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Hydrological impact of forest-fire from paired-catchment and rainfall–runoff modelling perspectives

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Abstract This study deals with the Rimbaud catchment, a sub-catchment within the Réal Collobrier hydrological observatory in southeastern France, managed by Irstea since 1966. This observatory suffered a wildfire in 1990. Because of the dense network of streamgauges and raingauges available, this site provides a unique opportunity to test and compare two types of analysis, one based on paired catchments and the other a rainfall–runoff model, used to assess the hydrological impact of forest fire. In the present case, more than 20 years of pre-fire and post-fire data are available. We compare the ability of the two approaches to detect gradual changes at a daily time step. This case study illustrates how natural climatic variability (here a long drought which preceded the wildfire) can make the identification of hydrological changes extremely difficult.

Key words paired catchments; rainfall–runoff modelling; hydrological impact of wildfire; change detection

Mise en perspective de la méthode des bassins appariés et de la modélisation pluie-débit sur l'impact hydrologique d'un incendie de forêt

Résumé Cet article traite du bassin versant du Rimbaud situé dans le Sud de la France. Il fait partie de l'observatoire hydrologique du Réal Collobrier suivi depuis 1966 par Irstea. Cet observatoire a subi un incendie de forêt en 1990. Grâce à son réseau dense de stations hydrométriques et pluviométriques, ce site fournit une occasion unique de comparer la méthode des bassins appariés et la modélisation pluie-débit pour évaluer l'impact hydrologique de l'incendie de forêt. Dans notre cas, plus de 20 années de données avant et après incendie sont disponibles. Nous pouvons donc comparer la capacité des deux méthodes à détecter des changements graduels au pas de temps journalier. L'étude illustre comment la variabilité climatique naturelle (ici une longue sécheresse précédent l'incendie) rend extrêmement difficile toute interprétation de modification du comportement hydrologique.

Mots clefs bassins versants appariés ; modélisation pluie-débit ; impact hydrologique d'un incendie de forêt ; détection de changement

1 INTRODUCTION

This study proposes a detailed analysis of a French catchment that was used as one of the case studies for the workshop: *Testing simulation and forecasting models in non-stationary conditions*, organized within the IAHS/IAPSO/IASPEI Joint Assembly in Gothenburg, Sweden in July 2013. More information on the workshop is available in

Thirel *et al.* (2015). This analysis focuses specifically on comparing two approaches to identifying post-wildfire change.

1.1 Catchment evolution

Changes in the hydrological response of catchments are caused by changes in climate and/or physical conditions. Catchment characteristics, such as climatology, geology, lithology, geomorphology and land cover, influence the hydrological response. Quantifying how changes in catchment conditions may impact on the hydrological response is essential to enable water managers to prepare long-term adaptation strategies. Multiple factors may be acting in parallel and interacting with each other.

A catchment changes over time in response to climate (climate governs changes in catchment state variables, e.g. soil moisture). Changes affecting the catchment surface (e.g. agricultural practices, fires, deforestation, forest management) can also have an impact, in this case on the catchment's intrinsic parameters. Isolating these simultaneous effects is very difficult, because the hydrological response of a catchment integrates climate variability, environmental change and anthropic influences.

Throughout the 20th century, experimental catchments and the paired-catchment principle have allowed hydrologists (in particular forest hydrologists) to detect and study the impact of different types of anthropogenic changes on small catchments: deforestation, partial cutting, felling and thinning.

1.2 Different methods to study hydrological changes

In this study, we analyse in detail two approaches to characterize catchment behavioural changes.

1.2.1 Paired-catchment analysis The first, more classical approach is based on a paired-catchment analysis. Paired-catchment studies are used around the world mostly to evaluate and quantify effects of land-use or land-cover change on hydrology. The hydrological literature is full of examples of the use of paired-catchment techniques to examine the hydrological effects of various forest management activities. When looking at the analysed results in the literature, we can see that they focus mostly on the impact of the land-use change on annual flow and flood peaks, and sometimes only on the impact on low flows and baseflow. It is not our intention to review this voluminous literature, as several reviews on this subject are available (e.g. Hibbert 1967, Hewlett 1982, Andréassian 2004, Brown *et al.* 2005, Ssegane *et al.* 2013), but rather to outline this conceptual approach. The theory of the paired catchment is simple. Bates and Henry (1928) used simple ratio comparisons between the paired catchments, while current research uses regression methods. The basic concept involves use of two neighbouring catchments (one as a control and another as a treatment) where precipitations inputs, soil and geology conditions, and other variables may be more homogeneous between the treatment and the control catchment.

1.2.2 Rainfall–runoff model-based approaches The second method uses a rainfall–runoff model. It is not always possible to identify a stable, unchanged neighbouring control catchment or to find enough time to wait for the results of a controlled experiment on a paired catchment. Models can also be applied to a single

catchment to analyse the hydrological changes over time. In this case, the model replaces the control catchment. Approaches based on hydrological modelling have been used widely for change detection and attribution. Andréassian *et al.* (2003, 2004), Seibert and McDonnell (2010), and Gebrehiwot *et al.* (2013) list many studies. Most older hydrological studies deal with the subject by separating the analysis into two distinct, stable periods: before and after the event. But it is now clear that a rainfall–runoff model calibrated on a given period may not have the capability to simulate flows with a similar efficiency on another period, especially when it differs climatically (Coron *et al.* 2014): hydrological models often lack robustness when used in contrasted climate conditions. Thus, earlier studies divided the study period into sub-periods and defined a model of catchment behaviour for each one in order to detect non-stationarities. Siriwardena *et al.* (2006) examined eight different parameter sets derived for a conceptual runoff model using different calibration strategies to detect impact of land-use change on catchment hydrology. Siebert and MacDonnell (2010) used a modelling approach to detect hydrological changes caused by land-cover change resulting from a wildfire. Evaluation of residuals, changes in parameter values, and simulations based on different parameter sets calibrated into eight sub-periods, are three ways in which models can be used to detect hydrological changes in a single catchment over time. Gebrehiwot *et al.* (2013) used a conceptual rainfall–runoff model over three periods. Parameter sets for each period were found using a Monte Carlo approach. The results showed that change detection analysis using only parameters can be misleading and that change detection modelling should include comparisons of simulations that do not just analyse individual parameter value changes, but also use the different parameter sets to see the overall changes of the simulated hydrological regime. They also highlighted that the choice of the modelling and statistical methodology can have important influences on the outcome.

1.3 The Rimbaud catchment and the issue of the hydrological impact of wildfire

The catchments under study are located in the French Mediterranean coastal zone. The catchment geology is mostly crystalline of variable metamorphic grade. The 1.5-km² Rimbaud catchment under study here has a relatively homogenous, entirely gneiss bedrock. Before the wildfire, the catchment was covered by a dense maquis scrubland composed of tree heath, arbutus and a sparse growth of cork-oak. Thin sandy soil of ranker type covers the catchment. According to Martin and Lavabre (1997), the soil depth is less than 30 cm, with frequent occurrence of bedrock at the surface. In our study, the Rimbaud catchment is referred to as the burnt catchment, or B1. The fire spared two other catchments, Vaubarnier (1.5 km²) and Valescure (9.3 km²), so these were used as control catchments and are referred to as catchments C1 and C2. Valescure (C2) faces south and geologically is less homogenous than Rimbaud, having bedrock composed of metamorphic gneiss, micaschist and amphibolite. Soil depth varies as a function of the lithology, and overall is deeper than on the Rimbaud catchment (although it does not exceed 50 cm). The vegetation is more developed, with a maquis of heath, cork-oak, maritime pine and groves of chestnut. Vaubarnier (C1) is located about 1 km away from the burnt catchment and is covered by a well-developed forest composed mainly of chestnut trees on deeply weathered schist bedrock. The anthropogenic influence on both control catchments is currently negligible. Of the two, catchment C2 is better suited to serve as a control, because its vegetation and soil characteristics are more similar to the burnt catchment (B1).

Climate-forcing and flow measurements are available at the daily time step from 1969 to 2010, a 43-year period that covers a wide range of hydrometeorological conditions. Annual potential evapotranspiration ranges from 1000 to 1200 mm year⁻¹. The mean annual precipitation falls within this range, although the range of its fluctuations is much wider. The catchments have a Mediterranean rainfall regime, where specific features are severe summer drought and wide inter-annual fluctuations that subject the vegetation to repeated water stress.

Mean annual runoff is close to 40% of mean annual rainfall for the control catchments C1 and C2, and 55% for catchment B1, where the shallower soils are more susceptible to runoff (Table 1).

In August 1990, a forest fire burned the western part of the Maures mountain range. The Rimbaud catchment was severely affected, with an estimated 85% of its initial maquis scrub cover destroyed by the fire (Puech *et al.* 1991), which by chance spared the two control catchments.

To provide an overview of the evolution of measured flows, we traced the evolution of the ratio to the normal annual average flows for each catchment. Figure 1 shows the ratio averaged over 3 consecutive years in order to smooth the signal. We can observe several drought periods: 1980-1981, 1988-1991 and 2004-2007. Table 1 summarizes these significant values. All three catchments show slight differences, however. Catchment (C1) seems to react more to longer drought periods. It presents the lowest flow values, whereas its average annual flow is about the same as catchment C2. Figure 1 also appears to indicate that Valescure (C2) would be the best control for the Rimbaud flow up until the wildfire, after which Rimbaud systematically flows more than Valescure. This can be explained by a decrease in actual evaporation observed around 1994 (i.e. four years after the wildfire), due to the destruction of the vegetative cover. Subsequent flows give similar responses. The shrub cover made a fast recovery on burnt areas, and by August 1993 already covered around 50% of the catchment.

Several studies (Lavabre *et al.* 1993, 1999, 2000, Martin and Lavabre 2000, Fourcade 2001) have reported on the subsequent changes observed on catchment hydrological behaviour and the acceleration of erosion processes. Only flood analysis using small time steps showed a clear change in the catchment's hydrological patterns after the fire. The hydrological changes induced by the wildfire were sudden but short-lived on this resilient catchment. However, the hydrologists focused only on the years immediately following the fire, and no study attempted to assess the hydrological impact of the recovery of the shrub cover. Now, 20 hydrological cycles after the fire, we attempt to assess the impact of the fire on the overall catchment hydrology. The approaches used to compare the reactions of the catchment affected by the fire with those of the control catchments are use of a rainfall-runoff model and of a streamflow-streamflow model simulated at a daily time step.

1.4 Scope of the study

Our purpose here is to explore the change in hydrological response of a small Mediterranean catchment subsequent to the destruction of the vegetation cover by wildfire. The impact of wildfire has already been covered by a few papers published shortly after the fire (Lavabre *et al.* 1993, 1999, 2000, Martin and Lavabre 2000, Fourcade 2001). This study is an attempt to assess - more than 20 years after the fire - the impact of the fire on the overall catchment hydrology, by putting it into perspective with the natural hydrological variability observed on this catchment.

In this study, we use two methods for assessing the long-term impact of the 1990 wildfire on the Rimbaud catchment. Section 2 presents the two hydrological models to be tested (section 2.1), the numerical criterion used for model calibration (section 2.2) and the graphical representation chosen for change assessment (section 2.3). Section 3 presents the results obtained with the neighbour-catchment model (section 3.1) and with the rainfall-runoff model with (section 3.2). In section 3.3, we discuss the similarities and the differences, and in section 4, we summarize and draw a few conclusions.

2 METHODS

The hydrological literature mentions two commonly-used methods for assessing catchment behaviour changes. One is the paired-catchment approach, where the streamflow from a control catchment is used to predict the streamflow of a treated catchment based on a regression relationship between the two. This approach involves selecting two similar catchments, that are monitored simultaneously for a given time period to establish a definitive relationship between their hydrological behaviours (Hewlett 1982). It is widely used in studies on the impact of forestry practices on hydrology.

The second method uses a rainfall-runoff model. A common practice consists in calibrating the model on pre-treatment streamflow, then using it to predict post-treatment streamflow as if no change in the catchment behaviour had occurred between the first and the second periods. Treatment effects are then deducted by comparing the simulated and observed flows, based on the hypothesis that the model fully captures the catchment behaviour under the conditions of the first time period.

2.1 Hydrological models

The first model is the neighbour-catchment (NC) model introduced by Andréassian *et al.* (2012a). Its only input is the measured streamflow of a neighbouring streamgauge. It requires calibration over a period during which the streamflow of both catchments is measured. The NC model allows simulation of the flow of one catchment (the treated catchment) based on the flow measured at the outlet of the other catchment (the control catchment). Equation (1) gives the formula used in the NC model.

$$\hat{Q}_{\text{treated}}(t) = \theta_1 Q_{\text{control}}(t - \theta_3)^{\theta_2} \quad (1)$$

where θ_1 , θ_2 and θ_3 are the three parameters of the NC model to be calibrated; t is time (in days); and \hat{Q}_{treated} and Q_{control} are the daily streamflows of the 'treated' and 'control' catchments, respectively. Although this relationship is extremely simple, it can give good results (Andréassian *et al.* 2012a).

The second model is the GR4J (Fig.2), a lumped continuous daily rainfall-runoff model (RR) presented by Perrin *et al.* (2003). There is no need to detail the model here: it is sufficient to mention that it is a conceptual model widely used in France that requires calibration over at least three years to yield a satisfactory identification of its parameters. The method applied here is obviously not specific to GR4J, and could be reproduced with any other equally performing model. The important point is that the model must be able to capture the rainfall-runoff relationship.

2.2 Criteria used to evaluate model simulations

To calibrate both models, we use a single criterion, the Kling-Gupta efficiency, KGE, suggested by Gupta *et al.* (2009):

$$KGE = 1 - \sqrt{(1 - \alpha)^2 + (1 - \beta)^2 + (1 - \rho)^2} \quad (2)$$

Where α ($= \sigma_{obs}/\sigma_{sim}$) is the ratio of the observed standard deviation to the simulated standard deviation; β ($= \mu_{obs}/\mu_{sim}$) is the volume bias, i.e. the ratio of the observed average to the simulated average; and ρ is the Pearson correlation coefficient. These three components are combined into the KGE criterion, which is optimal for a value of 1, such as the widely known Nash-Sutcliffe criterion.

2.3 Testing procedure and graphical representation

The testing procedure proposed by Schreider *et al.* (2002) and adopted by Andréassian *et al.* (2003) and Coron *et al.* (2014) is used in the study. Figure 3 illustrates this method. To analyse the hydrological impact of the wildfire on the Rimbaud catchment and its subsequent recovery, the model (either RR or NC) is calibrated over three-year periods. We divided the entire available time series into short overlapping time periods and we use overlapping slices for a smoother evaluation of the hydrological signature. A 3-year calibration period seems sufficiently long to capture the response of a catchment's streamflow, and short enough to represent a quasi-steady-state of land use conditions (Schreider *et al.* 2002). Each parameter set allows for reconstruction of a representative flow time series, over the same time length as the control catchment time series. Thus, we obtain 41 series. This long reconstructed time series (from 1969 to 2011) allows the derivation of all the classic flow quantiles in order to fully characterize (synthesize) the average hydrological behaviour over the three years of observation.

Visually comparing the simulated flow duration curves (FDC) with those observed for all periods is oneway to compare the distribution, but it is not easy in our study, due to the number of simulated periods (41) for each catchment. Also, for better readability, three specific quantiles, focusing on average flows, high-flows and low flows, were calculated. These different quantiles can be represented as the graphical representation that was presented in Andréassian and Trinquet (2009) and Andréassian (2012). The FDCs for each catchment are generated using the Weibull plotting position (Cunnane 1978), expressed by:

$$F = \frac{r}{n + 1} \quad (3)$$

Where F is non-exceedence probability, r is the rank of flow, and n is the size of the dataset.

Our catchments have streams that are intermittent in the same season each year. For these, null discharges are quite common and the observed and simulated quantiles are equal to 0. Figure 4 presents the FDC for the catchments studied (burnt and control catchments) on observed daily flow data. It shows that 'cease-to-flow' values for catchment B1 are less than 27% of the non-exceedence probability. Thus, the catchment is under zero-flow condition for at least 30% of the total period. For this reason, $Q_{0.5}$ will be considered as a 'low-flow indicator' because its value is low but not null, even though it represents the non-exceeded discharge value 50% of the time. The $Q_{0.9}$ is a high-flow indicator, as it represents the exceeded discharge value 10% of time.

Figure 5 presents the proposed visual interpretation of the results. The x -axis represents time, and corresponds to the middle of the period on which the parameters were obtained (calibrated). The y -axis represents each quantile simulated over 43 years using the parameters sets. To aid interpretation, each graph includes: a vertical

line for the date of the forest fire, and a horizontal line for the average value of each quantile corresponding to the pre-forest fire period.

The advantage of the method lies in its ease of interpretation: There is no need to try to interpret the conceptual parameters of the two models; each parameter set is 'translated' into a series of flow quantiles, that represent a hydrological signature which is much easier to interpret. Parameter interactions can in fact complicate the interpretation of changes in parameter values.

We therefore also examined changes in system behaviour with the model-to-model comparison, i.e. the comparison of model simulations using different sets of parameters. The comparison of simulated flows is a way to overcome the problems of parameter interactions, because instead of looking at individual parameter values, you investigate the system behaviour.

3 RESULTS AND VISUAL ASSESSMENT OF EFFECTS OF FOREST-FIRE ON HYDROLOGICAL RESPONSE

The study period was divided into 41 3-year sub-periods, with a 2-year overlap. The model was calibrated over each period and the simulation was applied to the entire time series. Three quantiles were extracted from the simulated time series for analysis: $Q_{0.9}$, $Q_{0.5}$ and Q_{mean} .

3.1 Results for Rimbaud catchment with the NC model

For this analysis, the time series for the burnt catchment (B1) were created from the control catchments (C1) and (C2). For each calibration sub-period, KGE values were calculated. An overview of the model performances over the calibrated period is provided in Fig. 6. For each catchment the box plot provides the minimum, 25th, 50th, 75th and maximum percentile values for the KGE distribution.

On average, high efficiencies are reached. However, we note that the lowest KGE scores occur during the 1989–1992 sub-period, which is the only one to score low in calibration; the other sets remain acceptable. In validation, the efficiency criterion deteriorates more. The decrease is more significant in the lowest efficiencies, suggesting that characterizing the burnt catchment is more difficult using the neighbouring C1 catchment.

Figure 7(a) and (b) shows the simulated results obtained on the burnt Rimbaud catchment (B1), based on the paired-catchment method with C1 (Vaubarnier) and C2 (Valescure) control catchments, respectively. We analyse the evolution of the statistical flow values as defined in Section 2.3.

Temporal variations are clearly visible for high flow, based on the simulation data with reference catchment C1 (Fig. 7(a)). As mentioned in the introduction, initial studies of the wildfire showed an impact on peak flows just after the wildfire. Figure 7(a) shows such a behaviour, and it could validate the positive impact of wildfire on high flows. This impact can be observed for two years after the wildfire. The mean flow was also disturbed during the same period, as apparent in Fig. 7(a), where the flow curve presents the highest flood flows and mean flows of the entire period. So, this analysis confirms the positive impact of the wildfire on flow, with the exception of low flows.

However, because two other periods show a similar behaviour in the absence of fire, i.e. in 1982 and 2003, we cannot rely too much on this result; and because the wildfire occurred in the middle of the worst drought on record, it seems difficult to determine

whether this change in behaviour was caused by the drought or by the wildfire. Even for two adjacent catchments that are small (drainage area $<1.5 \text{ km}^2$) but similar, the paired-catchment approach yields results that are not easy to interpret. Similar, though weaker trends can be seen in Fig.7(b), where the C2 catchment (Valescure) is used as a reference.

3.2 Results obtained on the Rimbaud catchment with the rainfall–runoff model

The rainfall–runoff model was calibrated on both the burnt catchment and the control catchments. The data from the rain gauges located on and around the periphery of the catchments were interpolated to produce the rainfall input. In light of previous studies, the rain gauge located directly on the Rimbaud catchment was excluded from the interpolation due to serious doubts concerning the stationarity of its time series (Lavabre 1999, 2000), in connection with fire-induced changes to the environment surrounding the rain gauges.

For the rainfall–runoff analysis, the calibration and simulation periods were exactly the same as for the neighbour-catchment model. Figure 8 indicates the variability of model performance depending on the sub-period used to calibrate the parameters. As previously, high KGE criteria are obtained in calibration. Note that the variability of results is less than with the neighbour-catchment model (compare with Fig. 6): even during the drought periods, GR4J manages to find a satisfactory parameter set representing the rainfall–runoff relationship. But the drop in performance when applying these sub-period-specific parameter sets to the entire record shows that many of them lack the capacity to represent the long-term rainfall–runoff relationship of the Rimbaud catchment.

Note that catchment C1 (Vaubarnier) obtains its lowest efficiencies in validation ($\text{KGE} < 0.5$) for the sub-periods between 1987 and 1992. This seems to indicate that its behaviour during this drought period is extremely unusual.

Figure 9 shows the simulated results obtained on the three catchments B1, C1 and C2 with the rainfall–runoff model. The most surprising thing is that Fig. 9(a) shows no unusual reaction from the simulated burnt catchment (B1) for any of the flow quantiles. As we can see in Fig. 9(b), the trend with the Vaubarnier catchment is towards a long-lasting decrease in flows during drought. Figure 9(c) indicates a similar behaviour for Valescure (1989–1992), although with less amplitude. On Rimbaud, however, we observed no drought effects. It could be hypothesized that the wildfire on Rimbaud had the effect of limiting the impact of the long drought.

3.3 Discussion

The comparison of the similarities (and sometimes the contradictions) between the two different methods is extremely interesting.

Since we tested two model-based methods here to assess the hydrological impact of the Rimbaud wildfire, we need to raise the possibility of an artefact, i.e. a change that is not naturally present, but which occurs due to the limitations of the models used to reveal it. Andréassian *et al.* (2012b) discussed the potential risks when calibrating hydrological models, and Coron *et al.* (2012) gave examples of the risks arising with multiple calibrations on climatically contrasted periods. All this obviously has an impact on the calibration of a streamflow–streamflow hydrological model.

It is somewhat disturbing to note that the rainfall–runoff model does not register any significant impact of the forest fire on the Rimbaud (B1) catchment. However, based on what we can see in Fig.9(b) and (c) (which refer to catchments that were not affected by the fire), we could suggest an hypothesis: the long-term drought during

the years 1988–1991 had a profound impact on the hydrological behaviour of all catchments, and this impact concealed the impact of the wildfire. Of course, this does not explain why the drought had this effect on the behaviour. The effect of this drought blurs the analysis. One explanation could be the time step of analysis: in fact, flood analysis using short time steps showed a clear (but short-lived) change in the catchment's hydrological patterns after the fire, while Lebedeva *et al.* (2015), found no significant changes after the 1990 fire in the Rimbaud catchment's hydrological regime at the daily time step.

Andréassian *et al.* (2012) analysed several catchments in Australia and the USA using the neighbour-catchment model, where the forest cover is artificially modified. All deforested catchments show a rise in all flow quantiles as an immediate impact. That study confirmed and illustrated previous studies (Hornbeck *et al.* 1993). For the Rimbaud case, all we can conclude is that the method does not allow demonstration of a significant impact of the wildfire, because the long drought is overwhelming.

4 CONCLUSION

Our aim was to explore the limits of two methods, both subject to the same climatic variability and natural catchment behaviour variability. Both methods are model based (rainfall–runoff model and streamflow–streamflow model), although they differ in terms of degree of uncertainty:

- a rainfall–runoff model makes hypotheses about the catchment hydrological behaviour and requires rainfall input that is difficult to estimate without introducing errors;
- the neighbour-catchment model is a streamflow–streamflow model, that involves selecting two similar catchments to establish a definitive relationship between their hydrological behaviours. However, even when the catchments are subject to the same climatic variability, their hydrological reaction to a disturbing event (here, a long drought) may differ.

The Rimbaud catchment presented a particular challenge because the hydrological changes induced by the wildfire were sudden and short-lived, and occurred during a long drought period. The neighbour-catchment model shows greater changes for high flows and mean flows than the rainfall–runoff model. The reason may be that the rainfall–runoff model is less adapted to the detection of sudden changes and so was not able to distinguish between the effects of the wildfire and those of climatic fluctuations. But even if we wanted to stick to the NC model, the amplitude of the demonstrated changes would be quite different depending which control catchments we choose.

It is not easy to assess the hydrological impact of wildfires, even when we look at catchments for which there is a wealth of long-term series for observed streamflow. Going beyond models, differentiating between the impact of climate and that of wildfire does require lengthy time series. And precisely because a longtime series was available, we were able to assess the intrinsic noise of the models used. We need to improve our understanding of catchment behaviour in order to reduce (and hopefully one day eradicate) the dependency of calibration on the climatic characteristics of the calibration period. This will considerably facilitate the study of the impact of catchment perturbations on their hydrological behaviour.

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Table 1 Annual rainfall, runoff and runoff deficit in the catchments studied from August 1968 to July 2011. Hydrological year (n): August of year n to July of year $n+1$. P_A : annual rainfall; L_A : annual runoff; D_A : annual runoff deficit ($= P_A - L_A$).

Variable	Rimbaud (B1)			Vaubarnier (C1)			Valescure (C2)		
	P_A	L_A	D_A	P_A	L_A	D_A	P_A	L_A	D_A
Mean (mm)	1137	624	513	1020	400	621	1025	405	734
Standard deviation (mm)	326	304	132	268	280	269	320	246	114
Correlation coefficient for variation (%)	29	49	26	26	70	43	28	61	15
Extreme low-flow values (mm):									
1980–1981	758	314	444	756	126	630	762	122	639
1988–1991	807	303	504	713	75	638	800	107	693
2004–2007	799	278	522	705	86	619	771	160	611

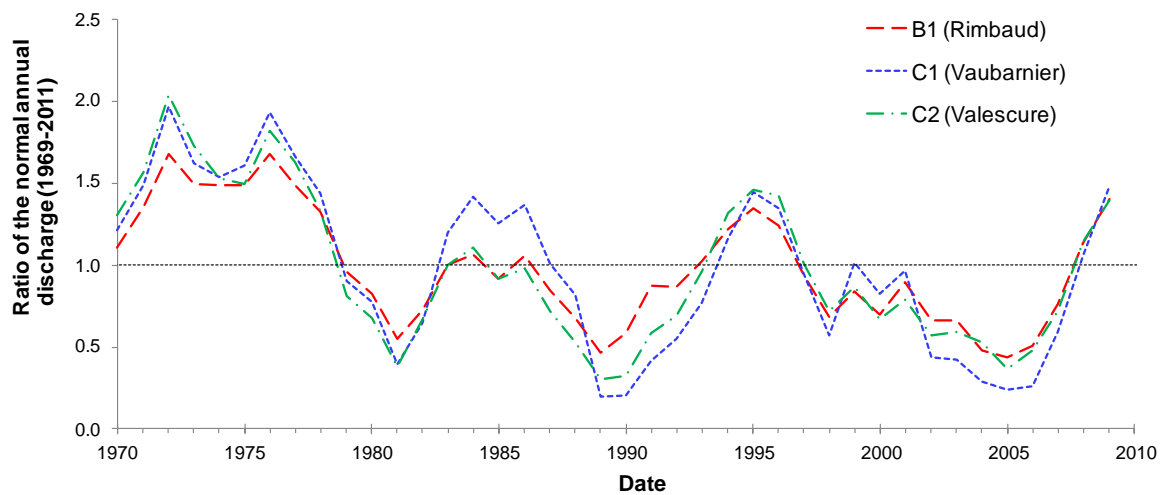


Fig. 1 Mean 3-year ratio of the annual discharge (observed data).

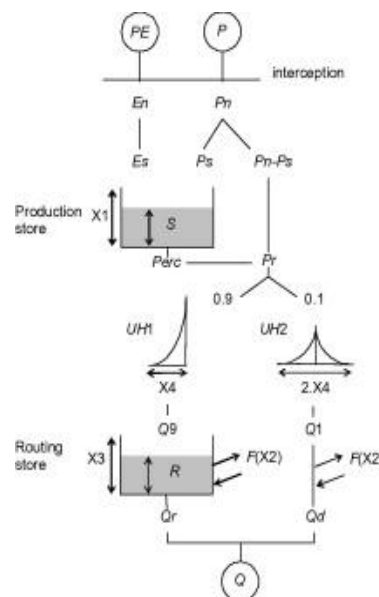


Fig. 2 Schematic diagram of the structure of the four parameter GR4J model.

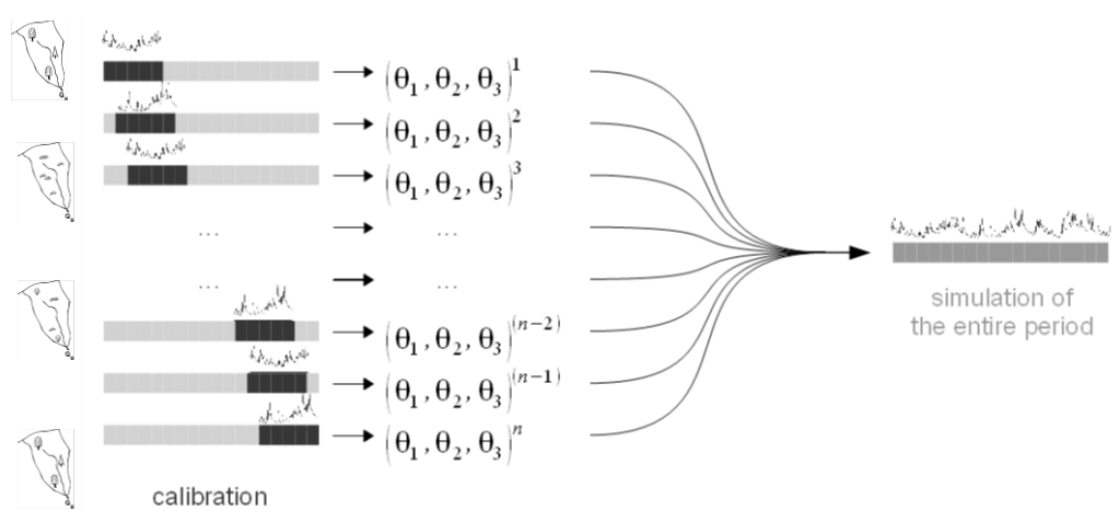


Fig. 3 Dividing procedure. Each successive overlapping slice yields one set of parameters for either the rainfall-runoff (RR) or the neighbour-catchment (NC) model. Each parameter set allows the reconstruction of flow for a long-term period, on the basis of which any meaningful hydrological statistics can be computed.

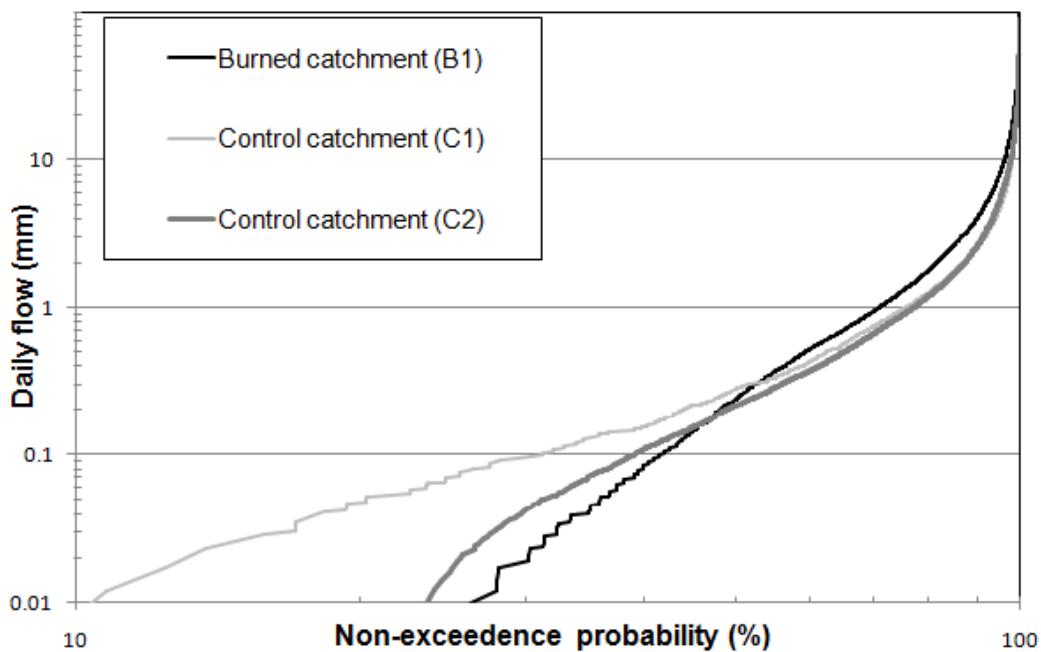


Fig. 4 Flow duration curve on observed daily data of studied catchments for the period 1969–2011.

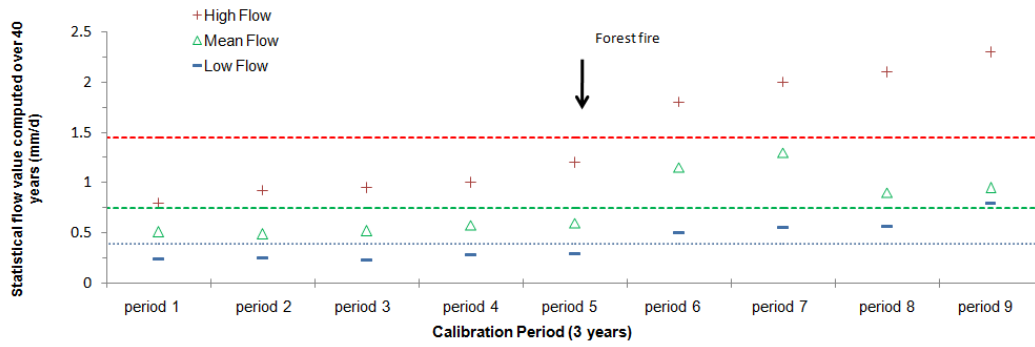


Fig. 5 Example graph showing successive flow quantiles computed for the overlapping periods. The horizontal lines show the average value of each quantile corresponding to the pre-forest fire period.

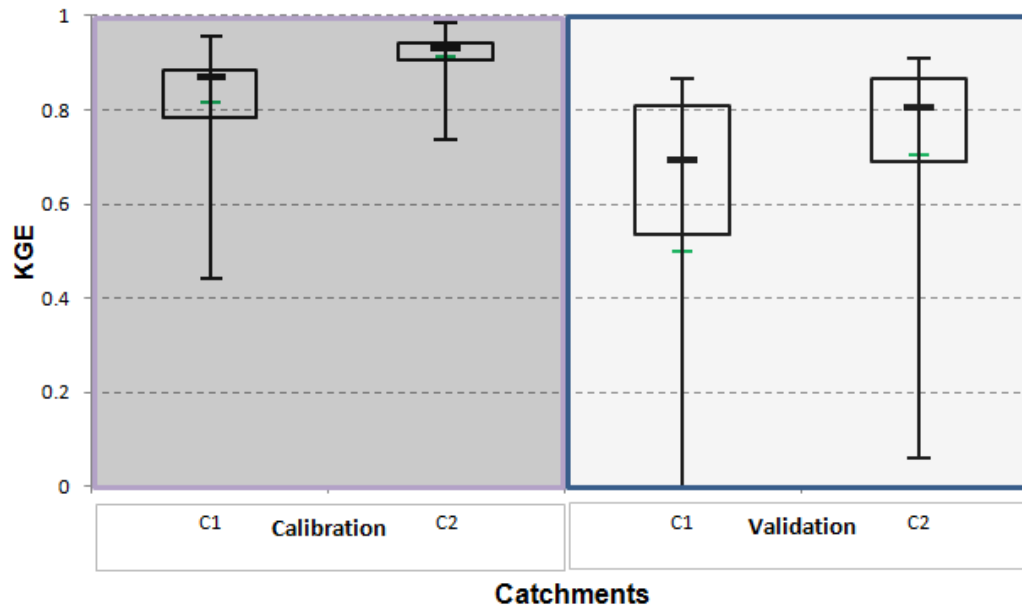


Fig. 6 Efficiency(KGE) of the Neighbour Catchment model, in calibration and validation, with the two different control catchments (C1 and C2).

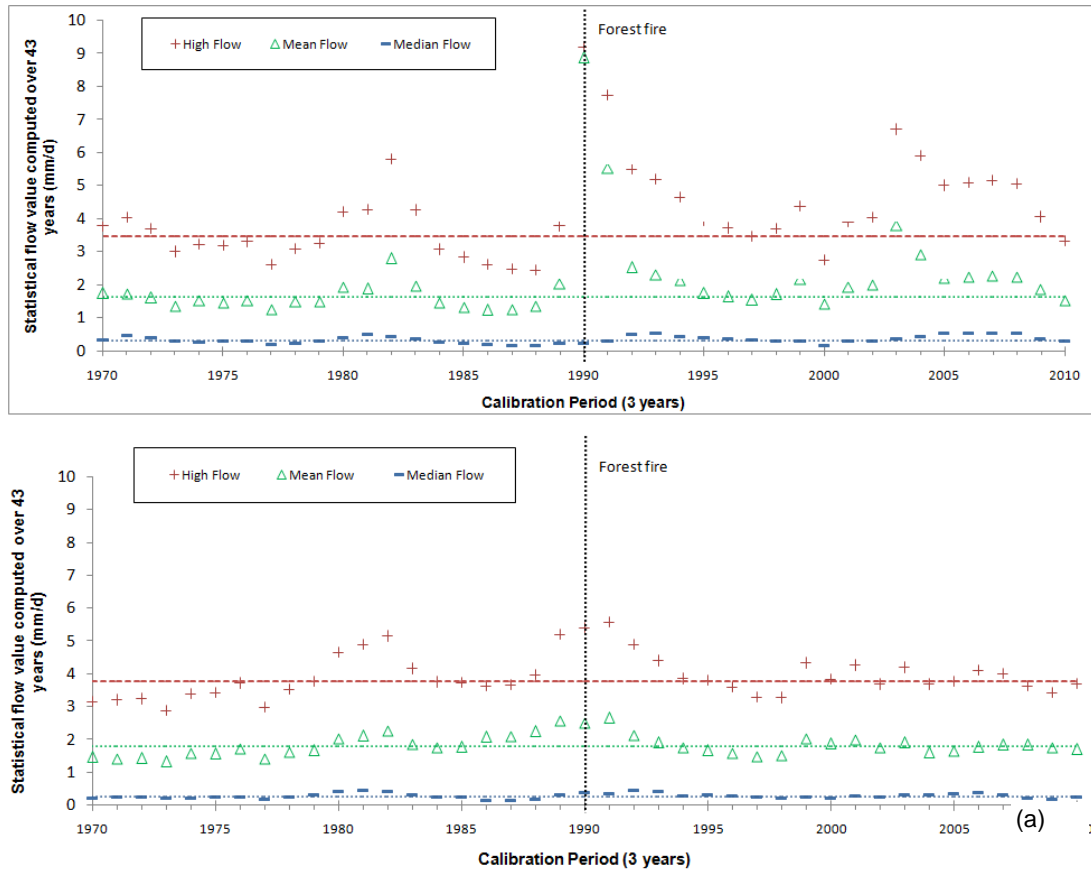


Fig. 7 Evolution of the long-term behaviour of the burnt catchment (B1), simulated by the NC model with:(a) control catchment C1 (Vaubarnier) and (b) control catchment C2 (Valescure). The horizontal lines are the average value of each quantile corresponding to the pre-forest-fire period.

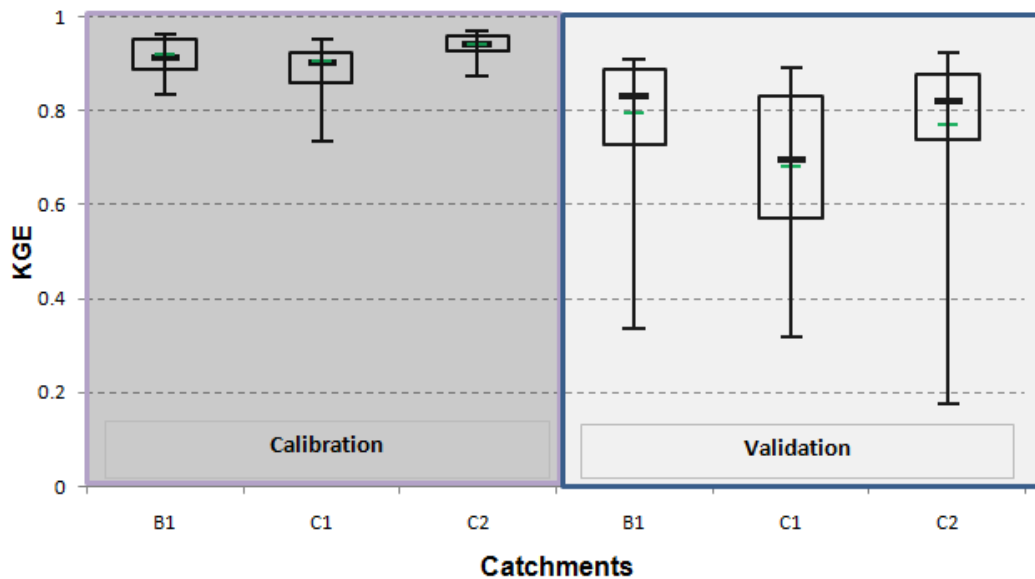


Fig. 8 Efficiency (KGE) of the rainfall-runoff model, in calibration and validation, for the three catchments (the burnt catchment, B1, and the two control catchments C1 and C2).

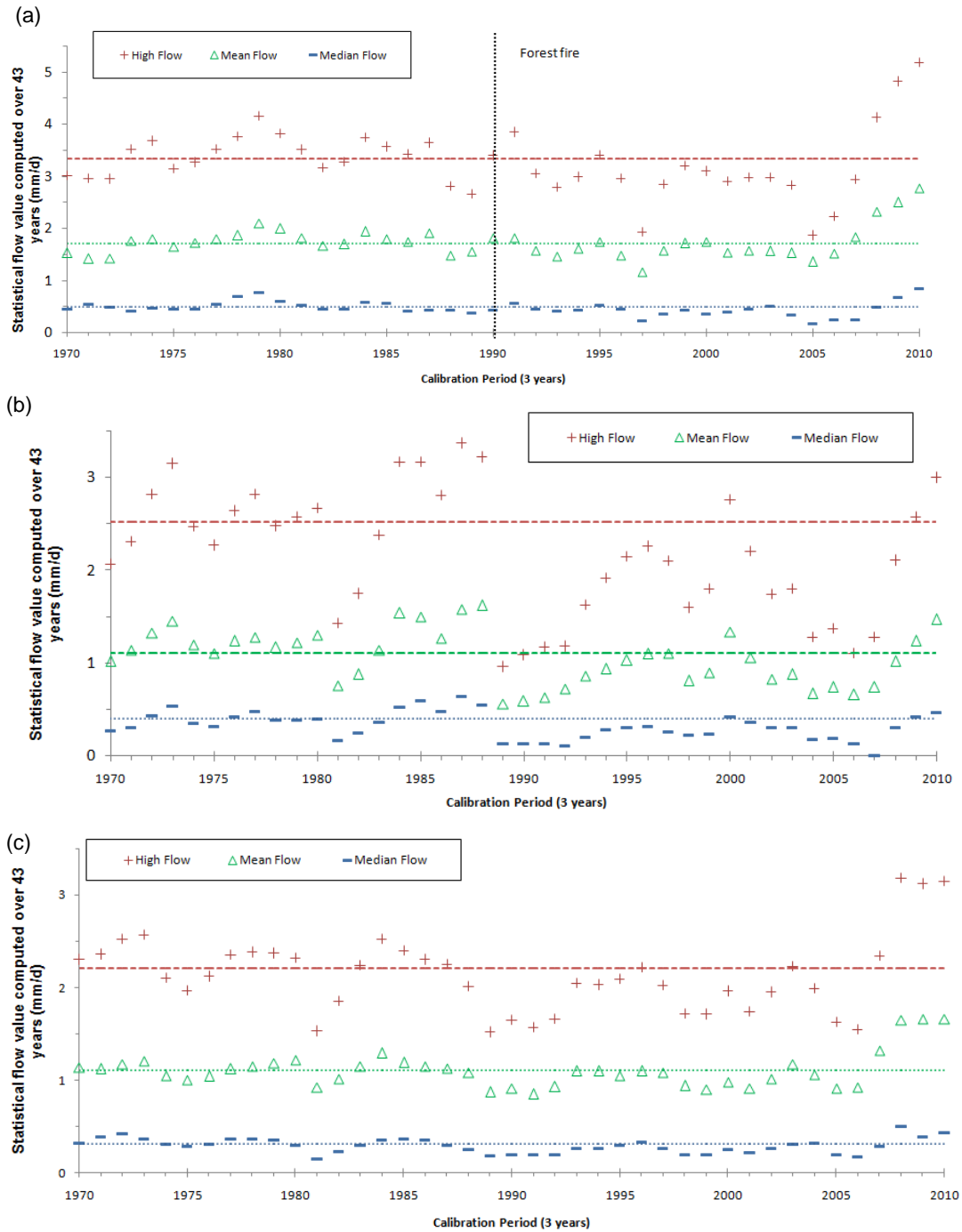


Fig. 9 Long-term behaviour of: (a) the burnt catchment B1 (Rimbaud), affected by the 1990 wildfire; and (b) and (c) the control catchments C1 (Vaubarnier) and C2 (Valescure), respectively. Flow quantiles are obtained from simulated data using the GR4J rainfall-runoff model. The horizontal lines indicate the average value of each quantile corresponding to the pre-forest fire period.