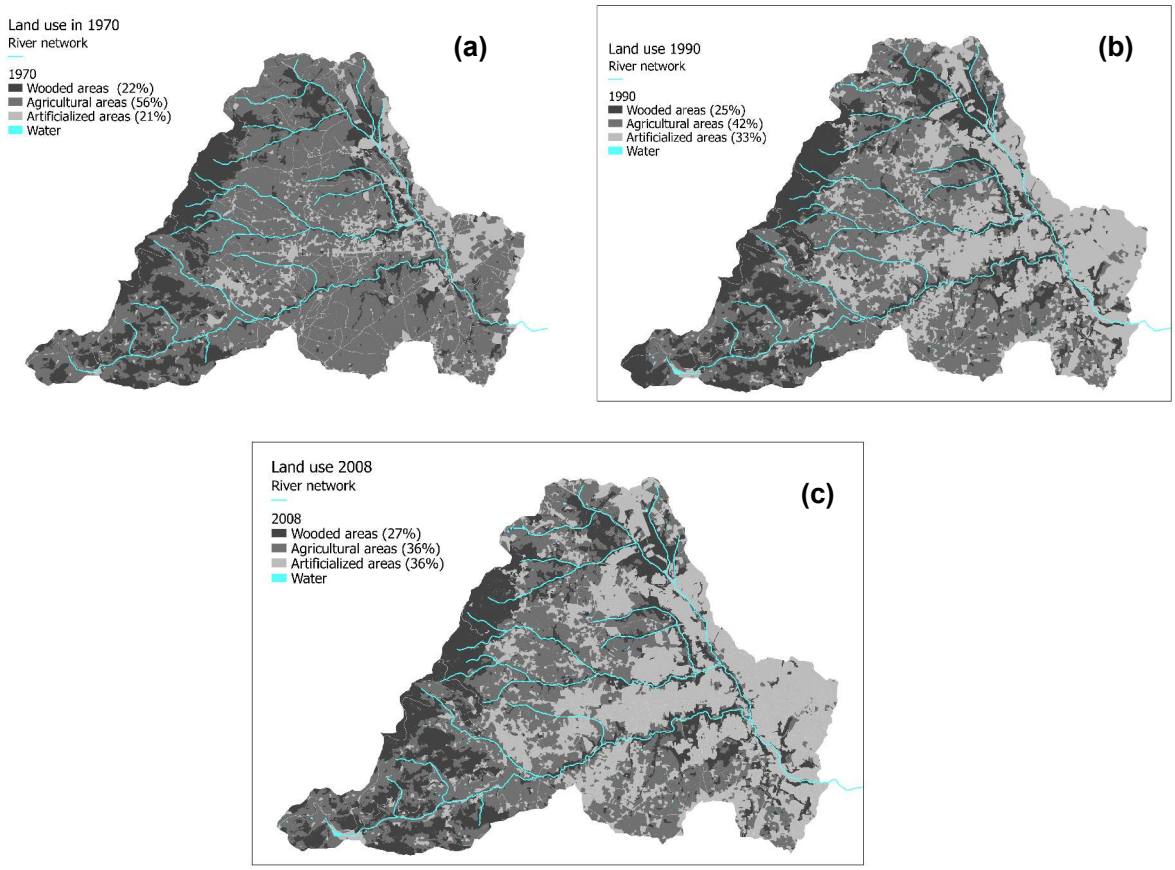
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1Figure 1
2



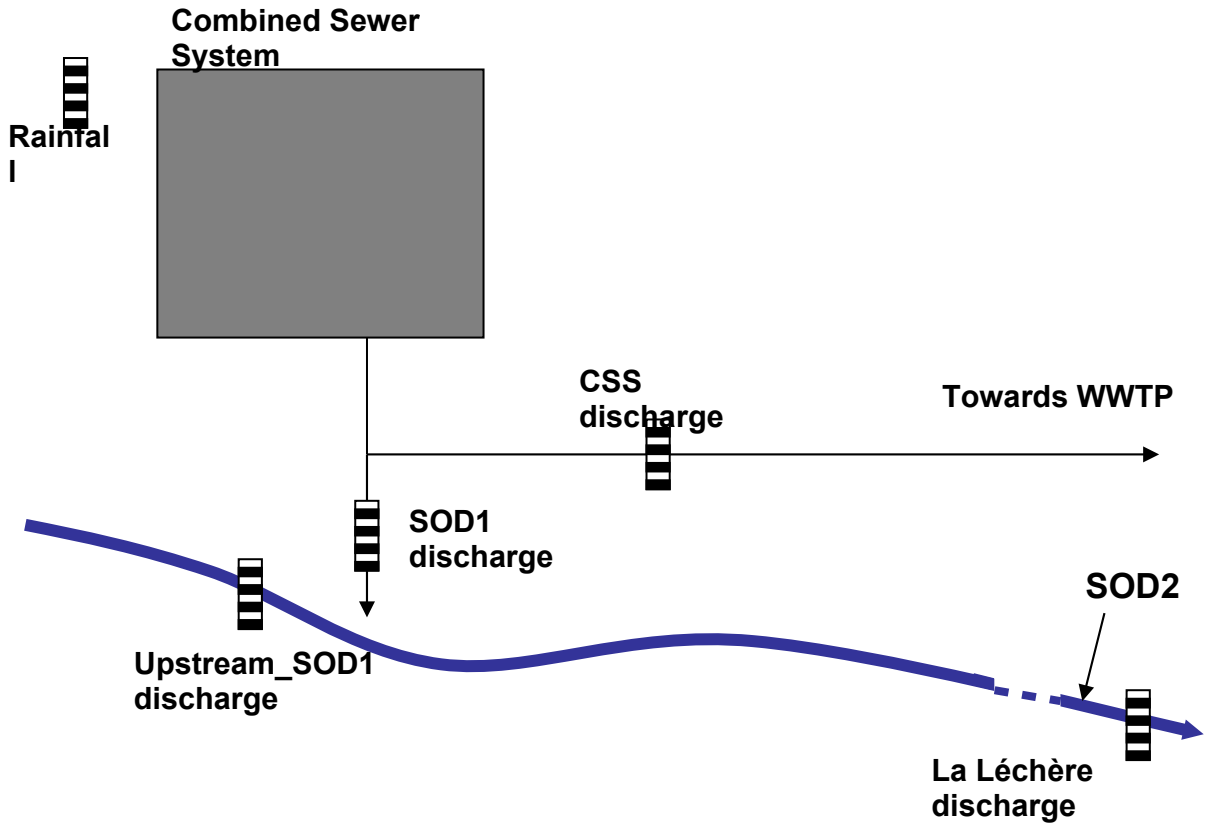
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1Figure 2
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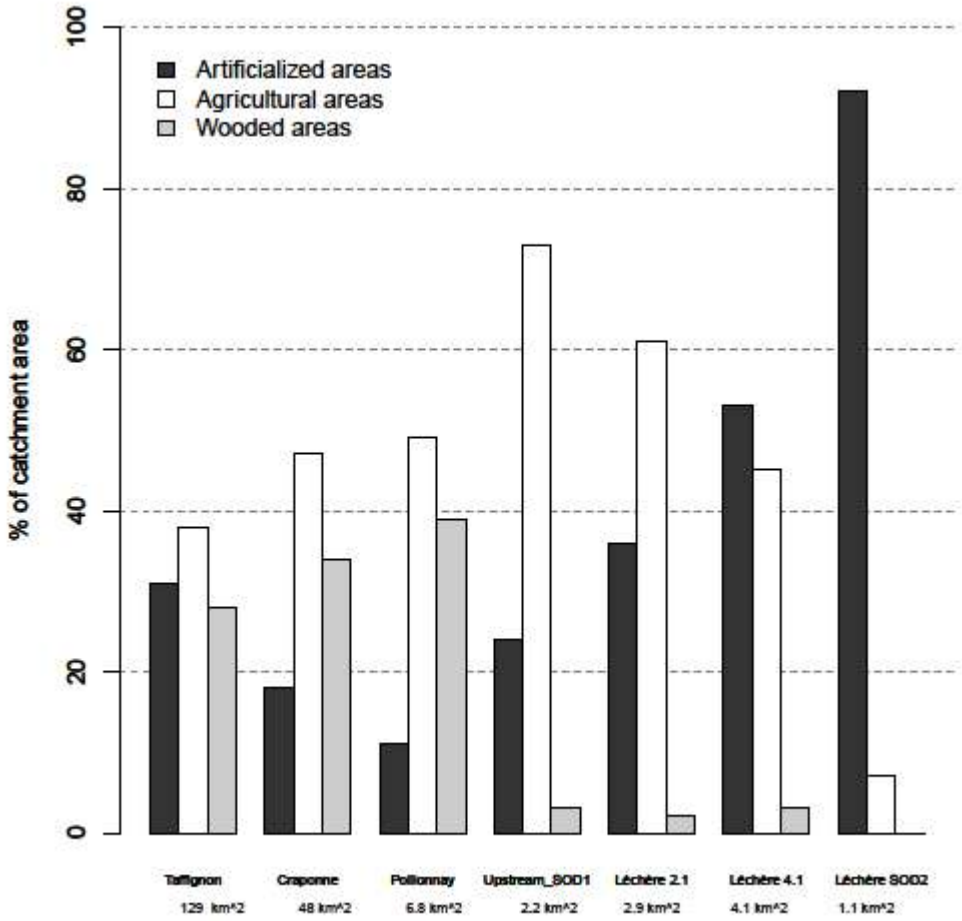
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1Figure 3
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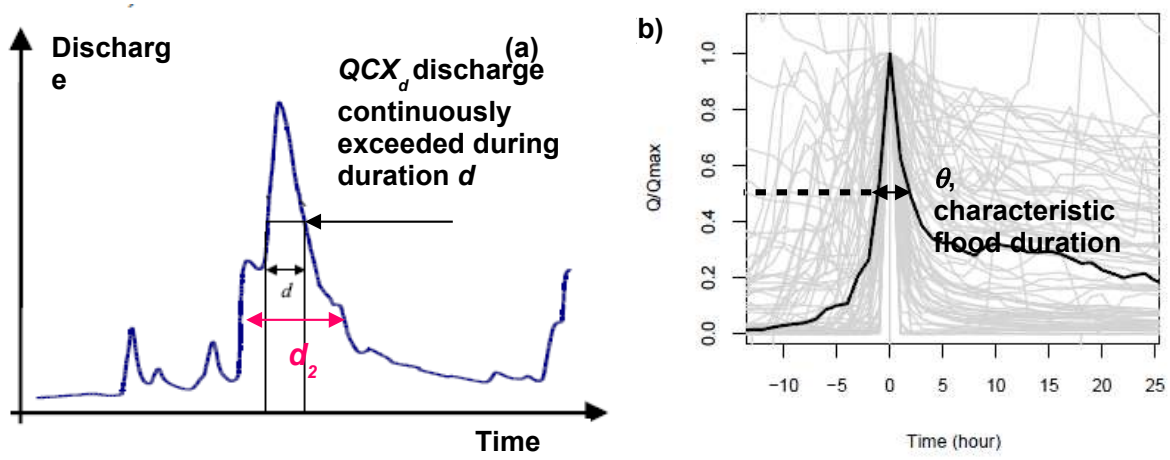
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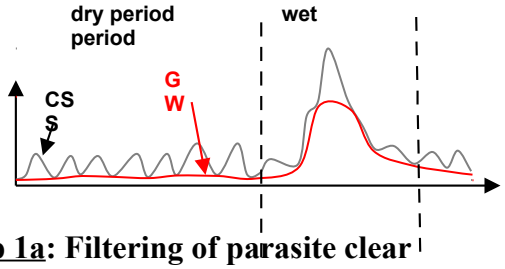
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1Figure 5
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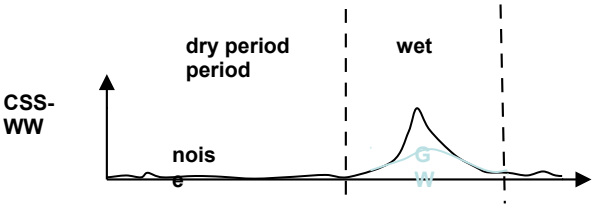


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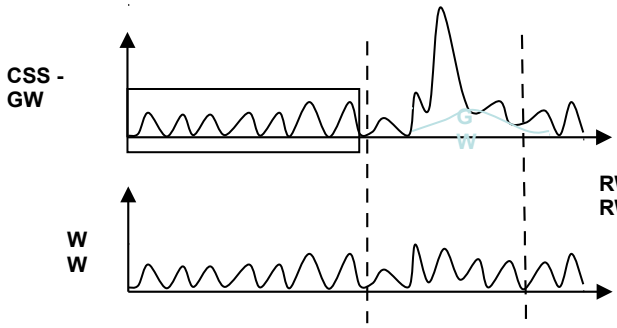
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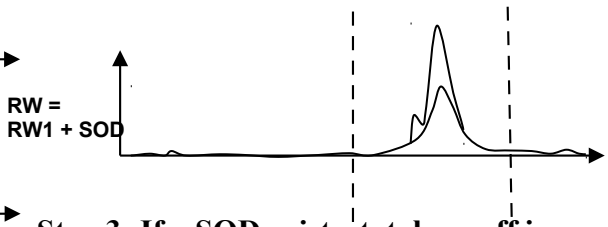

**Step 1a: Filtering of parasite clear groundwater (GW) from the combined sewer system (CSS) discharge**




**Step 2: Filtering of the CSS – WW time series to derive the runoff + parasite clear groundwater discharges (RW + GW). New filtering to separate runoff RW and GW.**



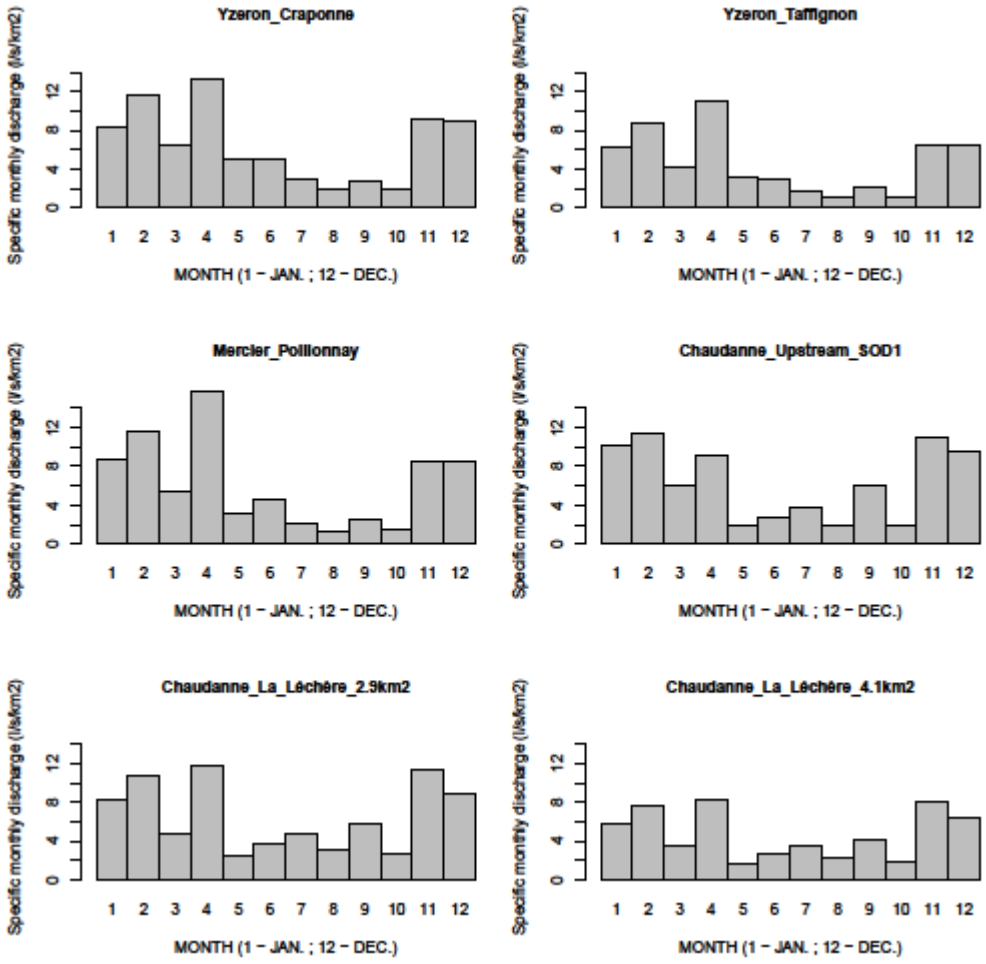

**Step 1b: Extraction of the dry period data and building of an average weekly waste water WW cycle**




**Step 3: If a SOD exists, total runoff is given by the RW +SOD discharge**

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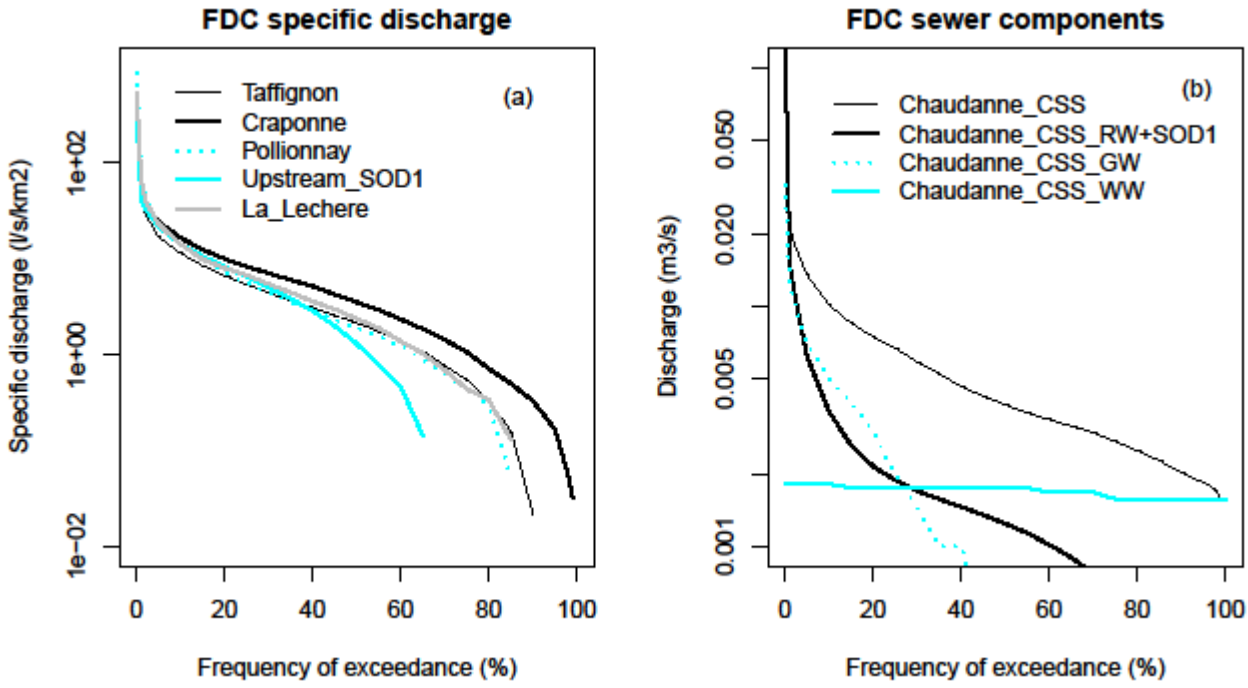
1Figure 7




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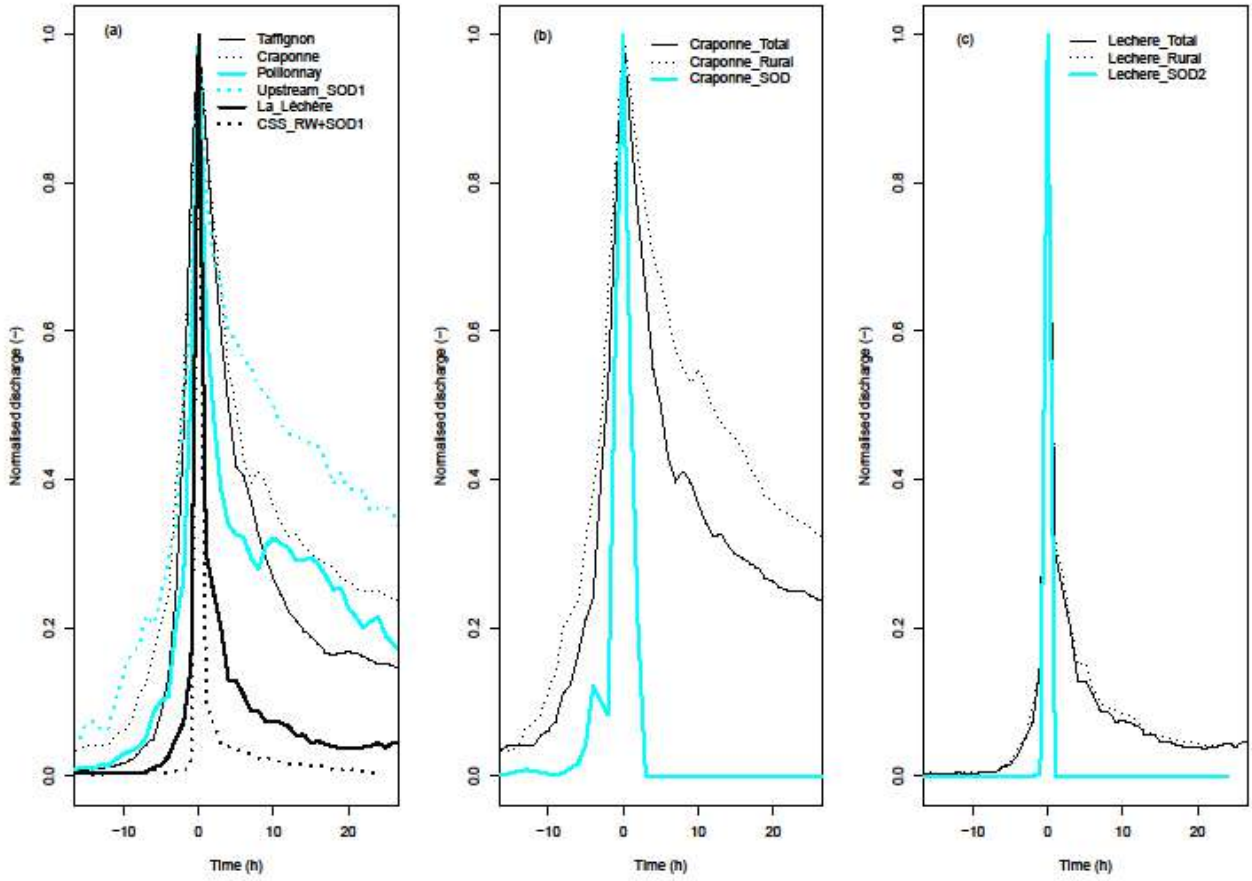
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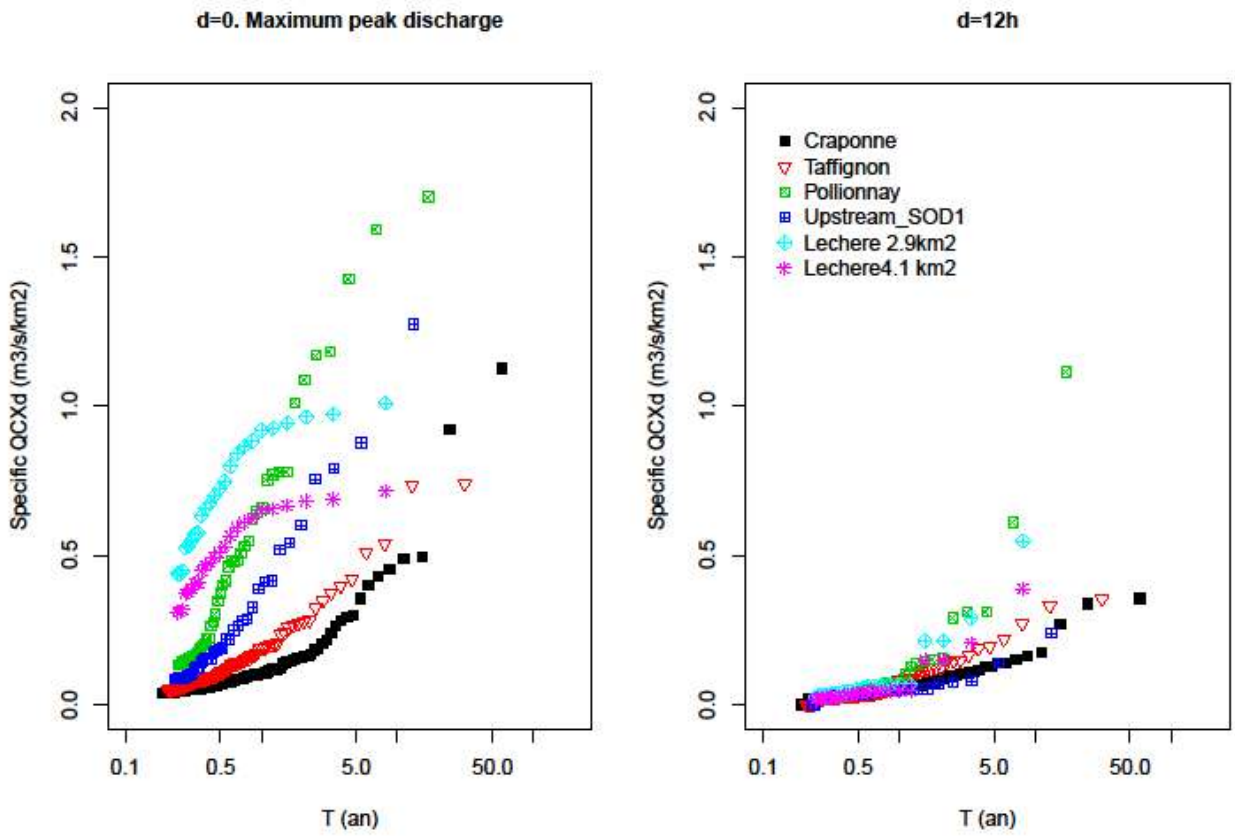
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1Figure 10

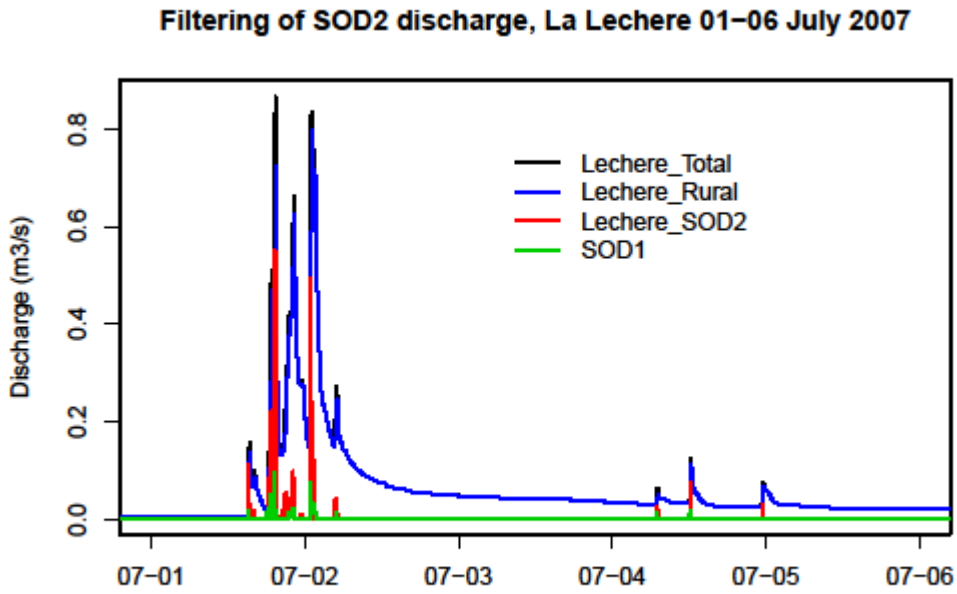



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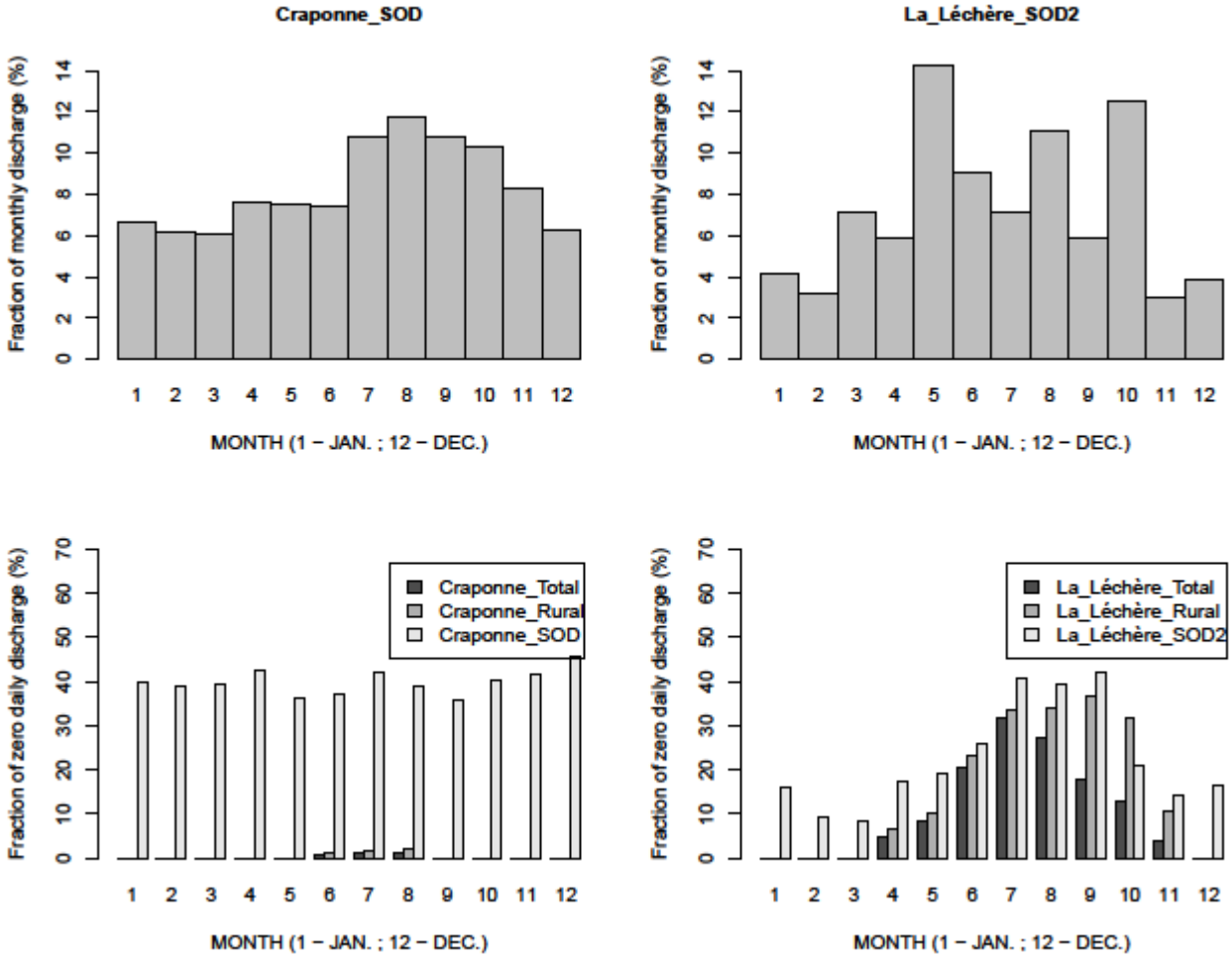
1Figure 11




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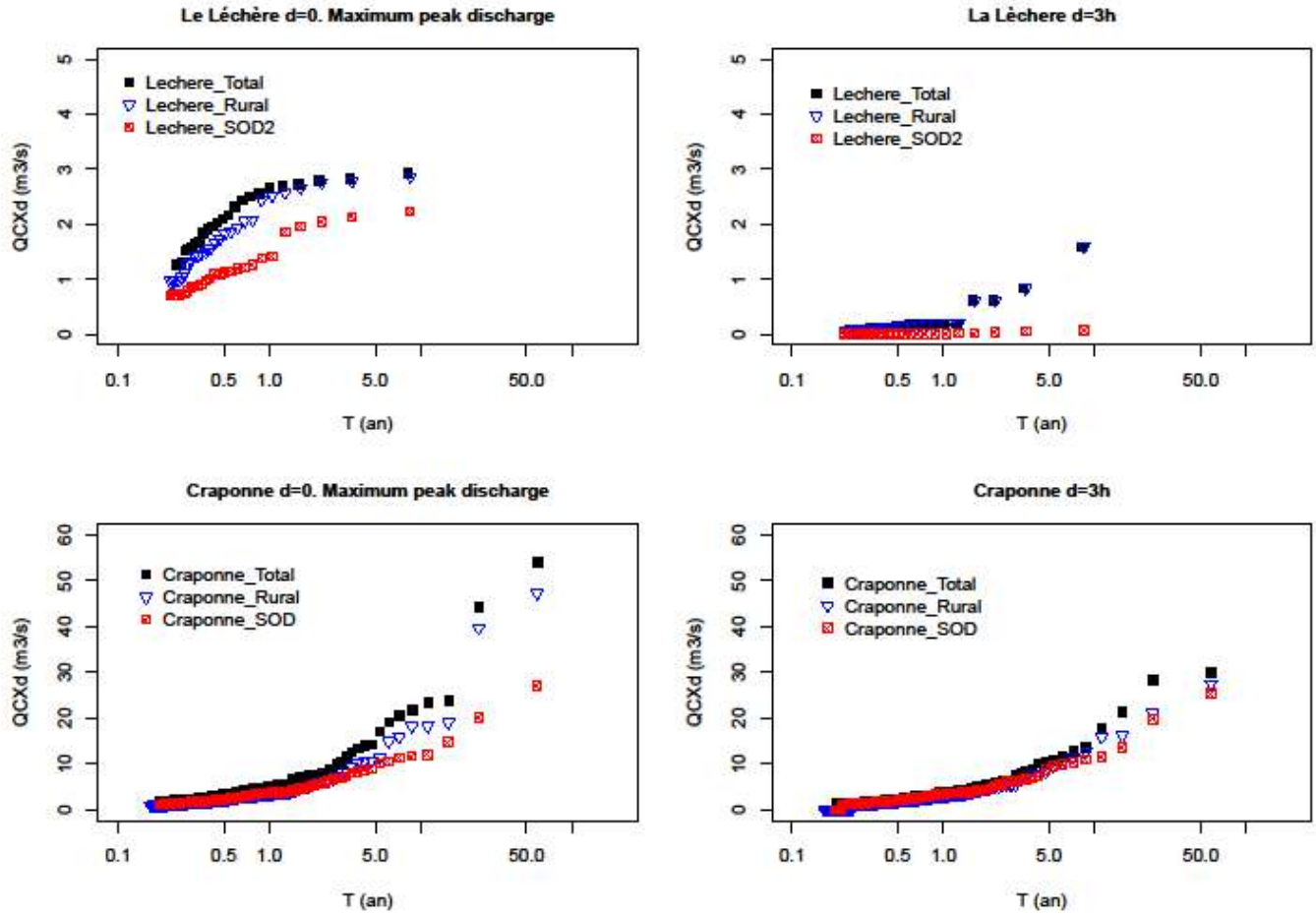
1Figure 12




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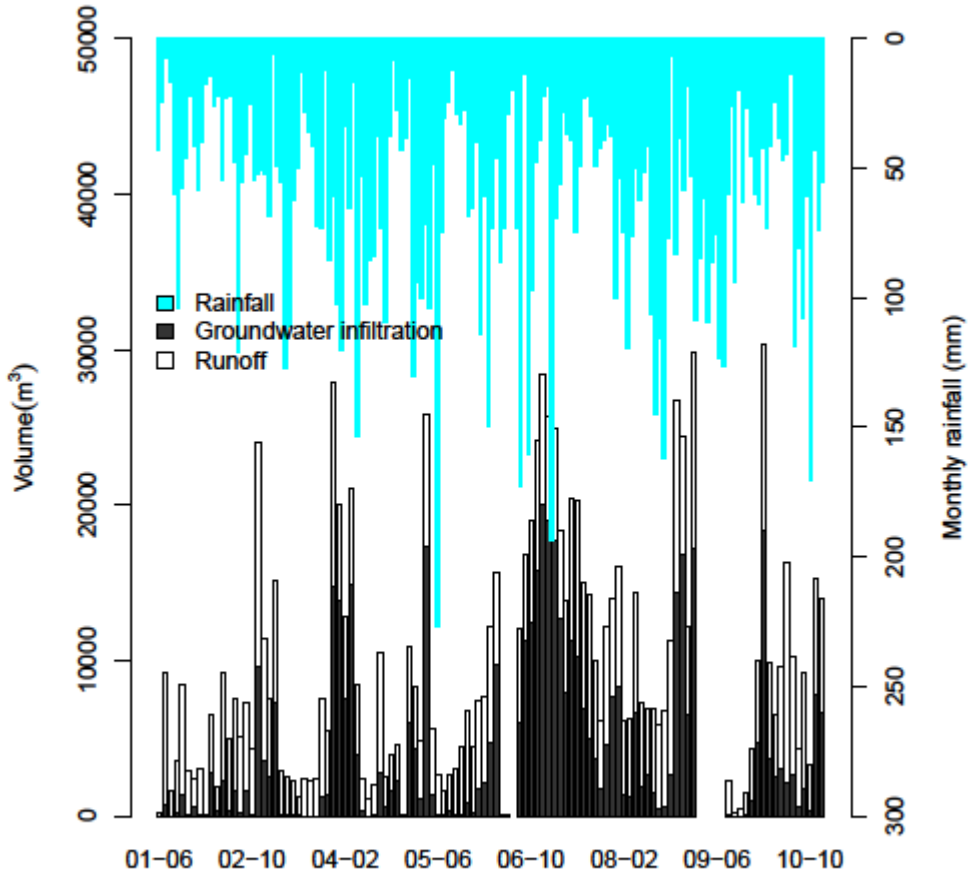
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1Figure 14




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