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4 Braud, I., Breil, P., Thollet, F., Lagouy, M, Branger, F.

5

6 Irstea, UR HHLY, Hydrology- Hydraulics, CP 220, 3bis Quai Chauveau, F-69336 Lyon,
7 France

8

9 Jacqueminet, C., Kermadi, S., Michel, K.

10 Université de Lyon, UMR CNRS EVS, 18 Rue Chevreul, 69363 Lyon Cedex 7, France

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22 Corresponding author: Isabelle BRAUD, Irstea, UR HHLY, CP 220, 3bis Quai Chauveau, F-
23 69363 Lyon, France. Isabelle.braud@irstea.fr

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32

1Abstract

2In this paper we explore several indicators to evidence the impact of land use change, and
3particularly of urbanization/artificialization on discharge series of periurban catchments. A
4first set of indicators is derived from the literature and describes the monthly and annual
5hydrological regime, low flows and high flows, and flow components. Statistical tests are also
6applied to assess the existence of trends/ruptures on the longest time series. In addition, new
7indicators, especially built to show the impact of Sewer Overflow Devices (SODs) and
8infiltration into sewer networks are proposed. The method is applied to the Yzeron (150 km^2)
9catchment, located close to Lyon city (France) where various discharge gauges with a variable
10time step are available on sub-catchments ranging from a few to 130 km^2 (some of them
11nested), with a large variety of land uses (forest, agricultural land, artificialized areas). In
12addition, discharge is also measured in a SOD and a combined sewer network so that the
13relevance of the new proposed indicators can be assessed. In the largest sub-catchments, the
14results show a decrease of specific discharge from upstream to downstream corresponding to
15an increase of artificialized areas, except for high flows. When a SOD is present, the specific
16discharge is increased for frequencies larger than 50%, and the frequency of zero daily
17discharge is decreased. Waste water can be the only source of water in autumn month in a
18 4.1 km^2 sub-catchment. Base flow is also decreased for the most urbanized catchments. Our
19results confirm the impact of SODs on the modification of the flood regime, with an increase
20of frequent floods, but a marginal impact on the largest floods, mainly governed by saturation
21of the rural parts of the catchments. The decomposition of the sewer discharge shows that, on
22an annual basis, infiltration in the sewer network accounts for 30% of the total discharge and
23runoff due to rainwater to about 40% (the remaining being composed of the waste water
24discharge). It can explain the decrease of base flow. Our analysis shows that, for periurban
25catchments, a long term monitoring of nested sub-catchments and infrastructures (SODs,
26sewer networks) with a small time step, is very valuable and provides data allowing a
27quantitative assessment of the impact of urbanization on the whole hydrological regime.

28

29Keywords: Suburban/periurban rivers, hydrological regime, high flow, low flow, impact of
30urbanization

11. Introduction

2

3Projections of population growth states that about 60% of the worldwide population is
4expected to live in towns in 2030 (Paul and Meyer, 2001). Around big cities, periurban areas
5are often the most affected by the corresponding urbanization (e.g. Meija and Moglen., 2010).
6In this paper, the word periurban, used in Europe and Australia, will refer to catchments made
7of a mixture of natural or agricultural lands, and urbanized areas. In the US, the word
8suburban is most often used, but it refers generally to residential areas with houses and
9gardens. Urbanization increases imperviousness of previously natural or agricultural areas.
10Construction of built-up areas is generally associated with the building of artificial structures
11such as road networks, drinkable, rainwater or sewer networks. These changes have an impact
12on the water cycle and aquatic ecosystems, due to the increase and acceleration of surface
13runoff, decrease of groundwater recharge and a modification of natural water pathways due to
14the artificial networks (e.g. Bras and Perkins, 1975; Chocat et al., 2001; Booth et al., 2002;
15Randhir, 2003; Matteo et al., 2006; Marsalek et al., 2007). This can lead to flooding, pollution
16and erosion problems within periurban rivers. In some areas, equipped with Combined Sewer
17Systems (CSSs), Sewer Overflow Devices (SODs) are introduced. When the sewer network is
18overflowed, it delivers polluted water to the river. This can lead to incision and erosion
19problems, which perturb the ecological status of the rivers (e.g. Hatt et al., 2004; Walsh et al.,
202005; Lafont et al., 2006). In addition, periurban catchments have a complex structure, made
21of a mixture of natural, agricultural and urbanized areas, and are evolving very quickly (e.g.
22Beighley et al., 2003; Radojevic et al., 2010; Jankowfsky, 2011).

23Studies of land use change impact on the hydrological regime generally analyse long term
24time series or long term simulations, and not only events. The objective is not to reproduce
25some historical events for sizing hydraulic works, but to get an appraisal of the change of the
26whole river regime. Appropriate criteria and indicators relevant to reveal the impact of land
27use change on this river regime must therefore be defined. In the following, the discussion
28will be restricted to indicators related to quantitative hydrology. Lots of other indicators have
29been defined to quantify the ecological status of receiving waters, based on chemistry,
30biology, etc (e.g. Walsh et al., 2005), in particular in Europe with the Water Framework
31Directive. But they are beyond the scope of this paper. In the remaining of the paper, the word
32indicator will be used in a broad sense and will include both hydrological variables and
33quantities derived from discharge data analysis.

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

17

18

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

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

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

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

1or their rate of change. These indicators are the number and duration of exceedance of
2multiple of the annual discharge. These indicators are relevant to identify quick disturbances
3in hydrographs.

4Finally the fifth class of indicators is based on statistical analyses of discharge time series,
5mainly relevant when long time series are available. This includes the results of statistical
6tests, comparing if differences between various periods are significant (e.g. Tong, 1990;
7Wang et al., 2007; Radojevic et al., 2010), the results of trend analysis (e.g. Claessens et al.,
82006). The results of regression analysis or neural network models, proposed by some authors
9to relate hydrological characteristics to climate or landscape variables such as imperviousness
10(Tetzlaff et al., 2005; Dow, 2007; Wang et al., 2007; Arrigoni et al., 2010) can also be
11included in this fifth class.

12

13In urbanized areas, as can be seen from Table 1, the analysis is often restricted to mean annual
14runoff (Beighley et al., 2003; Claessens et al., 2006); high flow with indicators such as annual
15peak discharge (Beighley et al., 2003; Burns et al., 2005), QdF analysis (Radojevic et al.,
162010) and/or to the study of selected events (Ott and Uhlenbrook, 2004; Chormanski et al.,
172008; Meierdiercks et al., 2010). But this may not be sufficient for all applications, in
18particular when addressing the quality of receiving waters. For ecological problems, the
19whole hydrological regime, and in particular low flows are also important. Walsh et al. (2005)
20suggest that a good target for the rehabilitation of rivers affected by urbanization would be to
21go back to “near natural” surface flow conditions. This requires the characterization of the
22whole range of discharges. Indicators of Hydrological Alteration (IHA) spanning all the
23hydrological regime to compare pre and post river flow management with an emphasis to
24stream ecology are proposed by Richter et al. (1996, 1997, 2003). It includes timing of annual
25extreme water conditions; frequency and duration of high/low pulses; rate/frequency of water
26condition changes. Jacobson (2011) also provides a review of the impact of imperviousness in
27urban catchments.

28Response times of impervious areas are much shorter than those of natural areas. For small
29periurban catchments, with response time of less than one day, indicators based on daily
30discharge may not be fully relevant. In addition, given the very short functioning time of
31SODs, specific analyses are required to fully evidence the impact of the urban areas on the
32river flow, especially for small catchments (a few km²). Therefore the analysis of indicators
33based on smaller time steps should be contemplated. Some authors also suggest that
34periurbanization mainly affect frequent floods (e.g. Radojevic et al., 2010) like observed

1when studying the impact of forest or deforestation on floods (Bathurst et al., 2011).
2Therefore indicators based only on peak discharge or extreme events may not be relevant for
3assessing the impact of urbanization on the water regime, and the whole range of floods must
4be investigated. Another specificity of periurban catchments is the impact of sewer networks,
5installed to manage both waste water and rainwater. In general those networks are not
6watertight and infiltration of clear water in the sewer system is very common (e.g. Breil et al,
71993; Berthier et al., 2004; Rodriguez et al., 2008). This may have an impact on the low flow
8within the rivers (e.g. Gufstafsson et al., 1997) and should also be considered.

9In order to characterize the impact of urbanization on periurban rivers discharge, paired
10catchments studies, comparing a natural and an urbanized catchments would be the best way
11to get the answer. When trying to assess land use change impacts on discharge, it is also
12sometimes difficult to distinguish between climate variability and land use impact (e.g.
13Ashagrie et al., 2006). Sub-periods comparison for instance may be affected by climate
14variability which can lower the significance of the results. Some authors have proposed
15methods to filter climate variability and highlight the impact of land use by removing climate
16variability using regressions from a reference period, in general considered as undisturbed
17(e.g. Dow, 2007; Wang et al., 2007; Arrigoni et al., 2010). However, those methods may be of
18limited use when recorded data have started as the same time as urbanization (i.e. in the
191970s, as it is the case in France). And it is not obvious to find “natural” catchments other
20things being equal. Therefore, there is a need to develop specific methods which cope with
21existing data series and try to separate the impact of land use change/ urbanization/
22management structures from the natural variability of discharge time series. This direction is
23explored in this paper for small to medium-sized periurban catchments, that range from some
24hectares to some tenth/hundreds of squared kilometres. This analysis is complementary to the
25set of indicators identified in the previous literature review.

26

27The objectives of the paper can therefore be stated as follows: are we able to define indicators
28revealing and possibly quantifying the impact of land use change and in particular
29artificialization on the hydrological regime of small to medium size periurban catchments?
30The study is conducted in two steps. First some indicators characterizing the discharge time
31series, derived from the above cited literature, are assessed. Then, given their identified
32limitations, essentially in taking into account the effect of sewer systems and SODs, specific
33approaches, adapted to periurban catchments are introduced and discussed. The methods are
34applied to the Yzeron catchment, located close to the city of Lyon, France where quite long

1time series of both rainfall and discharge are available for nested sub-catchments
2encompassing various ranges of urbanization and sizes. The results are discussed in order to
3define the advantages/limitations of the retained indicators.

4

5**2. Case study**

6**2.1. Context of the study and presentation of the catchment**

7The Yzeron catchment (150 km^2) is located to the south-west of Lyon city (Figure 1). It forms
8part of the Observatoire de Terrain en Hydrologie Urbaine (OTHU, 2011) long term
9observatory. It is representative of French periurban areas and is characterized by a marked
10topography (Figure 1). The outlet reaches the Rhône river at the elevation of 162 m and the
11highest points culminates at 917 m above sea level. The slope map calculated from a 25 m
12resolution Digital Elevation Model (DEM), derived from IGN BDTopo® shows that more
13than 50% of the catchment has slopes larger than 10% (Gnouma, 2006). The geology is
14contrasted with crystalline formations (granite, gneiss) in the western part of the catchment
15and more alluvial and glacier formations in the eastern part. This led to a complex soil types
16map with 22 cartographic units identified in the soil map (SIRA, 2011). The land use is
17heterogeneous. The upstream and western part of the basin is limited by a range of hills
18covered with forests. The intermediate part is mainly covered with grassland and cultivated
19lands, mixed with urban nucleus. Thin green corridors remain along rivers, covered with
20deciduous trees. The downstream part is mainly covered with densely urbanized areas (Figure
212c).

22A fast progression of urbanization is observed since the eighties (Cottet, 2005; Gnouma,
232006, Radojevic et al., 2010). This evolution generally develops in the form of small urban
24centres that expand from old villages, along road networks, following topographic constraints
25that are imposed by the river networks. A recent analysis was conducted to quantify the
26increase of urbanization in this catchment (Jacqueminet et al., 2011; Kermadi et al., submitted
27for publication). A manual digitalization of aerial photographs allowed the identification of
28artificialized surfaces including the urban parcels, parkings, industries and their green fraction
29(gardens, parks) (Figure 3). The percentage of artificialized surfaces was 22% of the
30catchment area in 1970, 33% in 1990 and 36% in 2008 (Figure 2), showing a slight decrease
31in the rate of urbanization between 1990 and 2008, as compared to the period 1970-1990. A
32similar analysis based on SPOT images analysis allowed the quantification of impervious
33areas which were found to cover 15% of the catchment area in 1990, 18% in 1999 and 23% in

12008. 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 km², 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
11pollutants, 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

222.2. 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 km² grid is also available for the grid points

1covering the Yzeron catchment over the 1970-2010 period with an hourly time step. This data
2set is the only one available to document the climate (air temperature and humidity, wind
3speed, long and short wave radiation). The SAFRAN data were used to compute the reference
4evapotranspiration, PET, following the FAO (1998) method.

5

6Stream flow data: Two gauges from the national HYDRO data base, maintained by DREAL
7Rhône-Alpes are available on the catchment: the Craponne station (48 km^2) since 1969, and
8the Taffignon station (130 km^2) since 1988 (Figure 1). These two stations are nested. The data
9are available with a variable time step. Three other stations from Cemagref are also available.
10They sample the Mercier (7 km^2), Chaudanne upstream a sewer overflow device
11(Upstream_SOD1) (2.19 km^2), Chaudanne at La Léchère ($2.9\text{-}4.1 \text{ km}^2$) experimental sub-
12catchments (Figure 1). The last two stations are nested. The data are registered with a variable
13time step. In addition, in the Chaudanne catchment, data are collected at the outlet of the
14sewer overflow device (SOD1) since 2001. Discharge is also measured since 2001 in the
15combined sewer system (CSS) which is directed to the WWTP but sometimes overflows in
16the SOD1 (Figure 3). The main characteristics of the gauging stations are summarized in
17Table 2 and Figure 4 provides the land use encountered within the sub-catchments, using
18three main classes: wooded areas, agricultural land and artificialized areas. We must also
19mention the existence of additional SODs just upstream the gauging stations of La Léchère
20(SOD2) (Figure 3) and Craponne. The methodology presented in section 3.2 will be used to
21assess the impact of these SODs on the discharge measured at the downstream gauging
22stations.

23The discharge gauging stations network is quite original due to the range of scales and variety
24of land uses which are sampled (Table 2 and Figure 4). The length of the series is also very
25valuable to evidence the impact of land use change on river discharge.

26

27*2.3. Summary of previous researches*

28The Yzeron catchment is studied for about 20 years. In the following, we only summarize the
29studies directly related with hydrology and water fluxes. Radojevic (2002) and Radojevich et
30al. (2010) analysed the rainfall and stream flow data (Craponne and Taffignon stations) over
31the 1969-1978 and 1988-1997 decades. The rainfall series showed significant differences
32between both decades, with an increase of maximum daily rainfall in the 1988-1997 period.
33This analysis was updated using the climatic data presented above (Bron rainfall daily time

1series and SAFRAN daily climatic data) in order to detect possible changes in the
2climate/rainfall forcing (Kermadi et al., 2011; Braud, 2011). On the rainfall data, a significant
3increase (Mann Kendall test (Mann and Whitney, 1947) at the 5% level) of the annual
4maximum of 5, 10, 15-day cumulative rainfall was found for the Bron station in the 1920-
52010 period, with a rupture detected in 1974 by the Pettitt test (1976). No significant
6trends/ruptures were found when the period was restricted to the 1970-2009 period. The
7analysis of the daily SAFRAN data on the 1970-2009 period showed a significant increase (at
8the 1% level) of the annual mean temperature of 0.52 °C every 10 years. But no significant
9trend in annual PET was found. On the other hand, the Pettitt test show a significant (at the
105% level) rupture of the annual PET in 2002, which will have to be confirmed in the future.
11From all the results obtained on the daily rainfall, temperature and PET data, we concluded
12that it was unlikely that change in the rainfall and climate could have affected the
13hydrological regime on the 1970-2010 study period. However, in the context of urban
14catchments with short response times, such an analysis should also be conducted with shorter
15time steps. It will be done when longer short time step rainfall series will be available (they
16are presently only 25 years long).

17In the study by Radojevic et al. (2010), the stream flow series showed an increase of frequent
18floods, whereas large floods were not so affected. The change in frequent floods was
19attributed to the impact of urbanization. Radojevic et al. (2010) also used a modelling
20approach to asses the possible impact of urbanization on the hydrological regime, through the
21impact on the discharge – duration – frequency (QdF) curves. But their analysis is restricted
22to two short periods of about 10 years, and more than 10 years additional data are now
23available. Gnouna (2006) analysed the data from the Craponne, Mercier and Chaudanne sub-
24catchments, and tried to propose monthly water balance. The analysis was restricted to the
251997-2004 period.

26In the present study, the discharge data analysis will be extended to include the whole
27available period (until 2010) and all stream flow gauges will be considered. The aim is the
28assessment of indicators, relevant to evidence the impact of land use change on the discharge
29time series. These indicators include annual and monthly discharge, base flow index, peak
30over threshold (POT), QdF analysis and flow components deduced from hydrographs
31decomposition. The analysis provides elements for a better understanding of the catchment
32behaviour, both for its rural and urban components. The derived data and synthesis are also
33useful for the evaluation/validation of the models developed within the AVuPUR project.

34

1

23. Methodology

3In section 3.1, we first assess indicators taken from the five classes that were identified in the
4literature review, as our objective was to qualify the impact of land use change and
5urbanization on the whole hydrological regime: flow duration curves, low flows, high flows.
6The flow components derived from the hydrograph decomposition were also considered as
7urbanization is suspected to increase quick flow and decrease base flow. Finally, as one of the
8discharge series was long enough, statistical tests (trends/ruptures) were also applied to this
9time series.

10In section 3.2, we present methods specifically developed to evidence the impact of sewer
11systems and sewer overflow devices (SODs) on the river discharge time series.

12

133.1. Indicators derived from the literature

14The objective of this analysis is to describe and characterize the discharges time series at a
15given location. Whenever possible the indicators will be adapted/normalized so that
16comparison between different catchments of various sizes and/or various land use become
17possible.

18 Hydrological regime:

19For the characterization of the hydrological regime (annual, monthly and daily time step), the
20variable time step stream flow data were first interpolated to a 30 (respectively 60) minutes
21time step for the Polionnay, Upstream_SOD1, La Léchère stations (respectively Craponne
22and Taffignon stations) and then aggregated to daily, monthly and annual time step from
23which the hydrological regime was calculated (Sauquet et al., 2000, 2008). Missing daily
24values were replaced by the interannual monthly average corresponding to the month of the
25missing data.

26From the daily discharges we also derived the flow duration curves (FDCs). They are
 27obtained by ordering all the daily discharge values in decreasing order. Each ordered
 28discharge value Q_f is associated with an empirical frequency which is the probability of
 29finding a value Y , larger or equal to Q_f .

$$30 \quad \Pr ob(Y \geq Q_f) = \frac{r}{N} \quad (1)$$

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

32

1In order to compare data from catchments of different sizes and identify the possible impact
2of land use on the discharge, it is convenient to normalize the discharge data before
3calculating the flow duration curves. The most obvious choice is to compute specific
4discharges by dividing all the data by the catchment area. The advantage is that this method
5provides water heights comparable to rainfall heights, which can be directly used to compute
6the water balance or runoff coefficients. However, in periurban catchments, especially
7equipped with combined sewer systems, this is not so obvious (Jankowfsky, 2011).
8Jankowfsky (2011) shows that, in such catchments, the boundary is not only dependent on
9topography, but is influenced by the sewer systems. The areas connected to the river via sewer
10overflow devices are only contributing to the streamflow when the sewer systems overflows.
11In addition, only part of this runoff drains into the river, because part of it continues to reach
12the Waste Water Treatment Plant (WWTP). For the Chaudanne at La Léchère catchment,
13Jankowfsky (2011) shows that under dry conditions, the area of the catchment is 2.9 km²,
14whereas it reaches 4.1 km² when all the SODs are activated. This result shows that using the
15specific discharge in periurban watersheds may lead to some problems and that this quantity,
16as well as runoff height and runoff coefficients must be used with caution.

17The second option is to normalize discharge data with the average annual discharge (e.g.
18Sauquet et al., 2008). This indicator is independent of the catchment area estimation.
19However, if the mean annual discharge changes with time due to land use modifications, this
20may bias the results. Comparison between catchments is therefore more difficult and only
21normalisation based on specific discharges will be discussed in the remaining of the paper.

22Low flows:

23The base flow was estimated using the Tallaksen and Van Lanen (2004) algorithm on the
24daily data. The base flow was estimated by linear interpolation between n points
25corresponding to the local minima of n periods of 5-days duration without intersection. The
26BFI (Base Flow Index), which is defined as the average of the base flow divided by the mean
27interannual discharge of the time series, was selected in this study. It is a non-dimensional
28index which allows comparison between catchments. Low flow were also characterized with
29the frequency of zero daily discharge (Richter et al., 1996).

30High flows:

31Variable time step discharge time series were used for the discharge- duration- frequency
32analysis (QdF). The method provides a theoretical description of floods for several durations.
33The studied variable was the maximum discharge continuously exceeded during the duration
34 d , QCX_d (Figure 5a) The analysis was performed in several steps.

1 • A characteristic flood duration was estimated for each gauge. The analysis was performed
2 using data from which the base flow (calculated as described above) had been removed. As
3 the base flow data were available at the daily time step, an interpolation of base flow at the
4 variable time step was performed before removing it from the variable time step time
5 series. An automatic program has been developed which selects the hydrographs around
6 major floods. A discharge threshold, determined from the POT analysis (see below) is
7 prescribed for the events selection and all the floods higher than this threshold are retained.
8 Each hydrograph is scaled by its maximum peak discharge Q_{max} . Therefore all the
9 hydrographs have a maximum value of 1 (and can be compared amongst catchments). From
10 all the hydrographs, we compute the median hydrograph. The characteristic flood duration
11 θ is then calculated as the duration where $Q/Q_{max} = 0.5$ in this median hydrograph (Figure
12 5b). An iteration with the next step may be required to properly fix the discharge threshold.

13 • The next step is the extraction of independent values of floods for various durations d . One
14 value per year (annual maximum) can be extracted, but in order to increase the sample size,
15 the Peak Over Threshold approach was used. We tested extractions with an average of 2
16 and 4 floods per year in the analysis. As we are interested not only in extreme floods but
17 also in frequent floods and given the shortness of some of the time series, the extraction
18 with 4 floods per year was finally used and will be presented below. The corresponding
19 threshold was automatically determined so that the target average flood number per year
20 was obtained (Lang et al., 1999). The procedure also ensures independence of the selected
21 events. The analysis was performed on the hydrological years (from September 1 to August
22 31) for the instantaneous flood peak ($d = 0$) and for $d/8, d/4, d/2, d, 3d$. For the various
23 gauges, the duration d was chosen close to the characteristic flood duration θ determined in
24 the previous step. Next, the empirical probability of non-exceedance of the value x

25
$$\text{Prob}(QCX_d \leq x) = F(x) \quad (2)$$

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

28 Hydrograph separation:

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

1method of Willems (2009) includes a second parameter w , which corresponds to the average
2fraction of the sum of the quick and inter flow volume over the total flow volume. The
3filtering procedure is first applied to extract the base flow. It is then repeated to extract the
4interflow on the (total – base flow) time series. The values of the k and w parameters were
5determined manually by trials and errors so that the base flow fraction was close to the BFI
6determined previously. The analysis was performed for the Craponne and Taffignon data
7using daily data, and the Pollionnay, Upstream_SOD1 and La Léchère gauges, using two-
8hours time step data in order to capture the inter flow.

9Statistical tests:

10The Craponne gauging station was the only station with a long enough (40 years) time series
11to perform trend/rupture statistical tests. The Mann Kendall (Mann and Whitney, 1947) and
12Pettitt (1979) tests were used for trend and rupture analyses respectively. The analysed
13variables were the mean annual discharge, BFI, components of the flow as derived from the
14hydrograph separation, the POT values (using an extraction of two and four floods per year
15on variable time step time series), following the methodology proposed by Renard et al.
16(2006) and Lang et al. (2006).

17

18***3.2. Methods specific to the existence of sewer overflow devices and sewer*** 19 ***networks***

20As said before, given the quick response time of the urban parts and the very short
21functioning time of SODs, the indicators proposed in the previous section are not sufficient to
22fully evidence the impact of the urban areas on the river flow, especially for small catchments
23(a few km²). Therefore, we propose specific methods, particularly adapted to these conditions.
24These methods rely on filtering techniques of the discharge time series. Two types of
25applications were developed (Table 3):

26Filtering of SODs discharge to derive “pseudo-natural” discharge series. In order to get a
27clear signature of the SOD on the river discharge time series, the SOD must be located
28upstream and close to the discharge gauging station (10 to 100 m). The filtering method is
29applicable to variable time steps time series as it takes benefit of the fact that, in case of SOD
30overflows, the discharge will increase rapidly and the measurement points will be more
31frequent. The filtering is based on a moving average with a *constant* number of points.
32Therefore the time step of the filtering will be much shorter when the response is quicker
33(activation of the SOD) than when the response is slower. The method was applied to the La

1Lèchere and Craponne stations where a SOD is present less than 100m upstream, with a 4
2points moving average. This leads to two additional time series corresponding to the SOD
3discharge (indexed SOD in Table 3) and the river discharge if the SOD was absent (indexed
4Rural in Table 3).

5Filtering of the combined sewer systems discharge (CSS) series. In this case, the method
6allows the separation of the measured discharge between waste water (WW), parasite clear
7groundwater infiltration in the sewer network (GW) and the runoff component (RW). Its
8application combines times series of Combined Sewer System (CSS) discharge, rainfall data,
9SOD discharge (when a SOD is present). Contrarily to the previous case, the filtering method
10is applied to fixed time step time series (in our case 6 min time step given the size of the
11catchment and the response time) in order to process simultaneously the various time series.
12The fixed time step time series are obtained from linear interpolation of the variable time step
13times series.

14The principles underlying the method are summarized in Figure 6 and detailed below.

15 • Step 1: determination of the WW fraction. This step is conducted in two phases. Step1a:
16 During the night, as the catchment is quite small, it is assumed that the waster water (WW)
17 is zero. In dry period conditions, the discharge measured in the sewer system during the
18 night can therefore be assumed to be clear parasite groundwater infiltration (GW). This GW
19 water is obtained by using a moving average tracking the daily minimum discharge (in our
20 case a moving average calculated using 240 points, corresponding to 24h of 6 min time step
21 data). Step 1b: This clear parasite water infiltration is subtracted from the CSS discharge,
22 leading to a residual time series (CSS – GW). To estimate the waste water discharge, it is
23 assumed that, during dry weather periods, the CSS-GW discharge is equal to the waste
24 discharge (WW). A weekly averaged cycle is calculated from the 6 min time step data
25 during dry weather. This weekly cycle takes into account week and week-end days that
26 have specific patterns.

27 • Step 2: The WW series is substracted from the CSS data. This leads to a time series of
28 runoff + infiltrated groundwater data (RW + GW). The same moving average tracking the
29 daily minimum discharge is applied once again to separate the RW and GW discharges.

30 • Step 3: If a SOD exists, its contribution is added to the runoff because the water which
31 overflows the SOD is also generated by runoff. This leads to the final value of the runoff
32 series (RW + SOD).

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

4

5 **4. Results**

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

9

10 **4.1. Analysis of observed discharge time series**

11

12

13 4.1.1. Hydrological regime

14 Table 4 provides the values of the mean annual discharge (and specific discharge when
15 relevant) and 50% quantile of the FDC. Figure 7 shows the average monthly specific
16 discharge for the 5 gauged stations for the 2005-2010 common measurement period. Table 4
17 and Figure 7 show that the “rural” catchments have an average annual specific discharge
18 ranging between 5.5 and 6.9 l s⁻¹ km². They also exhibit similar monthly patterns with higher
19 values in spring and winter and low discharge in summer and autumn (Craponne, Polionnay,
20 Upstream_SOD1). On the other hand, the Taffignon station exhibits systematically lower
21 monthly specific discharge than its upstream gauging station Craponne. This is also reflected
22 in the average annual specific discharge which is only 5.1 l s⁻¹ km² as compared to 6.9 l s⁻¹
23 km² for Craponne. An analysis of the annual runoff coefficient (not shown) confirms that the
24 Taffignon values are systematically lower than those of Craponne and the difference in mean
25 (0.26 for Craponne and 0.21 for Taffignon) is significant at the 5% level ($p=0.02$ for the t-
26 test). Figure 7 shows that the La Léchère station (when considering the most favourable case
27 with a 2.9 km² catchment area) has larger values of average monthly discharge than its
28 upstream station (Upstream_SOD1) in summer and autumn (May to October). It can be
29 explained by a larger contribution of artificialized areas in summer (see section 4.2.3).

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

1the whole range of discharges (except high flows – see section 4.1.3). The downstream
2La_Léchère station has significantly higher values than the Upstream_SOD1, which is much
3less urbanized than the La_Léchère station (Figure 4), for the frequencies larger than 40%.

4

54.1.2. Low flows and hydrograph separation

6Low flows are characterized using the % of zero daily discharge and the BFI (Table 4). For
7the gauged catchments, the % of zero daily discharge ranges between 0.25% (Craponne) to
831% (Upstream_SOD1). Note that the Taffignon gauge has a larger frequency of zero
9discharge (5.4%) than the upstream gauging station Craponne. This confirms the decrease in
10runoff production, already observed on the annual specific discharge and the FDC, from
11upstream to downstream. On the other hand, the % of zero daily discharge decrease from
1231.2% Upstream_SOD1 to 11.1% at the downstream La Lèchère station (see also Figure 8a).
13This increase can be attributed to the impact of urbanization as the additional area is mainly
14composed of artificialized areas (Table 4).

15

16The BFI values of the observed time series range between 0.26 and 0.54. Those values are
17quite low and are characteristic of catchments with a low storage capacity. For the catchments
18with the lowest % of artificialized areas (Upstream_SOD1 (24%), Pollionnay (11%),
19Craponne (18%)), the BFI increase with the catchment area, consistently with a decrease of
20the % of days with zero discharge (Table 4). The behaviour of the Taffignon station is, once
21again, inverse to what is expected: the BFI decreases between the upstream Craponne and
22downstream Taffignon stations. The lowest specific annual discharge could therefore be
23explained by a lower base flow.

24

25Table 5 shows the results of the discharge decomposition into base flow, inter flow, quick
26flow using the WETSPRO tool. The two small rural catchments (Pollanday and
27Upstream_SOD1) have similar values of the k recession constant (5 days). The quick flow
28represents 43.5% of the total flow for the Pollanday station and 49% for the Upstream_SOD1
29catchment. This can be explained by the difference in land use (mainly forest and crops for
30Pollanday and crops for Upstream_SOD1), and because crop land has been shown to have a
31lower infiltration capacity than forest (Gonzalez-Sosa et al., 2010). The recession constant of
32the La_Léchère station is smaller than that of the upstream station Upstream_SOD1, and the
33% of quick flow is higher (54.4% against 49%), with a lower base flow. This shows the
34impact of the SODs and the urbanized areas which is the dominant land use in the additional

1area between the two gauges. When comparing the Craponne and Taffignon stations, we can
2see that the k recession constant increase between the upstream and downstream gauge (28
3and 35 days respectively). However, the downstream Taffignon gauge has a smaller base flow
4(39.3% against 49.8%), as said before, and a higher portion of quick flow (37.6% against
525.6%). This corresponds to an increase of the artificialized surfaces (from 18% of the total
6catchment area at Craponne to 31% of the total catchment area at Taffignon – see Figure 4).
7This analysis confirms the expected impact of urbanization: an increase of quick flow at the
8expense of base flow, but this effect has been quantified here.

9

104.1.3. High flows

11The characteristic flood durations appear in Table 4. Figure 9a shows the normalised median
12hydrographs for the various observed time series. We remind that the base flow has been
13removed before performing the extraction. For all the catchments, Figure 9a shows that the
14rising limb of the characteristic hydrographs is very sharp (a few hours). On the other hand,
15the catchments with the lowest artificialized area (Craponne, Polionnay, Upstream_SOD1)
16have a quite heavy and long recession, although the characteristic duration, corresponding to
17 $Q/Q_{max}=0.5$ is short (between 3 and 7 hours, Table 4), except for Upstream_SOD1 where it
18reaches 10 hours. The most artificialized catchments (La Léchère and to a lesser extend
19Taffignon) present characteristic hydrographs with the sharpest rising limbs (less than 5
20hours) and a very quick recession (about 5 hours). Urbanization has therefore a significant
21impact on the hydrograph shape.

22The maximum daily discharge and their corresponding specific values are provided in Table
234. Figure 10 shows the result of the QdF analysis in terms of specific discharge, for durations
24 $d=0$ (maximum instantaneous peak discharge) and 12h for the 5 gauged stations. For all the
25stations, the flood discharge decreases sharply between the two durations, which is consistent
26with the peaky shape of the characteristic flood hydrographs (Figure 9a). For the duration $d=0$
27and for a return period of less than ten years, the highest floods are encountered for the
28Polionnay, Upstream_SOD, Taffignon and Craponne stations, in decreasing order. The most
29rural and natural catchment (Polionnay) appears the most productive in terms of high floods.
30Contrarily to what is observed for the monthly regime and the low flow, the downstream
31Taffignon station is most productive than the upstream Craponne one for high flows.
32Urbanization may be responsible for this larger runoff for the highest floods. These features
33also hold for the $d= 12$ h duration. The results for the La Léchère station are shown using the
34two extreme catchments areas. For the most frequent floods, the specific discharge for $d=0$, is

1significantly larger than that of the Upstream_SOD1 station, whatever the choice of the
2catchment area. We can deduce that the urbanization of the downstream part of the catchment
3increase the magnitude of the most frequent floods.

44.1.4. Statistical tests for the Craponne gauging station

5The results of the trend and rupture statistical tests performed on the Craponne time series
6(1970-2010) are summarized in Table 6. They show a significant decrease of the % of base
7flow and inter flow at the 5% and 1% level respectively, whereas the quick flow increase
8significantly at the 1% level. The increase in maximum annual discharge is not significant,
9nor the increase in maximum peak discharge. On the other hand, the POT analysis reveals a
10significant increase (at the 5 or 10% level) of the magnitude of floods for all the durations
11except $d=0$, when sampling the floods with two floods per year. If the sampling is performed
12to retain four floods per year, i.e to include less intense floods, none of the trend/rupture
13remains significant (not shown). These results show that a trend is only evidenced for the
14largest floods.

15

164.2. Application of the filtering methods

174.2.1 Evaluation of the SOD discharge filtering method

18The result of the filtering of SOD discharge is illustrated in Figure 11 for the La Lèchere
19station. This figure shows the initial time series, the calculated La_Léchère_SOD2 and
20La_Léchère_Rural time series. We have also added the SOD1 time series on the graph, in
21order to assess the relevance of the method. Although the La_Léchère_SOD2 seems to react
22much more frequently than the SOD1 (the frequency of zero daily discharge are 22.9 and 87%
23respectively, see Table 4), we can assume that when SOD1 is active, SOD2 should also be
24active. This can allow the validation of the timing of the filtering method. Figure 11 shows
25that the agreement is reasonable and similar results were obtained on the whole period. The
26total volume discharged by SOD2 represents 5.3% of the total discharge at La Lèchère
27gauging station.

28For the Craponne_SOD time series, no data were available for validation. The area drained by
29the SOD is estimated to be about 10% of the total catchment surface (Table 3). The total
30volume of the SOD discharge represents 7% of the total Craponne discharge. This figure is
31reasonable and comparable to that of the La Léchère catchment. In the near future, it will be
32possible to fully validate them, as the La Léchère and Craponne SODs are gauged since 2010.

1In the remaining of the paper, we will assume that the filtering method is accurate enough so
2that the corresponding data series can be analysed similarly to the truly gauged time series.

34.2.2. Hydrological regime

4When considering the reconstructed “rural” time series for the Craponne and La Léchère time
5series, the average annual specific discharge of the rural time series is 13% lower for the
6Craponne station and 5% for the La Léchère station (Table 4).

7This is confirmed (both for the Craponne and La Léchère station) by Figure 12 (top), which
8shows the fraction of the total average monthly discharge coming from the SODs. This
9contribution of the SODs to the monthly regime ranges from 2-3 to about 15% with a clear
10annual cycle. The highest values occur in summer and autumn, when the natural discharge is
11the smaller. In this period, the contribution of SODs to the discharge is therefore important in
12a period where the river can be dry (see next section). This can increase pollution problems,
13all the more than discharge is low and dilution effects cannot occur.

144.2.3. Low flows and high flows

15The frequency of zero daily discharge for the total, rural and SOD components of the
16Craponne and La Léchère stations (Figure 12, bottom), show very different behaviours
17between the two gauges. Whereas the frequency of zero discharge in the Craponne_SOD is
18quite constant throughout the year, it presents a clear annual cycle at La_Lèchère_SOD2.
19Values are higher in summer than in winter, which shows that the SOD2 is more frequently
20activated in winter, when the soil conditions are humid, than in summer when they are drier.
21For the two gauges, the % of zero daily discharge of the “rural” time series is systematically
22lower than that of the total discharge. For the La Léchère station, the difference can reach
2320% in September and October. It means that the discharge in the river only comes from the
24SOD2 during this period.

25We also see that, when the SODs contribution are filtered, the BFI values are larger than for
26the total discharge (Table 4), showing, as expected that SODs mainly contribute to quick
27flow.

284.2.3. Low flows and high flows

29Figure 9b and 9c show the normalized hydrographs for the total, rural and SOD components
30of the Craponne and La Léchère stations respectively. As expected the SOD hydrographs are
31very peaky with characteristics flood durations of about 1h. Although the total and rural
32hydrographs are very close for the La Léchère station, the rural Craponne series shows a

1much slower recession than the total curve with a doubling of the characteristic flood duration
2for the rural component. On this gauge, the impact of the SOD seems to be much influential
3on the hydrographs shapes than for the La Léchère catchment.

4Figure 13 shows the QdF analysis for the total, rural and SOD components of both the
5Craponne and La Léchère stations. This figure shows that, for the largest floods, the rural and
6total curves are very close. It suggests that the largest floods are mainly associated with a
7large contribution of the rural area. On the other hand, the impact of SODs is significant for
8frequent floods, with return period of less than 2 years.

94.2.4. Analysis of the sewer system components

10The mean annual values of the sewer discharge components are provided in Table 4. The
11waste water accounts for 33% of the total discharge, the rainwater runoff for 38% and the
12infiltration of groundwater into the sewer for 30%. The results of the filtering of the sewer
13discharge time series is illustrated in Figure 14 at the monthly time scale for the whole
14measurement period (2001-2010). It shows that the groundwater infiltration exhibits a clear
15annual cycle. It is almost zero in summer when the soil is dry and increases in winter and
16spring when the soil moisture is higher. The monthly pattern of rainwater runoff follows that
17of the monthly rainfall. Figure 8b shows the FDC of the CSS discharge and its various
18components. The FDC of the waster water (WW) is very flat as expected from its building.
19Values of CSS_RW+SOD1 below $0.001 \text{ m}^3 \text{ s}^{-1}$ can be considered as noise, which explain the
20low value of zero daily discharge (about 10% in Table 4). The average fraction of rainy days
21is about 50% and the CSS_RW+SOD component of the CSS discharge is only not null when
22it rains. For the values larger than $0.001 \text{ m}^3 \text{ s}^{-1}$, Figure 8b shows that the ranges of infiltrated
23groundwater and runoff discharges are very similar. Groundwater infiltration into the network
24is therefore a major problem for the efficiency of the sewer network. It may explain the larger
25activation of SOD2 in winter when the groundwater table is high (see Figure 12, bottom).

26

275. Discussion

28*The importance of data collection.* The analysis presented in this paper relies on a nested and
29complete network of gauging stations, monitoring discharges in sub-catchments with various
30land uses but also on some infrastructures such as SODs and sewer networks. The set up in
31the Chaudanne sub-catchment is very valuable, as it allows the quantification of the impact of
32SODs and infiltration into the sewer network. However, although lots of efforts were
33dedicated to monitor the various branches, it is still impossible to close the water balance of

1the catchment (uncertainty of the partition of water between SODs and the Waste Water
2Treatment Plant, partial measurements of the SODs).

3For the type of analysis presented in the paper, the data quality and length of the series is of
4prime importance. The data availability period is very variable (between 5 and 40 years).
5Except Figure 7, all the indicators are calculated using the largest available time series. Due to
6internanual climate variability, which is large in this catchment (the CV of average annual
7rainfall is 241 mm at Pollionnay for an average of 746 mm on the 1997-2009 period), this
8may induce sampling fluctuations of the indicators. We verified that the conclusions were
9similar when the indicators were calculated on the same period (2005-2010). Another
10important point is the accuracy of the discharge data. A diagnostic of the gauging stations
11showed that low flows are generally quite uncertain due to very large sections and a small
12water height (Pollanday, Upstream_SOD). This problem is being solved by adding a
13triangular device to get a higher accuracy for small discharges. The Craponne and Taffignon
14stations are considered reliable by their manager (DREAL) and therefore the decrease of
15runoff from upstream to downstream cannot be attributed to measurement problems. The La
16Lèchère station is the most accurate as it is equipped with a calibrated canal, but it may be
17overflooded for the largest discharges. This can explain the decrease in specific discharge for
18high flows (Figure 10). Branger et al. (2011) proposed a method to assess the accuracy of
19stage-discharge relationship and provide an error bound for each discharge measurement. The
20use of this information was beyond the scope of this paper, but will be useful to better assess
21the significant changes/trends. In terms of monitoring, progress is under way as new SODs
22are now monitored in the context of the quantification of rejected water in the receiving rivers
23(Water Framework Directive). These new data offer an opportunity to better understand the
24response of urbanized areas in periurban catchments and further validate the filtering method
25leading to the decomposition of total discharge into rural and SOD components. The
26Craponne subcatchment has a quite large area and it may be difficult to discriminate between
27the influence of the various infrastructures impacting the flow. The new discharges
28measurements in the SOD will be very valuable as they will allow a better assessment of the
29limits of applicability of the SOD filtering method.

30

31*Impact of artificialization on the regime and the flow components. Impact on low flows and*
32*the importance of the sewer network.* Two results of this study are particularly striking: the
33decrease of specific discharge from upstream to downstream between the Craponne and
34Taffignon gauges, and the large fraction (30% of the total discharge) of infiltration into the

1sewer system calculated for the Chaudanne subcatchment. This figure is high but consistent
2with independent estimation conducted using punctual measurements during the night by the
3services in charge of the network management. Recently Prigobbe and Guilianelli (2009)
4reported an infiltration of about 50% in the old Rome sewer network and 14% in a recently
5constructed area. Berthier et al. (2004) found that the contribution of soil water infiltration to
6runoff in sewer pipes was about 15% in a small residential periurban catchment. On the same
7catchment, Rodriguez et al. (2008) simulate 11% of infiltration into the rainwater sewer
8system and 18% in the wastewater sewer system. In the Yzeron catchment, the main pipes
9network was built along the valley bottom in the seventies to collect waters from the
10surroundings. Breil et al. (2010) analysed one year of discharge monitoring in the main sewer
11collector close to the Taffignon station. They estimated the infiltration into the network to be
1227% of the annual discharge. There is therefore a consistency in the results and infiltration
13into the sewer network can be considered as responsible for the decrease of base flow and
14average monthly discharge between Craponne and Taffignon. The impact of the SODs is also
15significant on low flows. They significantly impact the frequency of zero discharge and, for
16the smallest sub-catchments where the natural river regime is seasonal, water coming from the
17SODs is the only source of water during a significant part of the year. The impact in terms of
18water quality is of course important (Lafont et al., 2006). However, in order to conform to the
19water framework directive, the management of rainwater is being reconsidered: where
20possible rain waters are diverted to new separate sewers flowing to retention/detention basins.
21This process is under way in the Chaudanne catchment and should be monitored to quantify
22its future impact on the river discharge. Another lesson of this study is the importance of
23knowing precisely the catchments areas. This task is quite simple for natural catchments but is
24much more complicated for periurban catchments (Jankowfsky, 2011). However, such
25determination is essential to compare various catchments based on specific discharge. A
26normalisation with the mean annual discharge was attempted, but the interpretation of the
27results was not found relevant. This question of catchment area is therefore a major challenge
28for data interpretation and comparison in periurban catchments.

29*Impact on high flows.* The results obtained in this paper confirm that for the highest floods,
30the impact of urbanization (via the SODs) is limited. In this case, the rural part of the
31catchment is the major contributor to floods, which can be explained by saturation of the soil
32due to long rainfall events. It may be counter-intuitive to see that the most productive
33catchment for high flows is the less urbanized one (Polionnay). However, other studies
34(Sarrazin, 2012) have shown that the whole catchment is saturated during the largest floods

1(corresponding to long lasting events of at least 70-80 mm). The whole catchment area is
2therefore contributing to the flow, whereas a part of the rainwater is diverted towards the
3WWTP in the artificialized catchments, even if all the SODs are activated. Our results also
4confirm that SODs mainly impact frequent floods, as already shown by Radojevic et al.
5(2010) using model simulations. Urbanization and catchment artificialization have also an
6impact on the hydrographs dynamics as shown by Figure 9. The most urbanized catchments
7have more peaky flood hydrographs. In order to refine this type of analysis, approaches such
8as those proposed by Archer (2007), Archer et al. (2010) should be investigated in the future,
9as they allow a full exploration of the whole discharge series, by analysing the frequency and
10duration of exceedance of various threshold discharges. In the Yzeron catchment, it has been
11shown that these variables were very relevant to quantify the impact of SODs on the incision
12and bank erosion risk (Grospôtre, 2011). In the case of a upstream-downstream gradient of
13urbanization, like in the Yzeron basin, urban generated floods are flowing before the rural
14floods, avoiding peak flood accumulation. The effect of urbanization could be more sensitive
15and may be dramatic if impervious areas extension takes place upstream, increasing the
16probability of concomitancy between urban and rural floods (Ostrowski, 2000; Ostrowski et
17Bras, 2000.). Such an explanation may be invoked to explain the largest specific discharge of
18the downstream Taffignon station, as compared to its upstream Craponne one for high flows.
19Indeed, the Yzeron rivers receives a tributary flowing through a quite densely urbanized area
20before the Taffignon station.

21*Statistical tests.* Statistical tests were only applied to the longest Craponne time series. They
22highlighted a modification of the components of the flow, with a decrease of base and inter
23flow, and an increase of quick flow. The SODs in this catchment were installed between 1970
24and 1980 and therefore impact most of the available time series (1970-2010). There is also a
25significant increase of POT discharge (sampling with an average of two floods per year) for
26all the durations, except peak discharge. This can be put in parallel to the increase of
27artificialized surfaces in this catchment between 1970 (9%) and 2008 (18%), all the more than
28no significant change of maximum annual cumulated (1 to 15 days) daily rainfall can be
29evidenced. For the analysis of floods, an analysis of rainfall with a shorter time step (typically
30hourly) would be necessary but the available time series are too short up to now for such an
31analysis. In addition, those results on floods must be considered with caution as they are
32sensitive to the sampling strategy.

33*Towards a perceptual model of the Yzeron catchment behaviour.* From the data analysis
34presented before, we can propose a perceptual model of the Yzeron catchment hydrological

1functionning. The rural part of the catchment has a high infiltration capacity (Gonzalez-Sosa
2et al., 2010) but a small storage capacity. Therefore, for the small to medium events, the
3catchment response is mainly dominated by the quick response of urban areas for the
4formation of peak discharge and a delayed rural response mainly impacting the recession
5curve. Frequent floods are increased by the catchment urbanization. For the largest events
6(mainly long duration rainfall events), the catchment response is dominated by the rural
7response due to soil saturation. The river regime is also perturbed by the sewer systems
8through a high rate of infiltration of soil water which is diverted towards the WWTP and
9contributes to a decrease of base flow in the rivers. On the other hand, SODs have an
10antagonist impact as they provide a significant contribution to the river discharge in summer,
11especially for small catchments. But their impact is smaller than that of the sewer systems and
12the whole impact is mostly a base flow decrease. However, given the actions planned to
13improve the quality of the receiving waters (improvement of the tightness of the sewer
14systems, separation of rainwater and waste water, building of retention basin, etc), the
15discharge monitoring must be continued to see if those actions have a real impact on the
16discharge. The indicators presented in this study can help monitoring the system.

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196. Conclusions and perspectives

20The data analysis presented in this paper provides valuable insight into the periurban Yzeron
21catchment behaviour. We were able to highlight relevant indicators of the impact of
22urbanization/artificialization on the hydrological regime of periurban rivers. The results were
23obtained thanks to the availability of a long term and rich data set, sampling various aspects
24of the periurban water cycle. These series were relevant for our analysis. However, longer
25time series and sampling of more infrastructures would be necessary to fully close the water
26balance of such catchments. We have also seen that the determination of the periurban
27catchment area is also of importance for a correct data analysis. The filtering method
28proposed to decompose the measured discharge into rural and SOD component was found to
29be efficient in highlighting the major role of SODs on the whole hydrological regime,
30including, mean monthly regime, low flows and high flows. The application of the method
31requires the location of the SOD and gauging station to be very close, and data acquired with
32a variable time step. This findings provide guidelines for the setting of proper monitoring
33networks of those periurban catchments. Finally, the role of water infiltration within the sewer

1system was highlighted. It was found to account for 30% of the total combined sewer system
2discharge. There are evidence that this infiltration has an impact on low flow and on a large
3part of the hydrological regime, by decreasing the water into the stream. This impact is
4important to consider due to its large impact on water quality and on ecosystems.

5The indicators derived in this study are also very useful for the assessment of model results
6set up in the Yzeron catchment both at small scale (Chaudanne and Mercier catchments,
7Jankowsky et al, 2011) and the Yzeron catchment (Branger et al., 2012).

8Future work would be required to analyse more in depth the events characteristics, such as
9done in Sheeder et al. (2002) or Furusho et al. (2012) and characterize the impact of
10artificialization on the hydrograph shape using for instance methods derived from Archer
11(2007), Archer et al. (2010).

12

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1References

- 2Archer, D.R., 2007. The use of flow variability analysis to assess the impact of land use
3 change on the paired Plynlimon catchments, mid-Wales. *Journal of Hydrology*, 347(3-4),
4 487-496.
- 5Archer, D.R., Climent-Soler, D., Holman, I.P., 2010. Changes in discharge rise and fall rates
6 applied to impact assessment of catchment land use. *Hydrology Research*, 41(1), 13-26.
- 7Arrigoni, A.S., Greenwood, M.C., Moore, J.N., 2010. Relative impact of anthropogenic
8 modifications versus climate change on the natural flow regimes of rivers in the Northern
9 Rocky Mountains, United States. *Water Resour. Res.*, 46(12), W12542.
- 10Ashagrie, A.G., de Laat, P.J.M., de Wit, M.J.M., Tu, M., Uhlenbrook, S., 2006. Detecting the
11 influence of land use changes on discharges and floods in the Meuse River Basin - the
12 predictive power of a ninety-year rainfall-runoff relation? *Hydrology and Earth System
13 Sciences*, 10(5), 691-701.
- 14Bathurst, J.C., Iroume, A., Cisneros, F., Fallas, J., Iturraspe, R., Novillo, M.G., Urciuolo, A.,
15 de Bievre, B., Borges, V.G., Coello, C. et al., 2011. Forest impact on floods due to extreme
16 rainfall and snowmelt in four Latin American environments 1: Field data analysis. *Journal
17 of Hydrology*, 400(3-4), 281-291.
- 18Beighley, R.E., Melack, J.M., Dunne, T., 2003. Impacts of California's climatic regimes and
19 coastal land use change on streamflow characteristics, *Journal of the American Water
20 Resources Association*, 39(6), 1419-1433.
- 21Berthier, E., Andrieu, H., Creutin, J.D., 2004. The role of soil in the generation of urban
22 runoff: development and evaluation of a 2D model. *Journal of Hydrology*, Special issue on
23 Urban Hydrology, 299(3-4), 252-266.
- 24Blume, T., Zehe, E., Bronstert, A., 2007. Rainfall—runoff response, event-based runoff
25 coefficients and hydrograph separation. *Hydrological Sciences Journal*, 52(5): 843-862.
- 26Booth, D.B., Hartley, D. and Jackson, R., 2002. Forest cover, impervious-surface area, and
27 the mitigation of stormwater impacts, *Journal of the American Water Resources
28 Association*, 38(3), 8356-845.
- 29Boyle, D.P., Gupta, H.V. and Sorooshian, S., 2000. Toward improved calibration of
30 hydrologic models: combining the strengths of manual and automatic methods. *Water
31 Resources Research*, 36(12), 3663-3674.
- 32Branger, F., Kermadi, S., Jacqueminet, C., Michel, K., Labbas, M., Krause, P., Braud, I.,
33 2012. Assessment of the influence of land use on the hydrology of a suburban catchment
34 using a simplified distributed modelling approach, in preparation.

- 1Branger, F., Renard, B., Le Coz, J., Bonnifait, L., 2011. Assessment of uncertainty of stage-
2 discharge relations through hydraulic and bayesian approach. ICFM5: 5th International
3 Conference on Flood Management, 27-29 September 2011, Tokyo, Japan.
- 4Bras R.L., Perkins F.E. 1975. Effects of urbanization on catchment response. J. of Hydraulics
5 Division. Vol. 101, HY3 ,pp.451-466.
- 6Braud, I., 2011. Méthodologie d'analyse de tendances sur de longues séries
7 hydrométéorologiques. Fiche technique OTHU n°23, 6 pp.
- 8 http://www.graie.org/othu/publi3_FTtech.htm
- 9Braud I., Chancibault K., Debionne S., Lipeme Kouyi G., Sarrazin B., Jacqueminet C.,
10 Andrieu H., Béal D., Bocher E., Boutaghane H., Branger F., Breil P., Chocat B., Comby J.,
11 Dehotin J., Dramaïs G., Furusho C., Gagnage M., Gonzalez-Sosa E., Grosprêtre L.,
12 Honegger A., Jankowfsky S., Joliveau T., Kermadi S., Lagouy M., Leblois E., Martin J.Y.,
13 Mazagol P.O., Michell K., Molines N., Mosini M.L., Puech C., Renard F., Rodriguez F.,
14 Schmitt L., Thollet F., Viallet P., 2010. The AVuPUR project (Assessing the Vulnerability
15 of Peri-Urbans Rivers) : experimental set up, modelling strategy and first results,
16 Proceedings of the 7th Novatech 2010 Conference, June 28-July 1 2010, Lyon, France, 10pp,
17 <http://hdl.handle.net/2042/35712>.
- 18Breil, P., Joannis, C., Raimbaud, G., Brissaud, F., Desbordes, M., 1993. Drainage des eaux
19 claires parasites par les réseaux sanitaires. De l'observation à l'élaboration d'un modèle
20 prototype. La Houille Blanche N°1-1993, 45-57.
- 21Breil, P., Radojevic, B., Chocat, B., 2010. Urban development and extreme flow regimes
22 changes, Proceedings of the 6th Friend Conference “Global change: facing risks and threats
23 to water resources”, 25-29 October 2010, Fez, Morocco, IAHS Public., 340, 314-319
- 24Bullock, A., 1992. The role of Dambos in determining river flow regimes in Zimbabwe.
25 Journal of Hydrology, 134(1-4), 349-372.
- 26Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., Kendall, C., 2005. Effects of
27 suburban development on runoff generation in the Croton River basin, New York, USA.
28 Journal of Hydrology, 311(1-4), 266-281.
- 29Buytaert, W., Wyseure, G., De Bièvre, B., Deckers, J., 2005. The effect of land-use changes
30 on the hydrological behaviour of Histic Andosols in south Ecuador. Hydrological Processes,
31 19, 3985-3997.
- 32Chapman, T., 1991. Comment on “evaluation of automated techniques for base flow and
33 recession analyses” by R.J. Nathan and T.A. McMahon. Water Resources Research 27 (7),
34 1783–1784.

- 1 Chocat, B., P. Krebs, J. Marsalek, W. Rauch, and W. Schilling. 2001. Urban drainage
2 redefined: from stormwater removal to integrated management. Water and Science
3 Technology, 43, 61-68.
- 4 Chormanski, J., Van de Voorde, T., De Roeck, T., Batelaan, O., Canters, F., 2008. Improving
5 distributed runoff prediction in urbanized catchments with remote sensing based estimates
6 of impervious surface cover. Sensors, 8, 910-932.
- 7 Claessens, L., Hopkinson, C., Rastetter, E., Vallino, J., 2006. Effect of historical changes in
8 land use and climate on the water budget of an urbanizing watershed. Water Resour. Res.,
9 42, W03426.
- 10 Cottet, M. 2005. Evolution de l'occupation du sol dans le bassin versant de l'Yzeron au cours
11 du XXème siècle: premiers éléments pour un diagnostic hydrologique. Université Jean
12 Moulin, Lyon III, Lyon.
- 13 Dow, C.L., 2007. Assessing regional land-use/cover influences on New Jersey Pinelands
14 streamflow through hydrograph analysis. Hydrological Processes, 21(2): 185-197.
- 15 Elfert, S., Bormann, H., 2010. Simulated impact of past and possible future land use changes
16 on the hydrological response of the Northern German lowland [']Hunte' catchment. Journal
17 of Hydrology, 383(3-4), 245-255.
- 18 FAO, 1998. Crop Evaporation - Guidelines for computing crop water requirements. Irrigation
19 and Drainage paper n°56, FAO, Rome.
- 20 Furusho, C., Andrieu, H., Chancibault, K., 2011. Analysis of the hydrological functioning of
21 an Urbanizing River Basin, submitted to Hydrological Processes
- 22 Galéa, G., Prudhomme, C., 1994. Modèles débit-durée-fréquence et conceptualisation d'un
23 hydrogramme de crue synthétique: validation sur le BVRE de Draix. Hydrologie
24 Continentale, 9(2), 139-151.
- 25 Galéa, G., Prudhomme, C., 1997. Notions de base et concepts utiles pour la compréhension de
26 la modélisation synthétique des régimes de crue des bassins versants au sens des modèles
27 QdF. Revue des Sciences de l'Eau, 1, 83-101.
- 28 Gnouma, R. 2006. Aide à la calibration d'un modèle hydrologique distribué au moyen d'une
29 analyse des processus hydrologiques: application au bassin versant de l'Yzeron. Institut
30 National des Sciences Appliquées de Lyon, Lyon, France, 14 Novembre 2006, 448 pp.
- 31 Gonzalez-Sosa, E., Braud, I., Dehotin, J., Lassabatère, L., Angulo-Jaramillo, R., Lagouy, M.,
32 Branger, F., Jacqueminet, C., Kermadi, S., Michel, K., 2010. Impact of land use on the
33 hydraulic properties of the topsoil in a small French catchment. Hydrological Processes,
34 24(17), 2382-2399.

- 1 Groprêtre, L., 2011. Dynamique hydro-morphologique, modélisation et gestion de petits
2 systèmes fluviaux périurbains. Recherche méthodologique appliquée au bassin de l'Yzeron.
3 Thèse de l'Université de Lyon.
- 4 Gufstafsson, L.G., Winberg, S., Refsgaard, A., 1997. Towards a distributed physically based
5 model description of the urban aquatic environment. Water Science & Technology, 36(8-9),
6 89-93.
- 7 Gustard, A., Wesselink, A.J., 1993. Impact of land-use change on water-resources-
8 Balquhidder catchments. Journal of Hydrology, 145(3-4): 389-401.
- 9 Hatt, B. E., T. D. Fletcher, C. J. Walsh, and S. L. Taylor. 2004. The influence of urban density
10 and drainage infrastructure on the concentrations and loads of pollutants in small streams.
11 Environmental Management, 34, 112-124.
- 12 Jacobson, C.R., 2011. Identification and quantification of the hydrological impacts of
13 imperviousness in urban catchments: A review, Journal of Environmental Management,
14 92(6), 1438-1448.
- 15 Jacqueminet, C., Kermadi, S., Michel, K., Chocat, B., 2011. Comment cartographier
16 l'occupation du sol et son évolution pour le suivi des phénomènes hydrologiques? Fiche
17 technique OTHU n°24, 4 pp. http://www.graie.org/othu/publi3_FTtech.htm
- 18 Jacqueminet, C., Kermadi, S., Michel, K., Béal, D., Gagnage, M., Branger, F., Jankowfsky,
19 S., Braud, I., 2012. Land cover mapping using aerial and VHR satellite images for
20 distributed hydrological modelling of periurban catchments: application to the Yzeron
21 catchment (Lyon, France), Journal of Hydrology, Periurban catchments special issue, in
22 revision.
- 23 Jankowfsky, S., 2011 Understanding and modelling of hydrological processes in small peri-
24 urban catchments using an object oriented and modular distributed approach. Application to
25 the Chaudanne and Mercier sub-catchments (Yzeron catchment, France). Ph D thesis,
26 University of Grenoble, 331 pp.
27
- 28 Jankowfsky, S., Branger, F., Braud, I., Rodriguez, F., Debionne, S., Viallet, P., 2011.
29 Influence of urban expansion on the hydrology of small catchments: development of the
30 suburban PUMMA model by coupling of urban and rural hydrological models, 12th
31 International Conference on Urban Drainage, 11-15 September 2011, Porto Alegre, Brasil, 8
32 pp.

- 1 Javelle, P., Grésillon, J.-M., Galéa, G., 1999. Modélisation des courbes débit-durée-fréquence
2 en crues et invariance d'échelle. Comptes Rendus de l'Académie des Sciences - Series IIA -
3 Earth and Planetary Science, 329(1), 39-44.
- 4 Kermadi, S., Braud, I., Jacqueminet, C., Michel, K., Branger, F., 2011. Evolution de la
5 pluviométrie dans le bassin péri-urbain de l'Yzeron (Ouest Lyonnais) depuis les années
6 1970 et caractérisation de l'imperméabilisation, XXIVème Colloque de l'Association
7 Internationale de Climatologie, 6-11 Septembre 2011, Rovereto (Italie), 6 pp.
8 <http://www.climato.be/aic/colloques.html>
- 9
- 10 Kermadi, S., Renard, F., Braud, I., Jacqueminet, C., Michel, K., Branger, F., 2012.
11 Occupation du sol et pluviométrie dans un bassin versant péri-urbain soumis aux
12 inondations : Yzeron (Ouest Lyonnais), 14 pp, Climatologie, in revision
- 13 Kliment, Z., Matoušková, M., 2009. Runoff Changes in the Šumava Mountains (Black Forest)
14 and the Foothill Regions: Extent of Influence by Human Impact and Climate Change. Water
15 Resources Management, 23(9), 1813-1834.
- 16 Lafont, M., A. Vivier, S. Nogueira, P. Namour, and P. Breil. 2006. Surface and hyporheic
17 oligochaete assemblages in a French suburban stream. Hydrobiologia, 564, 183-193.
- 18 Lang, M., Ouarda, T.B.M.J., Bobee, B. 1999. Towards operational guidelines for over-
19 threshold modelling, Journal of Hydrology, 225(3-4), 103-117.
- 20 Lang, M., Renard, B., Sauquet, E., Bois, P., Dupeyrat, A., Laurent, C., Mestre, O., Niel, H.,
21 Neppel, L., Gailhard, J., 2006. A national study on trends and variations of French floods
22 and droughts, *Climate Variability and Change—Hydrological Impacts* (Proceedings of the
23 Fifth FRIEND World Conference held at Havana, Cuba, November 2006), IAHS Publ. 308,
24 2006, 514–519.
- 25 Madsen, H., 2000. Automatic calibration of a conceptual rainfall-runoff model using multiple
26 objectives. Journal of Hydrology, 235, 276-288.
- 27 Mann. H. B , Whitney.D. R., 1947. On a test of whether one of two random variables is
28 stochastically larger than the other. Ann. Math. Statist, 18(1), 50–60.
- 29 Marsalek, J., Jiménez-Cisneros, B.E., Karamouz, M., Malmquist, P.A., Gldenfum, J. and
30 Chocat, B., 2007. Urban water processes and interactions. UNESCO IHP-VI program,
31 UNESCO, Paris, 239 pp.
- 32 Matteo, M., T. Randhir, and D. Bloniarz. 2006. Watershed-scale impacts of forest buffers on
33 water quality and runoff in urbanizing environment. Journal of the American Water
34 Resources Association, 132, 144-152.

- 1 Meierdiercks, K.L., Smith, J.A., Baeck, M.L., Miller, A.J., 2010. Analyses of Urban Drainage
2 Network Structure and its Impact on Hydrologic Response1. JAWRA Journal of the
3 American Water Resources Association, 46(5), 932-943.
- 4 Meija, A.I., Moglen, G.E., 2010. Spatial distribution of imperviousness and the space-time
5 variability of rainfall, runoff generation, and routing. Water Resources research, 46:
6 W07509, doi:10.1029/2009WR008568.
- 7 Ostrowski, M.W., 2000. Anthropogenic impacts on the formation of flash floods and
8 measures for their compensation , in Flood Issues in Contemporary Water Management,
9 Proceedings of the NATO Advanced Research Workshop on Coping with Floods, Maleno-
10 vice, Czech Republic, Mai 2000, NATO Science Series, 2. Environmental Security - Vol.
11 71, Kluwer Academic Publishers, ISBN 0-7923-6452-X
- 12 Ostrowski, M., Bras,R.L. 2000 Simulation of the effects of urbanization on catchments
13 response. MS Thesis, MIT, Cambridge, MA.
- 14 OTHU, 2011. <http://www.graie.org/othu/>. Consulted on 2010/09/16.
- 15 Ott, B., Uhlenbrook, S., 2004. Quantifying the impact of land-use changes at the event and
16 seasonal time scale using a process-oriented catchment model. Hydrology and Earth System
17 Sciences, 8(1), 62-78.
- 18 Paul M.J. & Meyer J.L., 2001. Streams in the urban landscape. Annu. Rev. Ecol. Syst., 32,
19 333-365
- 20 Pettitt, A.N., 1979. A non parametric approach to the change point problem, Applied
21 Statistics, 28, 126-135.
- 22 Praskiewicz, S., Chang, H., 2009. A review of hydrological modelling of basin-scale climate
23 change and urban development impacts. Progress in Physical Geography, 33(5), 650-671.
- 24 Prigobbe, V., Guilianelli, M., 2009. Quantification of sewer system infiltration using d18O
25 hydrograph separation, Water Scienc & Technology, 60(3), 727-735.
- 26 Quintana-Segui, P., Le Moigne, P., Durand, Y., Martin, E., Habets, F., Baillon, M., Canellas,
27 C., Franchisteguy, L. and Morel, S., 2008. Analysis of near-surface atmospheric variables:
28 validation of the SAFRAN analysis over France. Journal of Applied Meteorology and
29 Climatology, 47, 92-107.
- 30 Radojevic, B., 2002. Méthode d'évaluation de l'influence urbaine sur le régime des crues d'un
31 bassin versant de 130 km², Institut National des Sciences Appliquées de Lyon, Lyon, 252
32 pp.

- 1 Radojevic, B., Breil, P. and Chocat, B., 2010. Assessing impact of global change on flood
2 regimes. International Journal of Climate Change Strategies and Management, 2(2), 167-
3 179.
- 4 Randhir, T., 2003. Watershed-scale effects of urbanization on sediment export: assessment
5 and policy, Water Resources Research, 39(6), 1-13.
- 6 Renard, B., Lang, M., Bois, P., Dupeyrat, A., Mestre, O., Niel, H., Gailhard, J., Laurent, C.,
7 Neppel, L. and Sauquet, E., 2006. Evolution des extrêmes hydrométriques en France à partir
8 de données observées. La Houille Blanche - Revue Internationale de l'eau, 6, 48-54.
- 9 Richter, B.D., Baumgartner, J. V. , Powell, J., Braun, D.P., 1996. A method for assessing
10 hydrologic alteration within ecosystems. Conservation Biology 10(4), 1163-1174.
- 11 Richter, B.D., Baumgartner, J.V., Wigington, R., Braun, D.P., 1997. How much water does a
12 river need? Freshwater Biology 37(1), 1-249.
- 13 Richter, B.D., Mathews, R., Harrison, D.L., Wigington, R., 2003. Ecologically sustainable
14 water management: Managing river flows for ecological integrity. Ecological Applications
15 13(1), 206-224.
- 16 Rodriguez, F., Andrieu, H., Morena, F., 2008. A distributed hydrological model for urbanized
17 areas - Model development and application to case studies. Journal of Hydrology, 351(3-4),
18 268-287.
- 19 Sarrasin, B., 2012. Approches spatiales pour décrire le réseau de drainage et suivre sa
20 dynamique de fonctionnement en milieu rural dans une perspective d'aide à la modélisation
21 hydrologique Ecole doctorale Terre, Univers, Environnement. l'Institut National
22 Polytechnique de Grenoble.
- 23 Sauquet, E., Gottschalk, L. and Krasovskaia, I., 2008. Estimating mean monthly runoff at
24 ungauged locations: an application to France. Hydrology Research, 39(5-6), 403-423.
- 25 Sauquet, E., Krasovskaia, I., Leblois, E., 2000. Mapping mean monthly runoff pattern using
26 EOF analysis. Hydrology and Earth System Sciences, 4(1): 79-93.
- 27 Sauquet, E., Leblois, E., 2001. Discharge analysis and runoff mapping applied to the
28 evaluation of model performance. Physics and Chemistry of the Earth, 26(5), 473-478.
- 29 Schmitt L, Grosprêtre L, Breil P, Lafont M, Vivier A, Perrin JF, Namour P, Jezequel C,
30 Valette L, Valin K, Cordier R, Cottet M. 2008. Préconisations de gestion physique de petits
31 hydrosystèmes périurbains : l'exemple du bassin de l'Yzeron (France). In. Actes du
32 Colloque « La gestion physique des cours d'eau : bilan d'une décennie d'ingénierie
33 écologique », Verniers G, Petit F (eds), Namur, 10-12 oct. 2007, Groupe Interuniversitaire
34 de Recherches en Ecologie Appliquée, Laboratoire d'Hydrographie et de Géomorphologie

- 1 Fluviaatile, Direction des Cours d'Eau Non Navigables, Direction Générale des Ressources
2 Naturelles et de l'Environnement - Ministère de Région wallonne : 177-186.
- 3Sheeder, S.A., Ross, J.D., Carlson, T.N., 2002. Dual urban and rural hydrograph signals in
4 three small watersheds, Journal of the American Water Resources Association, 38(4), 1027-
5 1040.
- 6SIRA, 2011. Sol Info Rhône-Alpes, sira@rhone-alpes.chambagri.fr - <http://www.rhone-alpes.chambagri.fr/sira/>. Consulted on 2010/09/16.
- 7 Stedinger, J.R., Vogel, R.M., Foufoula-Georgiou, E., 1992. Frequency analysis of extreme
8 events, Chapter18. In Handbook of hydrology. Ed.: Maidment D.R. Mc Graw-Hill, Inc.
9 New-York.
- 10 Tallaksen, L.M., Van Lanen, H.A.J., 2004. Hydrological drought: processes and estimation
11 methods for streamflow and groundwater. Developments in water science 48, Elsevier,
12 Amsterdam, The Netherlands, 579 pp.
- 13 Tetzlaff, D., Grottke, M., Leibundgut, C., 2005. Hydrological criteria to assess changes of
14 flow dynamic in urban impacted catchments. Physics and Chemistry of the Earth, Parts
15 A/B/C, 30(6-7), 426-431.
- 16 Tong, S.T.Y., 1990. The hydrologic effects of urban land use: a case study of the Little Miami
17 River basin. Landscape and Urban Planning, 19, 99-105.
- 18 Vázquez, R.F. and Feyen, J., 2010. Rainfall-runoff modelling of a rocky catchment with
19 limited data availability: Defining prediction limits. Journal of Hydrology, 387(1-2), 128-
20 140.
- 21 Vázquez, R.F., Willems, P. and Feyen, J., 2008. Improving the predictions of a MIKE SHE
22 catchment-scale application by using a multi-criteria approach. Hydrological Processes,
23 22(13), 2159-2179.
- 24 Vidal, J.P., Martin, E., Franchisteguy, L., Baillon, M., Soubeyroux, J.M., 2010. A 50-year
25 high-resolution atmospheric reanalysis over France with the SAFRAN system International
26 Journal of Climatology, 30(11), 1627-1644.
- 27 Wagener, T., Boyle, D.P., Lees, M.J., Weater, H.S., Gupta, H.V. and Soroshian, S., 2001. A
28 framework for development and application of hydrological models. Hydrology and Earth
29 System Sciences, 5(1), 13-26.
- 30 Walsh, C.J., Fletcher, T.D., Ladson, A.R., 2005. Stream restoration in urban catchments
31 through redesigning stormwater systems: looking to the catchment to save the stream.
32 Journal of the North American Benthological Society, 24(3), 690-705.

1 Wang, G., Liu, J., Kubota, J., Chen, L., 2007. Effects of land-use changes on hydrological
2 processes in the middle basin of the Heihe River, northwest China. *Hydrological Processes*,
3 21(10), 1370-1382.

4 Willems, P., 2009. A time series tool to support the multi-criteria performance evaluation of
5 rainfall-runoff models. *Environmental Modelling & Software*, 24(3), 311-321.

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3Figure 1: Map of the DTM (25m resolution) of the Yzeron catchment with location of the
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6in grey.

7Figure 2: Maps of land use of the Yzeron catchment in (a) 1970; (b) 1990; (c) 2008. The
8original maps were obtained by manual digitalization of aerial photographs by Jacqueminet et
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10and coniferous forests, moors), agricultural areas (crops, pastures, orchards, gardens) and
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12

13Figure 3: Zoom of the available gauging stations on the Chaudanne river, close to the Sewer
14Overflow Device (SOD1). It shows the location of the gauging stations in the stream, the
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27

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31

32Figure 8: (a) Flow duration curve (FDC) for the daily specific discharge of the Taffignon,
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2groundwater (GW), waste water (WW).

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5of the flood hydrographs for the Craponne gauge and its “Rural” and “SOD” components. (c)
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8Figure 10: Specific discharge from the POT analysis of the Taffignon, Craponne, Polionnay,
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11of four flood events per year. The x-axis provides the empirical return period of each event.

12Figure 11: Result of the filtering of the SOD2 discharge from the La Léchère gauge discharge
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14shown.

15Figure 12: Top: fraction of the total monthly discharge (%) coming from the SODs for the
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17Craponne and La Léchère stations and their filtered Rural and SOD components.

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19stations and their rural and SOD components for the duration $d=0$ (peak discharge) and $d=3$ h.
20The analysis was performed extracting an average of four flood events per year. The x-axis
21provides the empirical return period of each event.

22Figure 14: Partition of the monthly sewer discharge volume data into the runoff component
23(grey) and the groundwater infiltration (black) for the 2001-2010 period. The monthly rainfall
24is shown at the top of the graph. The date format in the x-axis is yy-mm where 01 is 2001 for
25instance.

Table 1: Indicators derived from discharge time series analysis found in the literature, and associated references. We distinguished studies based on model simulations and data analysis. In bold, we highlight references dealing with catchment urbanization. With a star, the study uses 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), Praskievicz and Chang (2009)	*Arrigoni et al. (2010), Bullock (1992), Wang et al. (2007)
Seasonal runoff		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)

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	Polionnay	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 km²) under dry conditions, and can reach 4.1 km²
3when all the SODs are activated (Jankowfsky, 2011)

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 contribution	SOD	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 contribution	SOD2	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	-

1 Table 4: Mean annual discharge Q_A ($\text{m}^3 \text{s}^{-1}$) and corresponding specific discharge q_A ($1 \text{s}^{-1} \text{km}^{-2}$), 50% quantile of the flow duration curves, $Q_{50\%}$; frequency of zero daily discharge and BFI; 3 maximum daily discharge Q_{max} ($\text{m}^3 \text{s}^{-1}$), and corresponding specific discharge q_{max} ($1 \text{s}^{-1} \text{km}^{-2}$); 4 characteristic flood duration for an extraction of 4 floods per year, θ (h), and duration, d (h), 5 retained for the QdF analysis. Specific discharges are not provided for the SODs and 6 CSS_RW+SOD components, due to the large uncertainty on their drained areas. For the La 7 Léchère station, figures in parenthesis correspond to a 4.1 km^2 catchment area.

8

Series	Q_A	q_A	$Q_{50\%}$	% of zero daily discharge	BFI	Q_{max}	q_{max}	θ	d
	$\text{m}^3 \text{s}^{-1}$	$1 \text{s}^{-1} \text{km}^2$	$\text{m}^3 \text{s}^{-1}$	-	-	$\text{m}^3 \text{s}^{-1}$	$1 \text{s}^{-1} \text{km}^2$	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
Polionnay	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	0.0069	11.15	0.260	1.58	544.8	1	4
		(4.63)					(385.4)		
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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1 Table 5: Decomposition of the discharge into base flow, inter flow and quick flow (in % of
2 the total volume) for the 5 gauged catchments. The values of the constant of the exponential
3 recession 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

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

10

Indicator calculated using the daily discharge at Craponne from 1970-2010	<i>p</i>
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 $d=1\text{h}30$	0.04** (+) 0.17
POT QCX duration $d=3\text{h}$	0.06 * (+) 0.13
POT QCX duration $d=6\text{h}$	0.07 * (+) 0.08* (1979)
POT QCX duration $d=12\text{h}$	0.06 * (+) 0.21
POT QCX duration $d=36\text{h}$	0.07* (+) 0.07* (1977)

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1Figure 1
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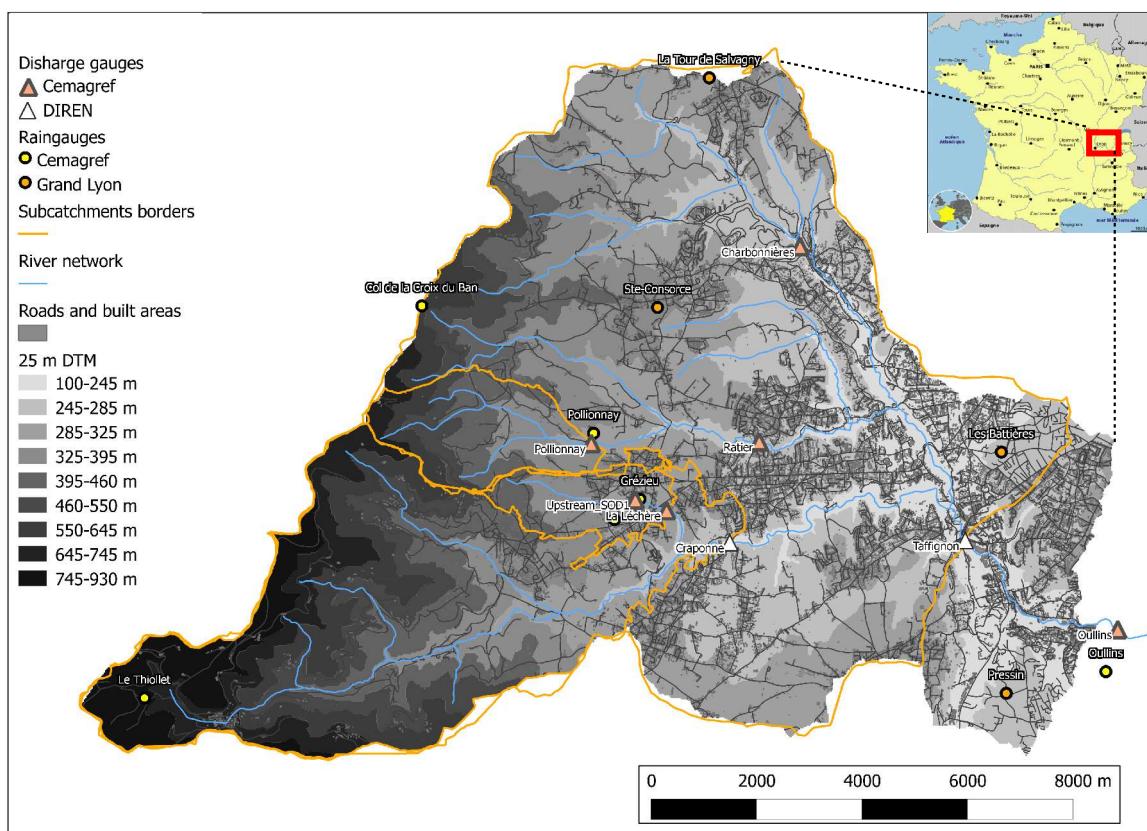
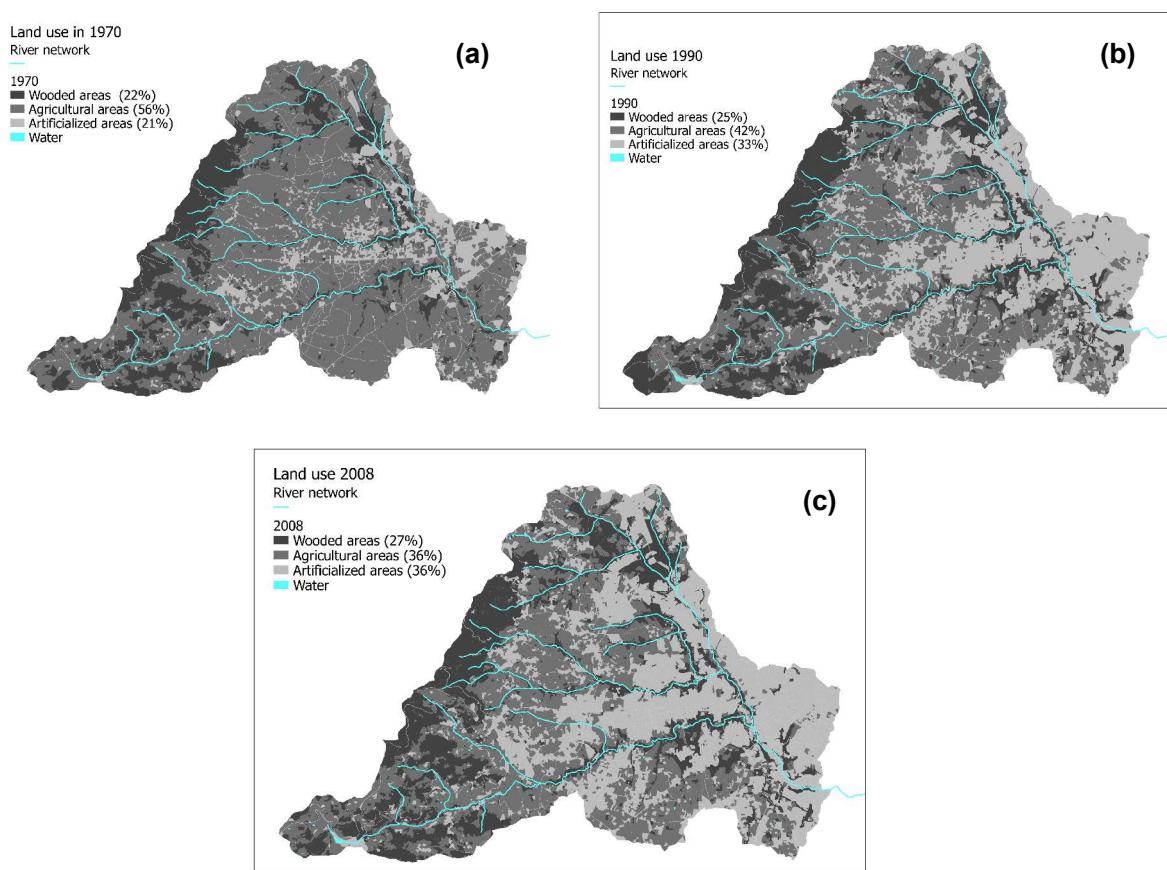
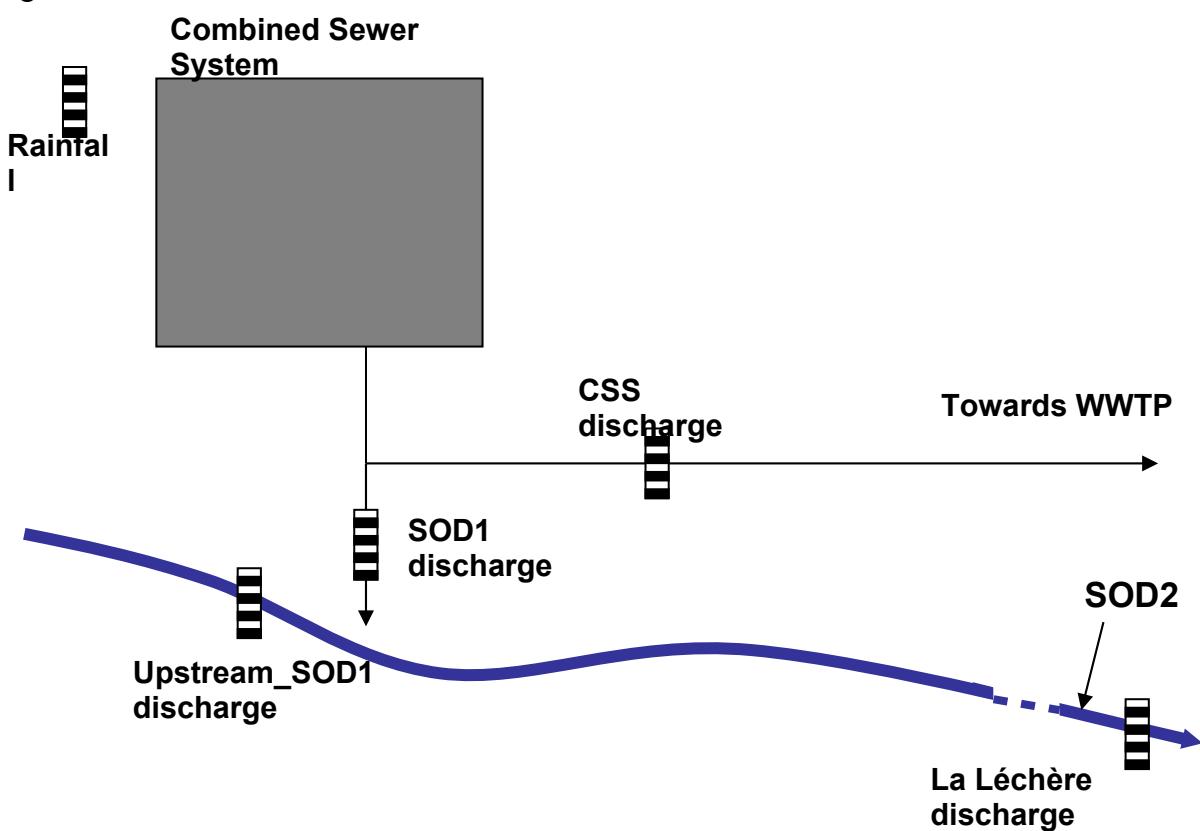


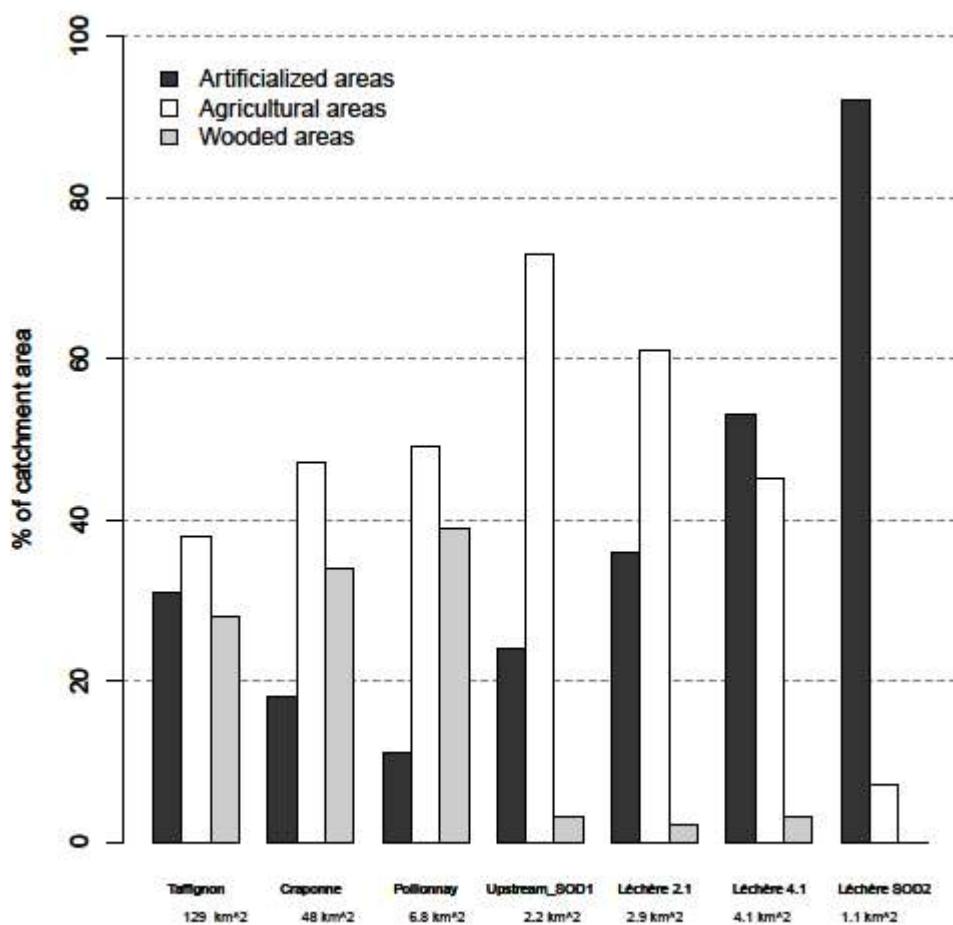
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1Figure 3
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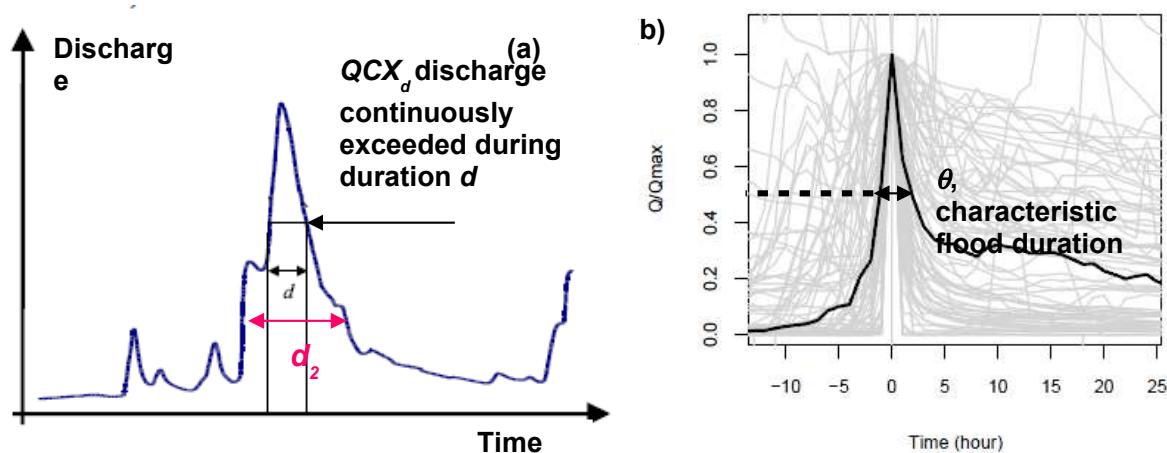


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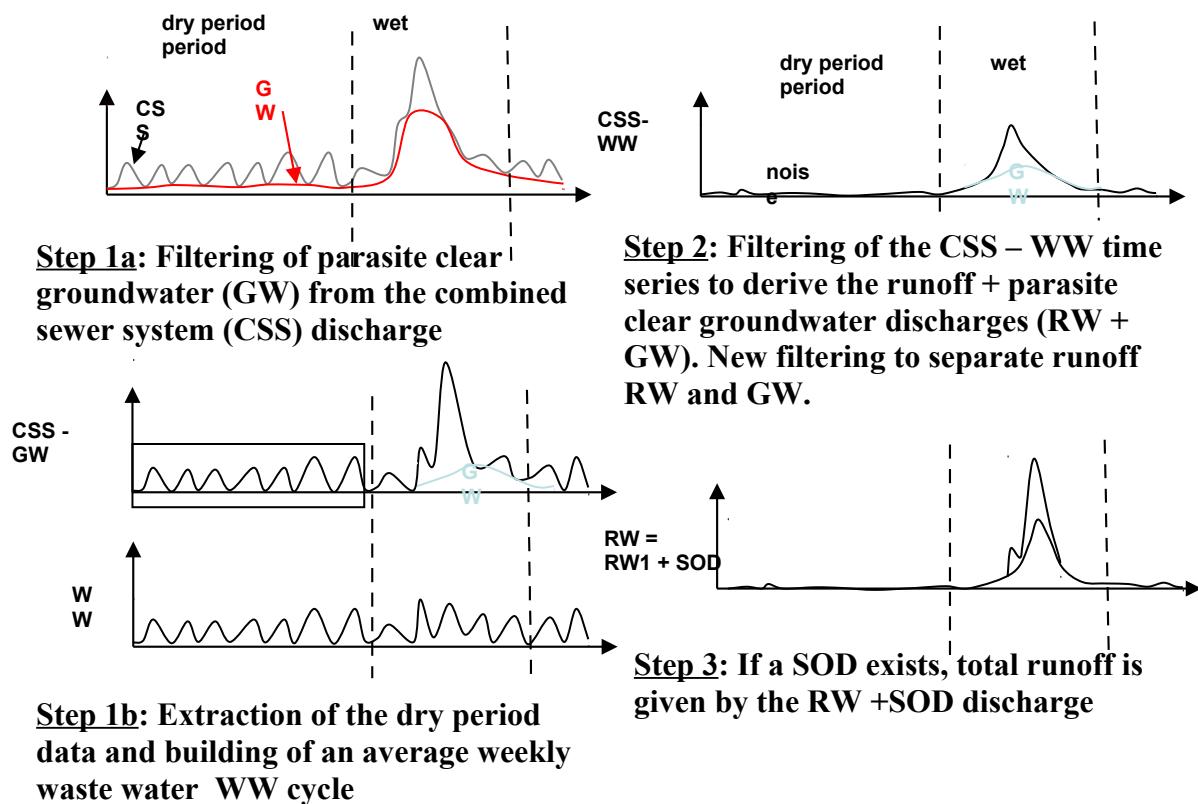


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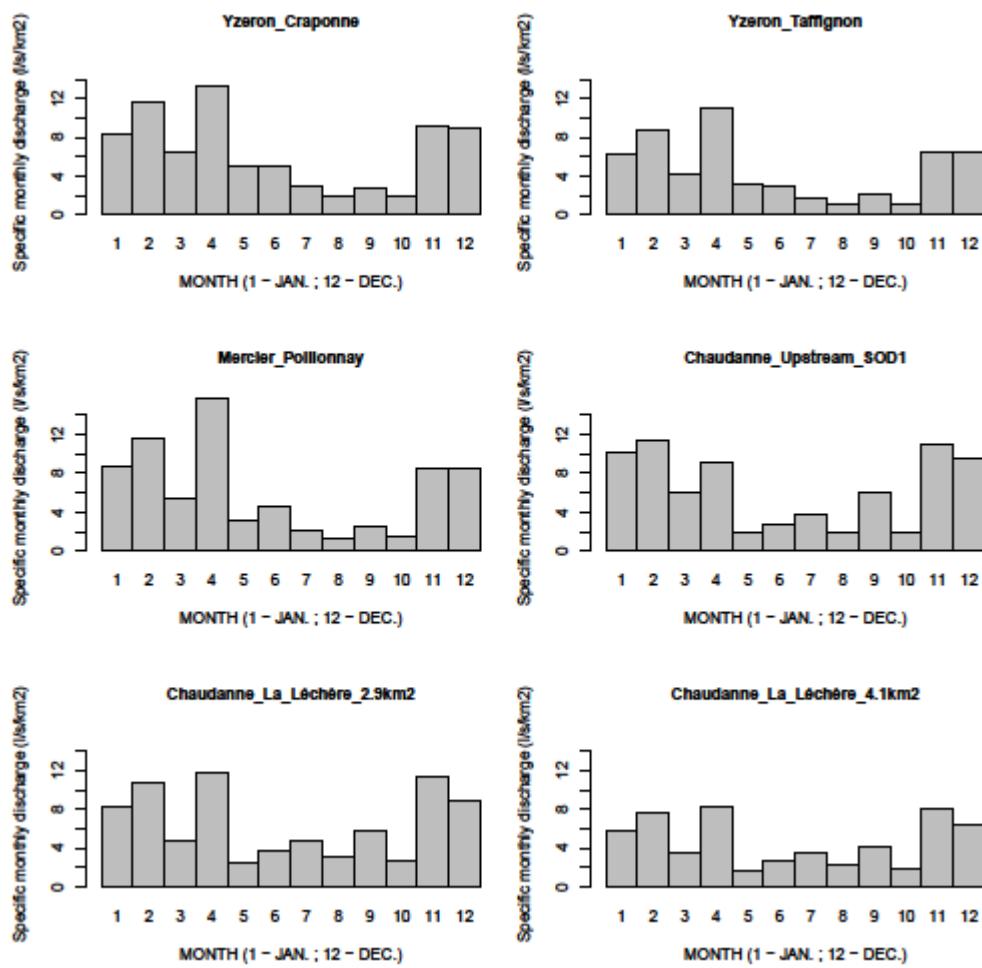
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¹Figure 6
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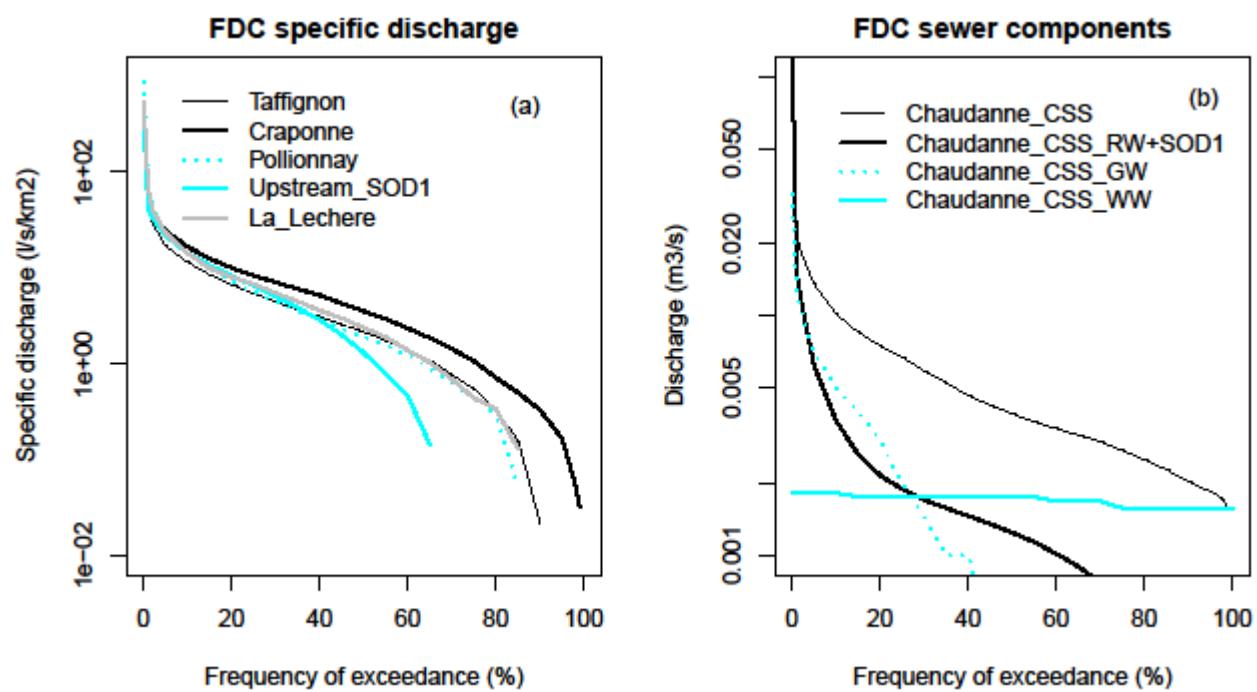


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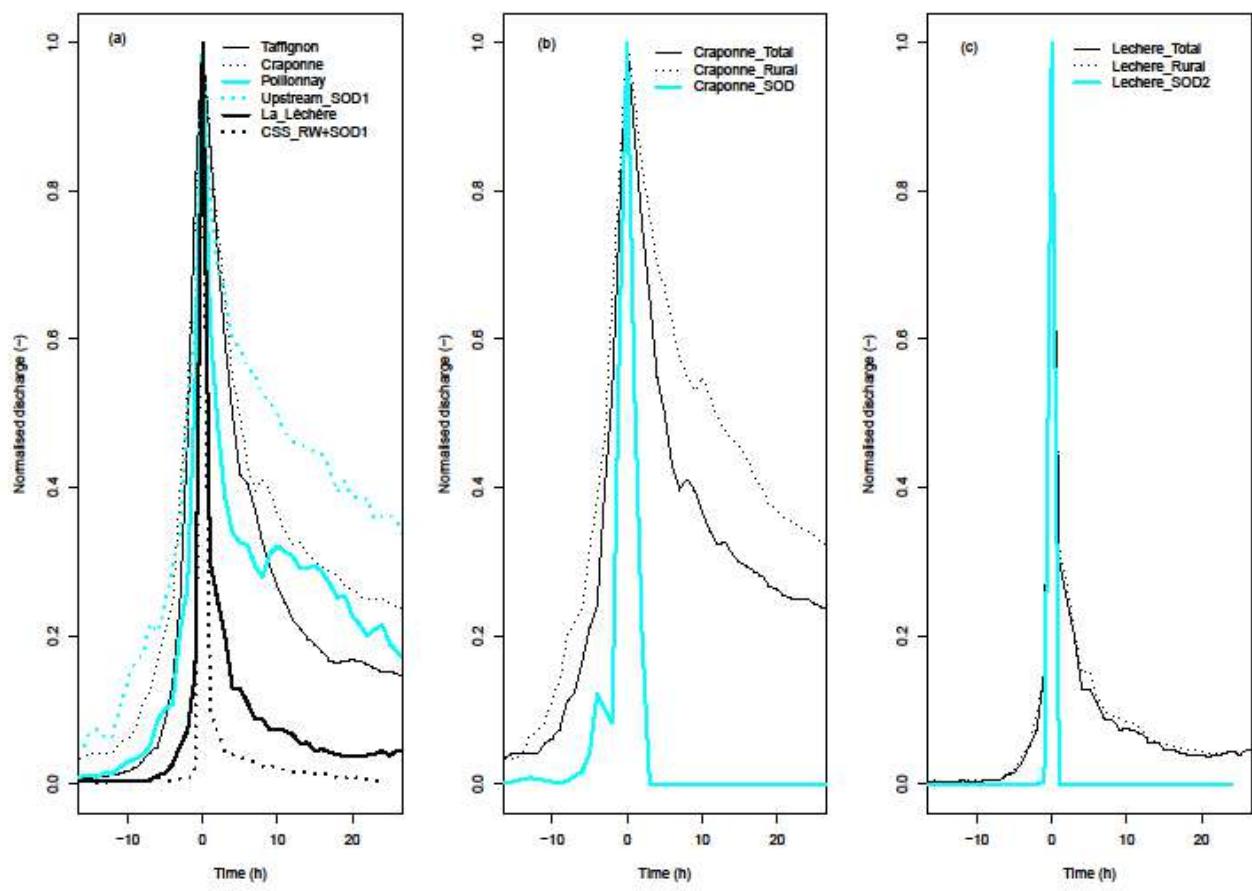
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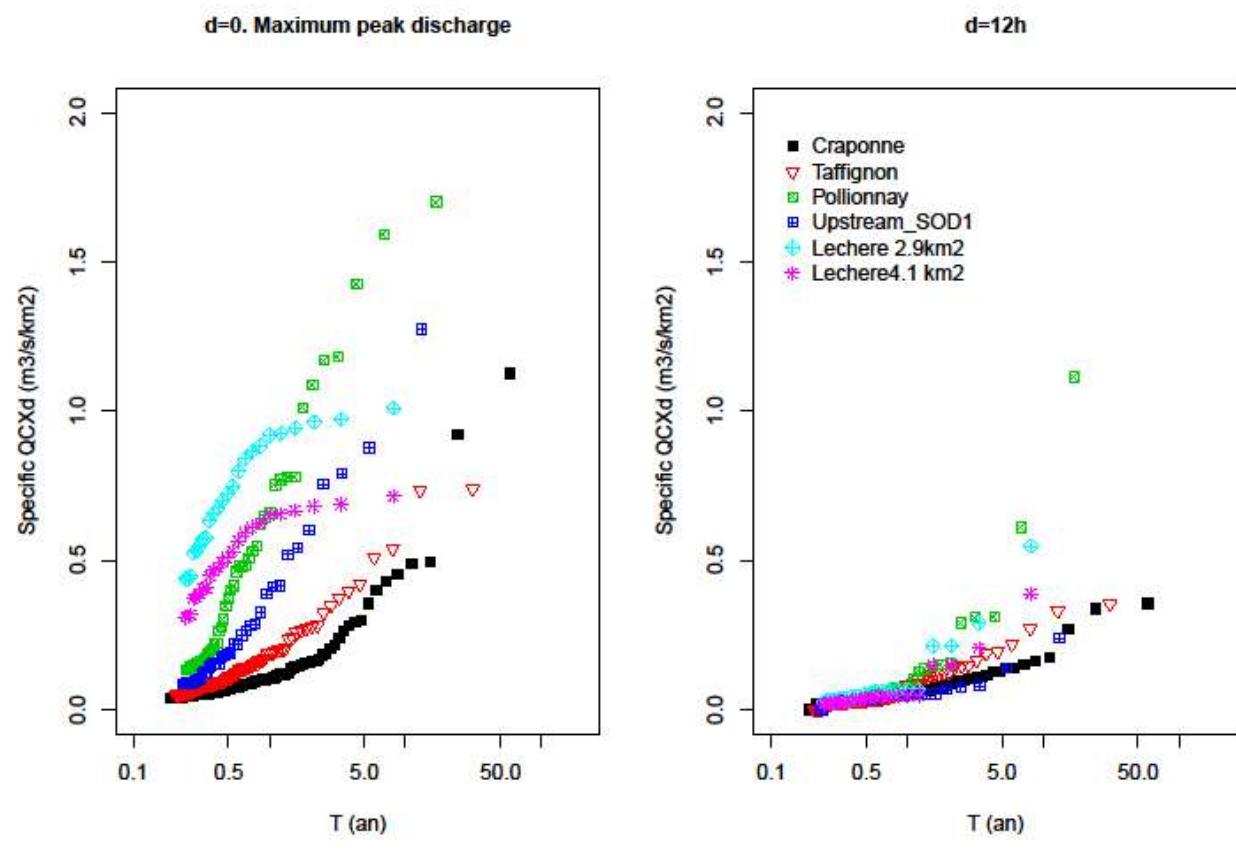
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1Figure 9



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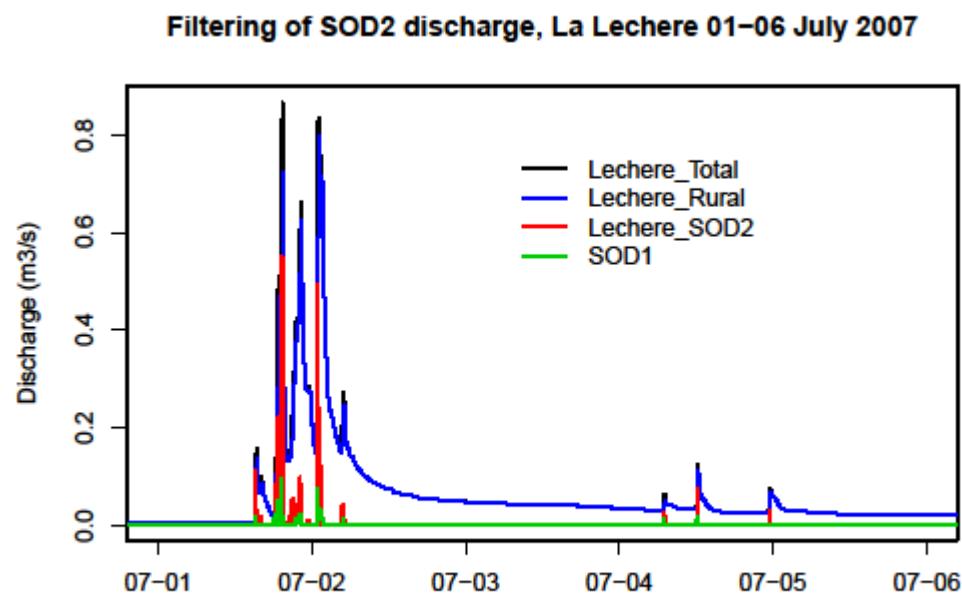


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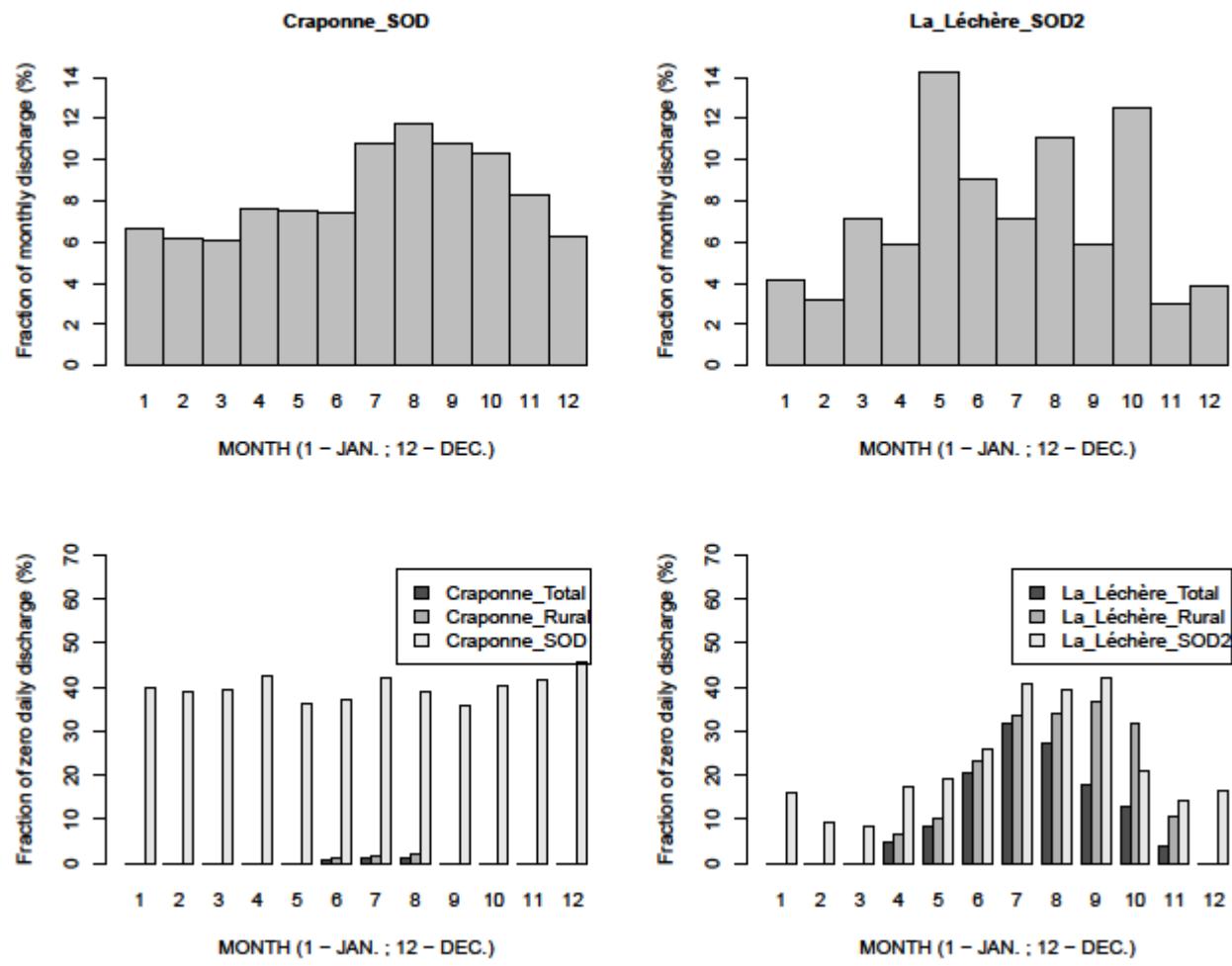
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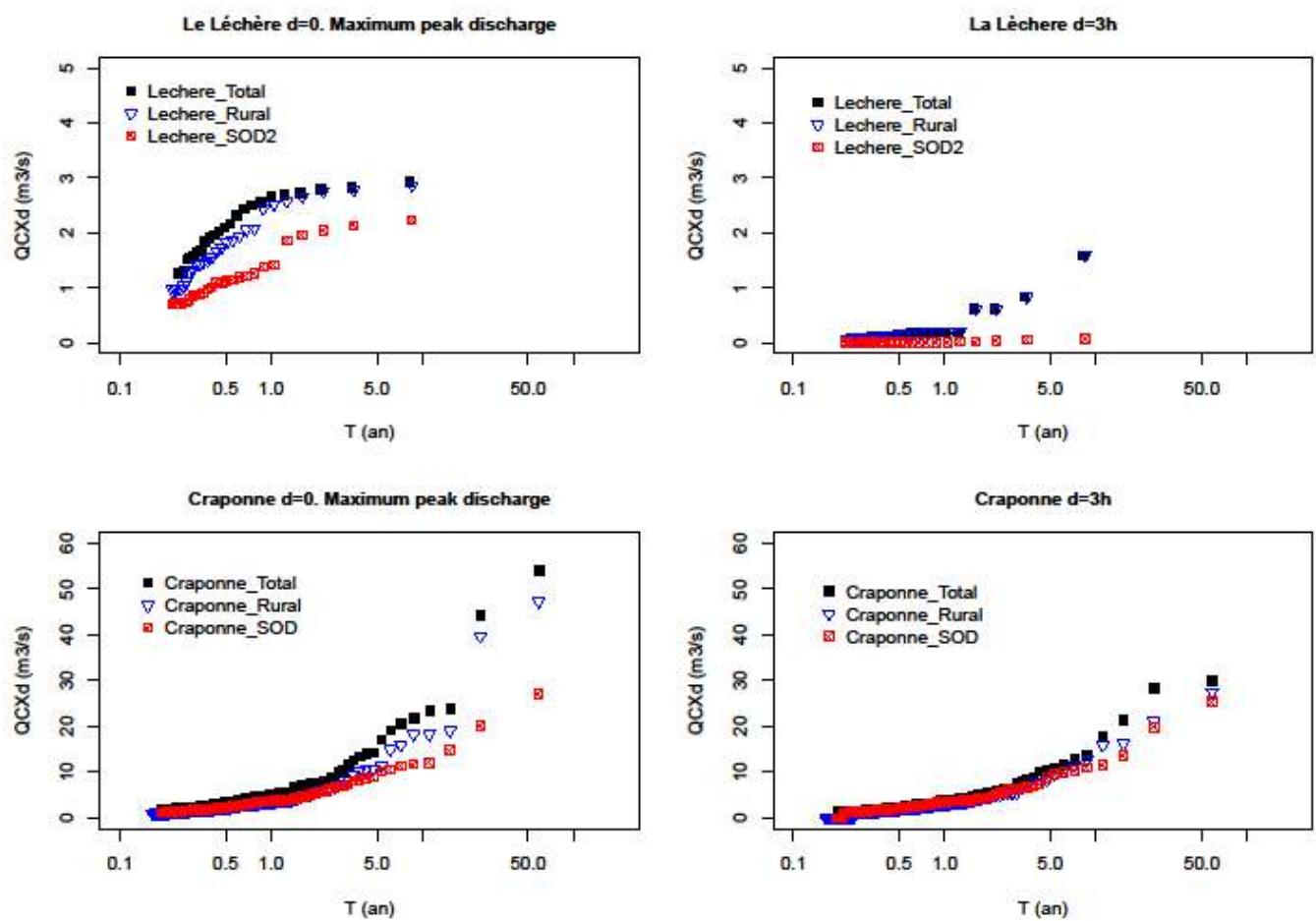


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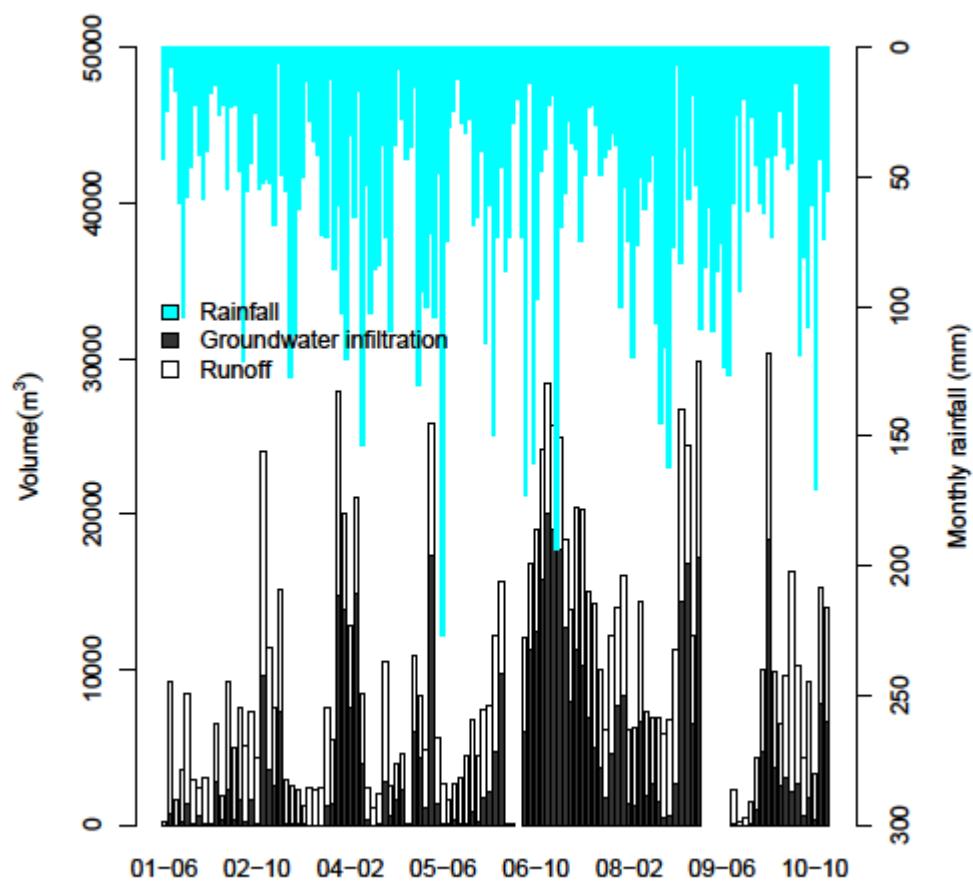
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1Figure 13



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1Figure 14



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