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S. Sandoval, A. Torres. Identification of dry/rainy periods from TSS loads' time series measured at the effluent of an urban catchment. Novatech 2013 - 8ème Conférence internationale sur les techniques et stratégies durables pour la gestion des eaux urbaines par temps de pluie / 8th International Conference on planning and technologies for sustainable management of Water in the City, Jun 2013, Lyon, France. <hal-03303440>

HAL Id: hal-03303440

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Submitted on 28 Jul 2021

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Identification of dry/rainy periods from TSS loads' time series measured at the effluent of an urban catchment

Identification de périodes temps sec / temps de pluie à partir de séries temporelles de charges en MES mesurées à l'exutoire de bassins versants urbains

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RÉSUMÉ

L'objectif de ce travail était de proposer une méthode pour identifier les périodes de temps de pluie du point de vue de l'influence sur l'exutoire d'un bassin versant urbain en termes de charges polluantes. A partir de l'utilisation de mesurages en ligne, une caractérisation probabiliste de temps sec et temps de pluie concernant les séries temporelles de charges polluantes de MES, fondée sur la technique *Kernel Density Estimators*, est mise en place. De plus, à partir de techniques de traitement de signaux (ACF, *Median Filter* et *Step Detection*), il a été possible d'établir des fenêtres de temps pour lesquelles les signaux de MES enregistrés se classent en dehors du comportement caractéristique de temps sec. Les méthodes proposées ont été appliquées à un cas d'étude particulier (sous-bassin *Gibraltar*, Bogotá, Colombie), obtenant sept événements de pluie identifiés. L'identification semble être appropriée compte tenu de sa cohérence avec les enregistrements de pluie.

ABSTRACT

The present work aims to propose a methodology for identifying the specific time periods in which rainfall influences the effluent of an urban catchment, in terms of pollutants loads. By the use of online measurements, a dry and wet weather probabilistic characterisation regarding the time series of TSS pollutants loads was undertaken (*Kernel Density Estimators*). In addition, by the use of signal processing techniques (ACF, *Median Filter* and *Step Detection*), the identification of complete time windows in which the recorded TSS signal ranged outside of its typical dry weather behaviour can be assessed. The proposed methods were implemented for a study case (*Gibraltar* sub-basin Bogotá, Colombia), obtaining a total of seven fully-identified rainfall events. The identification seems to be appropriate, as it was consistent with the recorded rainfall pulses.

KEYWORDS

Kernel density estimators, Online measurements, Pollutants loads, Probabilistic characterization, Signal processing.

1 INTRODUCTION

Experience has shown an important influence of rainstorm water on the arrival of pollutant loads and concentrations into the receipt water bodies (Warith *et al.*, 1998). For several flow rate values, wastewater composition varies due to wash-off phenomena as a consequence of rainfall-runoff processes (Warith *et al.*, 1998). Under this perspective, rainstorm events might represent a significant variability factor on water quality for receipt water bodies with important anthropic influences.

During the past years, advances towards the understanding of pollutants concentrations have been performed based mainly in data acquired from monitoring campaigns, samples collection and laboratory analysis (see Athayde *et al.*, 1983; Saget, 1994; Duncan, 1999; Pitt *et al.*, 2004; Brombach *et al.*, 2005; Ellis *et al.*, 2006). Hence, some significant restrictions can be mentioned from this approach: (i) campaigns with limited number of rainstorm events and operational high costs, (ii) limited observations of pollutographs dynamics, (iii) low representativeness of phenomena's variability and (iv) difficulties for statistical analysis due to a limited number of data (Métadier & Bertrand-Krajewski, 2012).

Since 90's, with the development of continuous and reliable measurements in the sewer system, water quality monitoring during rainy weather has been implemented with several purposes (Métadier & Bertrand-Krajewski, 2012). Furthermore, the variability of the pollutographs produced by the runoff during rainfall events at the effluent of an urban catchment requires detailed analyses of the variability and complexity of processes and interactions involved: for identical flow rate values, different pollutant concentrations have been observed. Mentioned variability has been addressed by multiple authors (e.g. Barraud *et al.*, 2002; Veldkamp *et al.*, 2002; Grüning and Orth, 2002; Gruber *et al.*, 2005; Hochedlinger *et al.*, 2006; Bertrand-Krajewski *et al.*, 2007; Aumond and Joannis, 2008; Lacour, 2009; Lacour *et al.*, 2009; Schilperoort, 2011; Métadier & Bertrand-Krajewski, 2012).

Although cited studies had detailed into the behaviour of various pollutants in urban drainage systems, nowadays, a relationship between rainfall characteristics and TSS loads' variability at the effluent of urban catchments can be still considered an open question. The complexity of this linkage can be attributed, in a certain sense, to the fact that the beginning and the ending of the rainfall effect over the effluent has been observed to be: (i) different from the temporal occurrence of the rainfall and (ii) not easily identifiable due to the variability of water quality/quantity (Métadier & Bertrand-Krajewski, 2012; Sandoval, 2013). Furthermore, response times and durations of the effect over the effluent caused by a given rainfall pulse has been reported to be different for TSS concentrations than for flow rate (Sandoval, 2013). In this sense, identifying time windows in which TSS loads (from flow rate and TSS concentrations) are ranging outside of typical dry weather behaviour (rainy/dry TSS loads' periods) becomes pertinent. Accordingly, the following sections are included: (i) a general methodology for determining rainy/dry periods of TSS loads (measured online) based on signal processing techniques (Kernel Methods, Median Filter, Step Detection and Autocorrelation functions –ACF–) and (ii) the results of its application to a study case (*Estación Elevadora Gibraltar*, Bogotá, Colombia).

2 MATERIALS

2.1 Experimental site

This section includes a description of the urban catchment (*Gibraltar* Sanitary Sub-basin) and its effluent (*Estación Elevadora Gibraltar*), place where the *in situ* water quality measurements were undertaken. Río Bogotá's principal sub-basins can be listed as follows: (i) *Fucha*, (ii) *El Salitre*, (iii) *Tunjuelo* (principal sub-basins), (iv) *Jaboque* and (v) *El Tintal* (secondary sub-basins). The study zone for the present research was a specific sub-basin located at the Northwestern area of *Bogotá* (Colombia), called *Gibraltar* (Figure 1), which constitutes about 90 % of *El Tintal* sub-basin's total area. The total area of *Gibraltar* that has a wastewater and stormwater contribution to the effluent is estimated in about 2226 ha. To year 2007, *Gibraltar* had an afferent population of 423 216 hab and a population density of 127 hab/ha (HMV, 2007). Although *Gibraltar* sub-basin was designed mainly as a separated system, due to presence of misconnections and an inappropriate separation of wastewaters in houses' facilities (roofs and sewages waters), this sewer system can be considered mainly as combined.



Figure 1. Map of the Gibraltar's Sanitary sub-basin. Source: adapted by author from Google Earth

2.2 Collected data

Regarding the online measurements undertaken at the effluent of the studied urban catchment, the flow rate was measured by means of a NIVUS OCM Pro CF. This flow monitoring device works for a velocities ranging between 0 m/s and 2 m/s and depths between 0.1 m and 1 m, giving a precision of about 1 % for the measured data (NIVUS, 2012). The measurement of Total Suspended Solids (TSS) was executed by the use of a Visolid 700 IQ sensor. This device has a measurement range from 0 mg/l to 400 mg/l, with a resolution of 0.1 mg/l (WTW on-line, 2010). The measurement devices are capable of registering data with a time-step of one minute. Hence, this was the time-step selected for registering the water quality and quantity data at the effluent of the catchment. The flow rate and TSS signals were not filtered aiming to test the performance of the proposed methodology with a non-processed input data (presence of outlier data). In the absence of laboratory validation samples, the TSS signal was reported by the use of the global calibration of the equipment. Rainfall raw data was recorded at the Bosa rain gauge station (located in proximities of the studied urban catchment), by the use of pluviographs. This information was processed with the "GetData Digitalizer" software, obtaining a rainfall time series for each rain gauge station with a temporal resolution of one minute. Data obtained from mentioned water quantity, quality and rainfall measurements was compiled in a data base. The TSS loads computation was done by multiplying the flow rate value with the TSS concentration, recorded at the same time. Therefore, a time series of TSS loads was proposed. This time series had a total length of about 34000 minutes corresponding to 25 days of measurements (October 18th to November 11th of 2011).

3 METHODS

3.1 Dry weather probabilistic characterisation

With the purpose of assessing the dry weather typical behaviour, all signals of TSS loads during dry days (in which no rainfall was recorded) are superposed for generating an envelope in which, for each time-step of a typical dry day, multiple realizations are recorded (about 12 realizations in each time-step due to the registration of about 12 completely dry days, for the study case). This curve can be useful to evaluate, for a given rainy day TSS load signal, how far is each of its values from the typical dry weather behaviour.

For performing an appropriate probabilistic characterization of each time-step for a typical dry weather day as a stochastic process with scarce realizations, a probabilistic density function (PDF) estimation technique can be used (Kernel Density Estimators). By the use of the mentioned 12 realizations, the PDF for each time-step of a typical dry weather day can be estimated. Furthermore, by means of the PDF and the cumulative distribution function (CDF) computed at any given time-step t_i , with t_i

belonging to $[1, 1440]_{\min}$ (corresponding to the length of a day), the probability that a given data can be part of the typical dry weather behaviour can also be assessed (specially for days in which rainfall pulses were recorded).

These PDF are useful for calculating, at a given time-step, the probability of being part of the typical dry weather behaviour, for any given TSS load value (from rainy days data). This computation can be executed as follows:

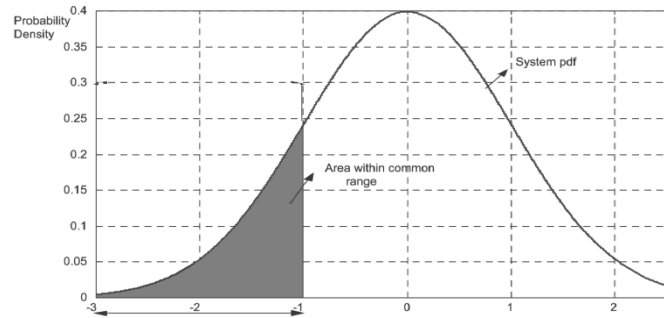


Figure 2. Estimation of a probability x , by the use of the PDF for the random variable X (adapted from Osman et al., 2005)

For a random TSS load value x , the probability that this value is “near” the typical weather behaviour will be expressed by the grey area multiplied by two (due to condition of a two tailed PDF). It is important to remember that the exposed PDF curve in Figure 2 will be different for any given time-step t_i , ranging from 1 to 1440 min (length of the typical dry weather day).

3.2 Identification of water quality's time windows ranging outside of typical dry weather behaviour

Once the probability density function for t_i is estimated, the probability that a TSS load value of the signal $X(t)$ at time t is part of the typical weather behaviour, can be computed. Next, all days of the time series in which rainfall was recorded (rainy days data) are evaluated with the purpose of detecting which time windows of the total rainy days' time series have a low enough probability of being part of typical dry weather behaviour. As a statistical proposal, each data part of a rainy day, with a probability equal or lower than 5 % of being part of dry weather behaviour can be considered part of a rainstorm event.

Due to phenomena's natural variability and possible outlier's presence, data with a high temporal closeness to rainfall pulses can report a high probability of membership to the dry weather envelope. Furthermore, data very far from rainfall pulses can report a low probability of membership to the dry weather envelope. In this sense, the exposed indicator presents discontinuities that should be treated.

With the purpose of dealing with discontinuities given by above reasons, average behaviour of the probability evolution over time, for a rainy day signal, should be assessed. For establishing time windows with a low probability ($< 5\%$) of being part of the typical dry weather behaviour over the output signal X (TSS load time series) with a consequent temporal continuity, it was considered that, whenever the output signal X is ranging outside of the typical dry weather behaviour during a considerable time, rainfall is influencing values of X . In order to treat these noisy discontinuities by estimating in which time windows the probability is in average $< 5\%$, a Median Filter is proposed over the probability of being part of dry weather signal $P_{dry}(t)$. Authors propose for the present study to support the selection of the length of the mobile time window for the Median Filter based on the autocorrelation function (ACF) concept. By the evaluation of the ACF of the TSS load X , it can be estimated how influenced is any value at $X(t)$ by their past observations, indicating how long the memory of the physical process can be. For any ACF, the correlation is still strong for the first lags and it starts to decay for longer lag values. The first lag in which the ACF is lower than the correlation's value for Gaussian Noise, will be the point in which a single observation $X(t)$ starts to forget its past. In this sense, the length of the Median Filtering's mobile window is proposed based on the lag for which the ACF will decay until a Gaussian Noise's correlation value. It is important to clarify that the ACF criteria is proposed over the TSS load $X(t)$, instead of over $P_{dry}(t)$. This decision had the purpose of achieving a more physically-based support to the proposed methodology, based in the memory of the

physical process rather than in the memory of a set of evaluated probabilities (given by $P_{dry}(t)$).

This new filtered signal $P_{dry}(t)_{filt}$, obtained by the use of a time window length estimated from the ACF of the $X_i(t)$ signal, will expose more clearly abrupt changes in time and groups of high or low values ($P_{dry}(t)_{filt} < 5\%$), by removing also isolated registers. These advantages are linked to median filtering technique rather than to the traditional moving average approach.

The following part of the proposed methodology consists in detecting for which instants of the signal $P_{dry}(t)_{filt}$ abrupt changes occur, by means of a Step Detection algorithm. Therefore, by the identification of a couple of Step Detection's neighbour points a, b (abrupt changes of the $P_{dry}(t)_{filt}$ signal), a time window $[a, b]$ in which the $P_{dry}(a < t < b)_{filt}$ behaviour can be appreciated as approximately constant (no abrupt changes inside the temporal interval $[a, b]$). Whenever the mean value $mean(P_{dry}(a < t < b)_{filt}) < 0.05$ (over the time window $[a, b]$), the TSS load signal $X(t)$ can be considered as "far" enough from the typical dry weather behaviour during the time window $[a, b]$. This fact makes the time window $[a, b]$ a continuous period in which the rainfall seemed to have an influence over the TSS load output signal $X(t)$ at the effluent of the catchment. The proposed methods were implemented in R-project (R Development Core Team, 2012) and a brief scheme of the data flow is shown in Figure 3.

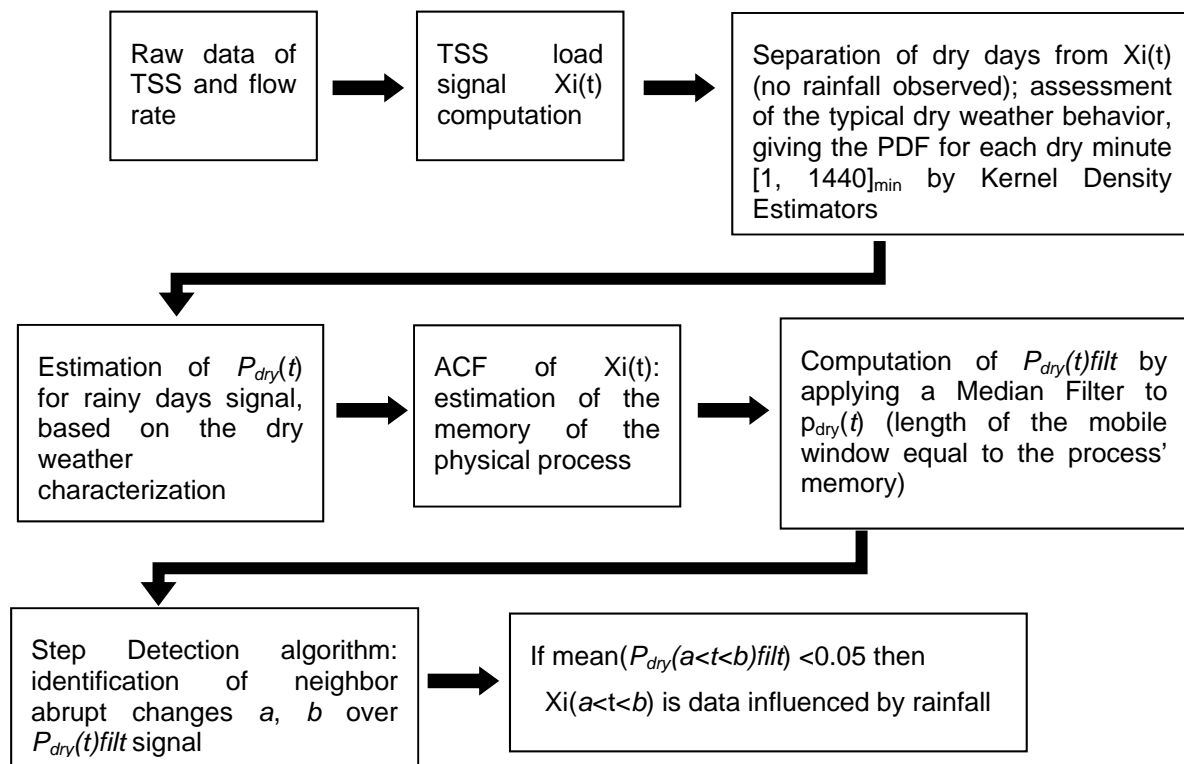


Figure 3. Data flow diagram of the proposed methodology

4 RESULTS AND DISCUSSION

The results of applying the methodology to the TSS loads (calculated from NIVUS OCM Pro CF and WTW measurements) will be exposed in the following lines. A dry weather probabilistic characterization could be assessed for the TSS loads at the effluent of the studied catchment, by the rainfall recorded at the Bosa rain gauge station (see Figure 4). Regarding these results, the time window from 300 to 600 min exposed a different behaviour in terms of the variability curves (Interquartile Distance and Standard Deviation). This fact may lead to conclude that during this period, the urban dumping and TSS load's productions by dry weather activities seem to be more dynamical. On the other hand, in agreement with the trend curves shown in Figure 4 (Median, Mode and Expectation), it can be stated that the minimum TSS loads values are about 50 g/s and occurs at 380 min. In addition, the maximum TSS values (about 200 g/s) were reported at 800 min (during a typical dry weather period). Analyzing the dry weather behaviour of the flow rate and the TSS independently,

it can be appreciated that the principal source of variability regarding the TSS load signal was the flow rate, fact that can be explained by possible turbulence effects (see details in Sandoval, 2013). With the purpose of establishing the Median Filter's unique parameter (the length of the mobile window), the ACF function of the TSS loads was computed (see Figure 5).

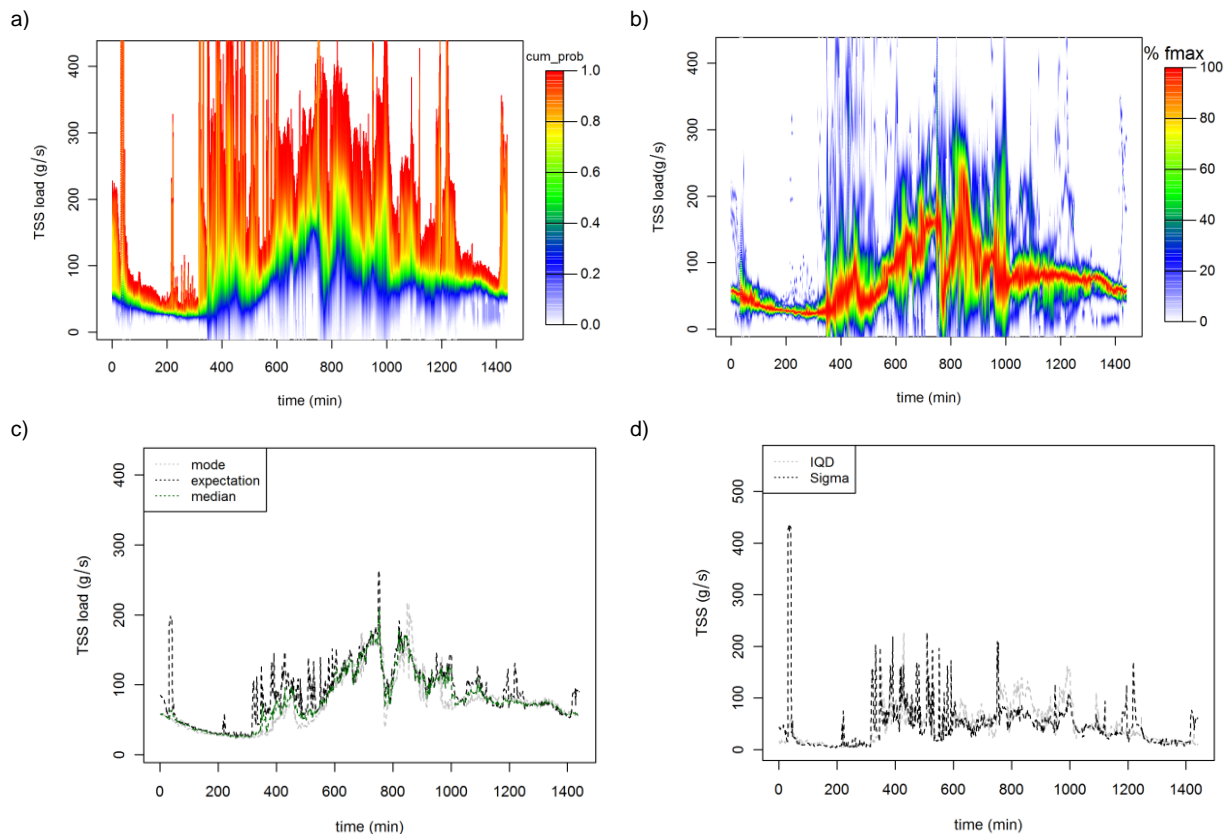


Figure 4. Dry weather probabilistic characterization for TSS loads, using rainfall registrations at the Bosa rain gauge stations; a) Probability density function (PDF) for each time-step; b) Cumulative probability function (CPF) for each time-step; c) Mode, Median and Expectation for each time-step; d) Interquartile distance and standard deviation for each time-step

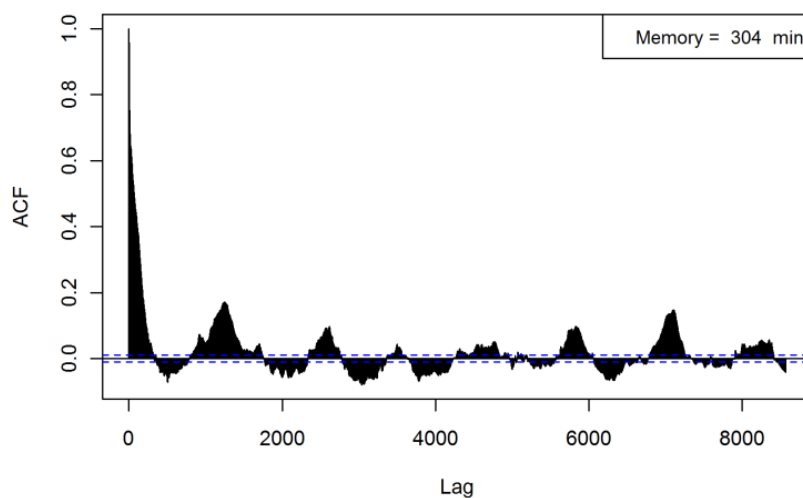


Figure 5. Autocorrelation function for TSS loads

From Figure 5, the memory of the process (pollutant's dynamics at the effluent) seems to be about 304 min. Therefore, the length of the mobile window used for estimating $P_{dry}(t)_{filtr}$ was defined as 304 min. Hence, additional analyses can be undertaken with the ACF: the response time of the system to a modification of the boundary conditions (e.g. rainfall pulses, hydraulic operation of the system, CSO or WWTP operations) can be roughly estimated by means of this approach. With the aim of assessing the response time for different treatment units at the WWTP (e.g. preliminary treatment, primary treatment and secondary treatment), the ACF of online measurements inside these components could be computed. Mentioned estimations are strongly recommended for incoming studies.

Once $P_{dry}(t)$ is transformed into $P_{dry}(t)_{filtr}$ (by means of the Median Filter), the points $[a, b]$ in which a couple of abrupt changes occurred can be identified (Step Detection Algorithm). Hence, the intervals $[a, b]$ in which $mean(P_{dry}(a < t < b)_{filtr}) < 0.05$ can also be established. Therefore, the results of $P_{dry}(t)_{filtr}$, jointly with time windows $[a, b]$ in which $mean(P_{dry}(a < t < b)_{filtr}) < 0.05$ (for the study case) are reported in Figure 6.

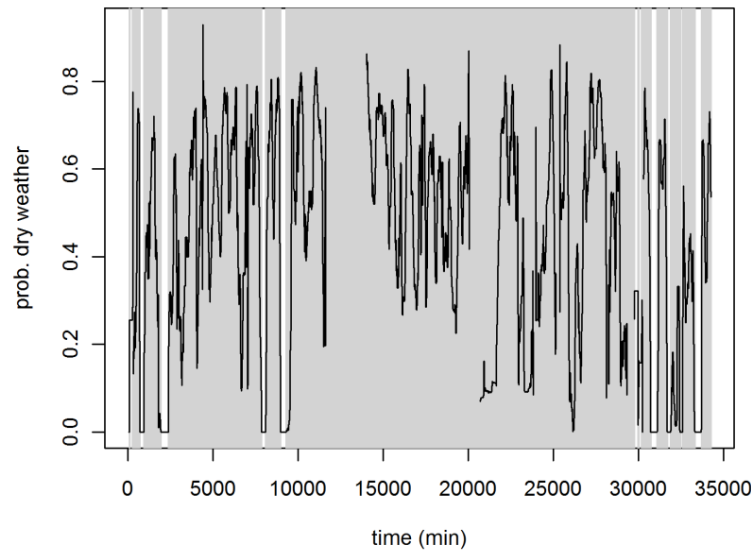


Figure 6. Probability of dry weather signal filtered by a Median Filter and Step Detection Algorithm for TSS loads signal

$P_{dry}(t)$ signal could be computed by the use of the dry weather probabilistic characterization (Figure 4). Thus, the signal is proposed to be filtered by a Median Filter with a length of 304 min's mobile time window. By the application of the Step Detection algorithm, time windows in which the mean of the $P_{dry}(t)_{filtr}$ signal was under 0.05, without reporting abrupt changes inside the interval, were identified (white stripes). The results obtained by applying the proposed methods, in terms of identifying time window ranging outside of their typical dry weather behaviour, jointly with the rainfall pulses from the Bosa rain gauge station, are shown in Figure 7.

By the proposed methodology, a total of seven complete rainfall events could be fully-identified (see Figure 7). Hence, the identification of time windows ranging outside of the typical dry weather behaviour seems to be in agreement with the registers of rainfall pulses at the Bosa rain gauge station, regarding the detected rainfall events. The outlier values, although were assigned with a low probability of being part of typical dry weather behaviour, were not included as complete time windows with a potential influence of rainfall. This fact can be explained from the Median Filter properties, which showed to be low sensitive to spurious data.

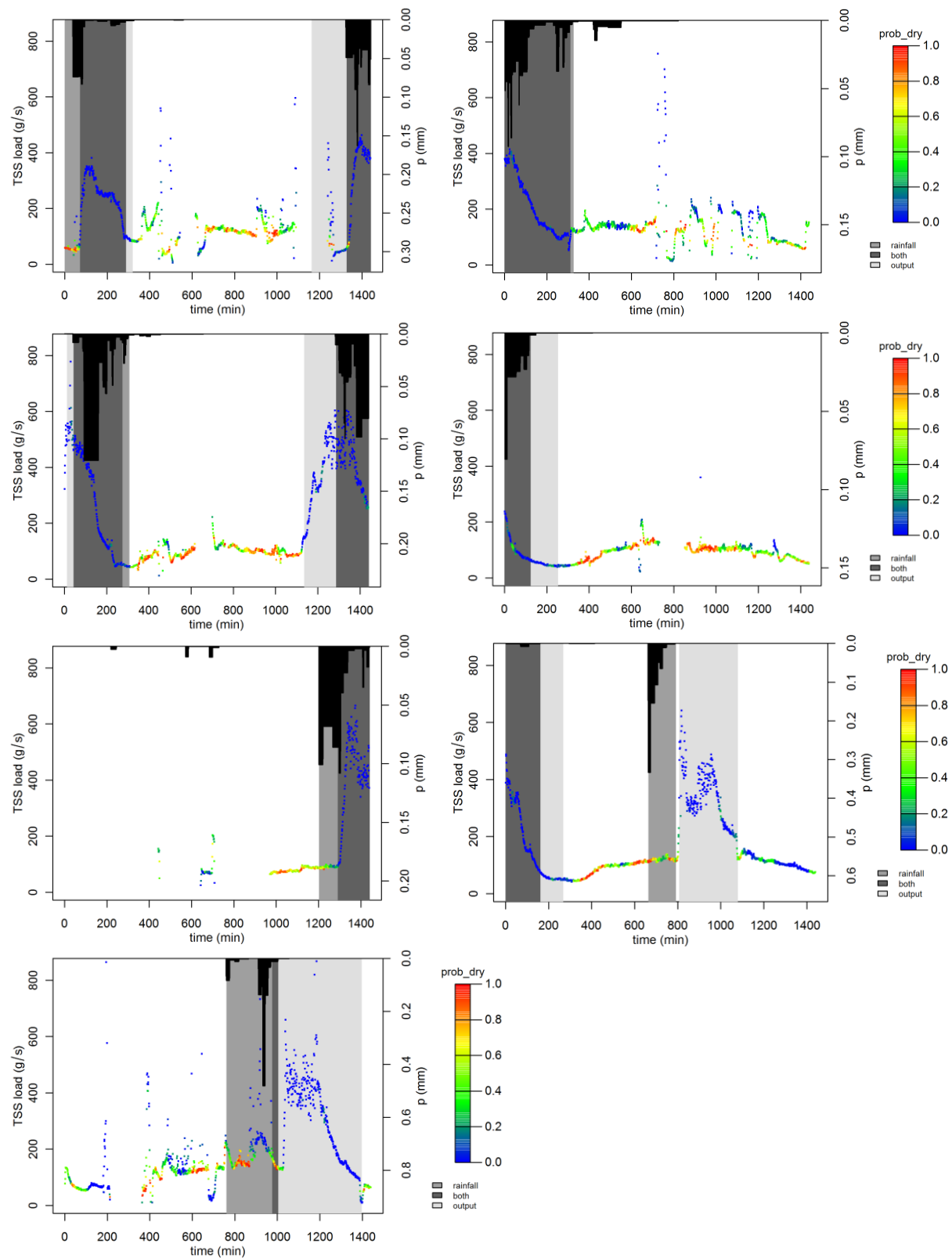


Figure 7. Rainfall pulses (“rainfall”), time windows raining outside of typical dry weather behaviour regarding TSS loads (“output”) and the overlap between the rainfall pulse and the influenced output (“both”), for rainfall from the *Bosa* rain gauge station

5 CONCLUSIONS

The present study aims to propose a methodology for identifying time windows in which the time series of TSS loads obtained at the effluent of an urban catchment seems to be ranging outside the typical dry weather behaviour. The proposed methods were designed by using signal processing and time series techniques (Kernel Density Estimators, Median Filter, Step Detection and Autocorrelation functions).

The methodology seems to report an accurate rainfall's influence delimitation over the TSS load signal computed at the effluent of a specific urban catchment (*Gibraltar* sub-basin Bogotá, Colombia) with a time-step of one minute (by means of WTW and NIVUS OCM Pro CF online measurements). The rainfall pulses from a rain gauge station in proximities of the studied urban catchment (*Bosa* rain gauge station) were consistent with the time windows in which the TSS load signal was identified to be ranging outside the typical dry weather behaviour. Therefore, a total of seven rainy periods could be fully-identified, with a temporal resolution of one minute time-step, by means of the proposed methods.

Considering that spurious data was also estimated to be outside the typical dry weather behaviour, the exposed filtering technique (Median Filter) exhibits the property of not reporting these data of the TSS load signal as a rainy time window. The memory of the physical process, estimated by the Autocorrelation Function of the TSS loads signal, seems to be an appropriate length for the mobile time window (unique parameter of the Median Filter). Hence, additional analysis regarding the ACF could be undertaken: response time of different components of a given urban drainage system can be estimated. These approaches can also bring up insights of operation and real time guidelines as coupled elements. Furthermore, the integrated and dynamical urban drainage modelling seems to be supported by this kind of results.

ACKNOWLEDGEMENTS

Authors acknowledge Bogota Water and Sewage Company (Empresa de Acueducto y Alcantarillado de Bogotá – EAAB), for providing under the Administrative Contract No. 9-07-25100-0763-2010 the information used in this research.

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