

# Using a Parsimonious Rainfall-Runoff Model to Detect Non-stationarities in the Hydrological Behaviour of Watersheds

**Vazken Andréassian<sup>1</sup>, Eric Parent<sup>2</sup> and Claude Michel<sup>1</sup>**

<sup>1</sup> Cemagref, Water Quality and Hydrology Research Unit, Antony, France

<sup>2</sup> ENGREF, Water-Related Risks Management Lab (GRESE), Paris, France

**Abstract:** The detection of non-stationarities (trends) in the hydrological behaviour of watersheds affected by environmental change has traditionally been achieved through the comparison of “control” (reference) and “modified” watersheds. These comparisons are probably the most efficient solution for trend detection, and are extensively documented in the hydrological literature. Outside experimental watersheds however, control watersheds are seldom available, and another approach is needed to assess the evolution of watershed behaviour. In this paper, we present a methodology using a parsimonious 4-parameter rainfall-runoff model (GR4J) to detect non-stationarities. The parsimony of the model makes it relatively easy to identify stable representative parameter sets over short time periods, and to quantify the calibration uncertainty for these parameters. Using this uncertainty knowledge, we generate equi-probable parameter quadruplets for successive periods of time, from which we derive through simulation a distribution of a hydrological variable (e.g. total runoff), representative of the watershed behaviour during this period. We then propose a non-parametric statistical test to identify non-stationarities from the distributions, and we validate this test on a deforested experimental watershed.

**Keywords:** rainfall-runoff models, trend detection, watershed behaviour, forest hydrology

## 1. INTRODUCTION

Human societies need a reliable supply of water for their development, and the stability of the water resource has always been a matter of concern, especially in dry areas. Direct rainfall can be used by wild and cultivated plants (provided there is enough soil to store the rain water) but society needs a “concentrated” resource (either surface water or ground water). Therefore, reliable supply of water has long been associated both with climatic stability and stationarity of watershed hydrological behaviour. Suspicion of non-stationarity in the hydrological behaviour of watersheds has caused a growing concern among the general public as well as among watershed management community during the last decades. For example, after the severe floods during the 2000-2001 winter in France and the United Kingdom, changes of land-use have often been presented as one of the causes of flooding.

How can we, as hydrologists, bring an answer to the concerns of the civil society? Concerning the stationarity of watershed behaviour, the ideal would certainly be a tool able to forecast the consequences of land-use changes at the watershed scale. However, since the hydrological validation of most “physically-based” watershed

models is still questionable, hydrologists must content themselves with a much more humble task, i.e. the detection of changes once they have taken place. And for this apparently simple task, difficulties are still considerable.

This paper deals with the possibilities of detecting changes in the rainfall-runoff relationship at the watershed scale. We first present a review of available methods for trend detection (section 2). Then, in section 3, we detail a new method to judge the probability of a trend, and we illustrate in section 4 this method on one experimental watershed known for a major change in land-use.

## 2. EXISTING METHODS FOR TREND DETECTION

Many methods have been proposed to detect changes in hydro-meteorological time series. [Perreault et al., 2000a,b] present an exhaustive analysis of this question within a Bayesian framework, addressing the problem of abrupt changes in observed series (rainfall or runoff). But we deal here with a phenomenon that is not directly observable, i.e. with the behaviour of a watershed. For this specific purpose, all the methods of detection presented in the hydrological literature are derived from paired

watershed approaches, the reference being either an actual (control) watershed or a virtual one.

## 2.1 Methods based on the paired watersheds approach

The paired watershed approach [Hewlett, 1982] involves choosing two similar watersheds, which are monitored simultaneously for a given time to establish a stable relationship between their hydrological behaviours. Then, a treatment is applied to one of them, the second remaining unchanged. After the treatment, the relationship initially derived is used to reconstitute the behaviour of the treated watershed. Comparison between actual (measured) flows and reconstituted ones allows assessing the hydrological impact of watershed treatment.

## 2.2 Simulation of virtual control watersheds

Unfortunately, when we leave the realm of experimental watersheds, and suspect a trend in hydrological behaviour on a real-world watershed, it is often impossible to identify a control watershed. We are usually limited to rainfall and runoff records for the treated watershed. In these conditions, it is difficult to judge the effects of change, as pre-change and post-change periods differ in terms of climate [Hewlett, 1982; Cosandey and Robinson, 2000]. To return to the situation of paired watersheds, we can imagine simulating a *virtual control watershed*, by means of a rainfall-runoff model. For example, a rather common practice consists in calibrating a model “before treatment”, and use it along with observed rainfall to reconstitute runoff “after treatment”. The *virtual control watershed* will consist of the model calibrated before the treatment, that can be used to simulate control flows. The effects of the treatment are then deducted from a comparison between simulated and observed flows.

Refsgaard et al. [1989] and Lørup et al. [1998] review existing methods involving a rainfall-runoff model to detect changes in watershed behaviour. Lørup et al. [1998] describe a three-step methodology for using rainfall-runoff models in this purpose:

- a. Selection of a “reference period”: part of this period is used to calibrate model parameters representative of the reference period;
- b. Validation of the rainfall-runoff model on the second part of the reference period, using a

classical approach in statistics: a split-sample test [Klemeš, 1986];

- c. Use of the model calibrated over the reference period to simulate runoff. Comparison of simulated and observed runoff allows drawing conclusions on the impact of change.

There are several examples of such studies in the hydrological literature. For example, Brandt et al. [1988] studied the impact of clear-cutting on the hydrological response of small forested watersheds. They calibrate their model on a 3-year period preceding clear-cutting, and use the calibrated parameters and observed rainfall to simulate runoff time series, which are then compared to the observed ones. Kuczera [1987] uses the same technique to analyze water consumption of forest regrowth in Australia.

Cornish [1993] looks at small ( $< 1\text{km}^2$ ) forested watersheds, where he compares two different approaches to detect changes in the annual water yield following forest exploitation: the “classical” approach uses a real control watershed, the “modeling” approach uses a rainfall-runoff model working at the annual time-step. The author showed that both approaches gave similar results, though the approach involving a model had a larger associated uncertainty.

## 3. A NEW METHOD OF TREND DETECTION

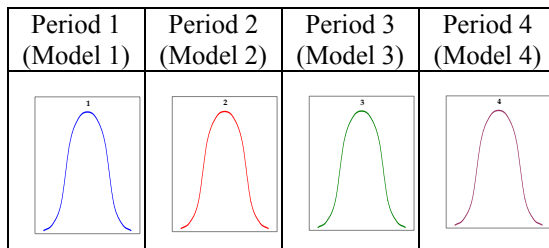
### 3.1 Method description

In this section, we present a method using a daily conceptual rainfall-runoff model conceived to detect a progressive change in the hydrological behaviour of a watershed. This method allows comparing watershed behaviour over several successive periods, and to characterize this behaviour not by a single value but by a distribution of possible values for a hydrological variable of interest. In the following discussion, we will consider that this hydrological variable of interest is total runoff (but note that the same analysis is possible on flood-flows, low-flows, baseflow, etc). Our method works in four steps:

1. We divide the period of study into  $n$  successive periods of equal length. Each period must be of sufficient length to allow for a proper calibration of the rainfall-runoff model. Here, we will consider 4 years as a minimum (one year for model warm-up and 3 years for calibration). Thus, the period 1970-1982 can be divided into 4 sub-periods: 1970-1973, 1973-1976, 1976-1979, and 1979-1982

(overlapping is permitted for the warm-up year only).

2. For each period  $i$  ( $i=1,4$ ), the model is calibrated. The optimal set of parameters is obtained by a local search algorithm, and the variance-covariance matrix is obtained by the method of Mein and Brown [1978]. Using this matrix (i.e. taking explicitly into account the covariation of parameters), we generate 100 possible parameter sets representing the behaviour of the watershed during period  $i$ .
3. We calibrate a daily rainfall simulator over the observed areal rainfall time series, and we use it to generate 65 years of daily rainfall
4. For each period  $i$ , we simulate the hydrological variable of interest (here, total runoff) using the 65 years precipitation time series, for each of the 100 possible parameter sets generated at step 4. For each period  $i$ , we have a model of the watershed ( $M_i$ ) which can be characterized by a distribution of total runoff (see Figure 1).



**Figure 1.** distribution (pdf) of total runoff characterizing each period

This method allows taking simultaneously into account climatic variability (runoff generated over 65 years covers a large spectrum of possible climatic situations), as well as modeling uncertainty (the hundred equi-probable parameter sets represent the uncertainty associated with model calibration).

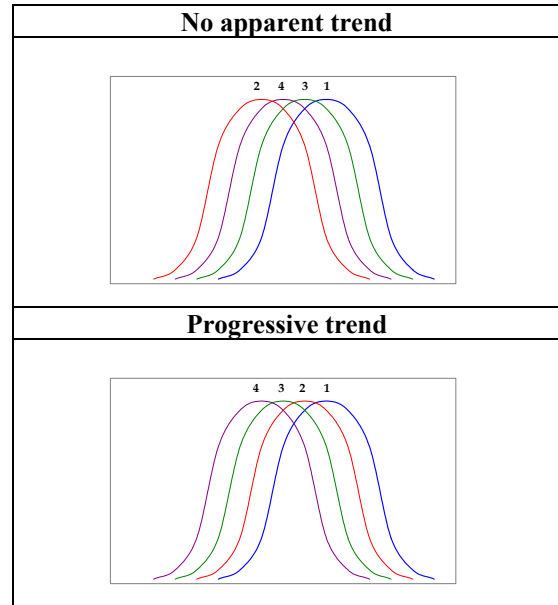
If we put the four probability density functions (pdf) of Figure 1 on the same graph, we can imagine two contrasted situations (Figure 2).

The two examples presented in Figure 2 can be interpreted as follows:

- in the first case, there is no link between the chronological order and the order of the pdf, therefore, there is no reason to suspect an evolution of the hydrological behaviour;
- in the second case, the pdf are ranked according to the chronological order, and we can thus suspect an evolution.

Note that in both cases, the pdf for each period partly overlap: this means that modeling

uncertainty remains large, in comparison to the difference between models.



**Figure 2.** example of two different situations illustrating the possible interpretation of pdf graphs

To be able to test the significance of a suspected non-stationarity, we need a statistical test. We present now a non-parametric statistical test of the following hypothesis:

$H_0$  : the order of the pdfs which characterize each model is independent of the chronological order

To build an adequate test, we first need a statistic representing the respective place of each model, and then a methodology to simulate equiprobable distributions under  $H_0$ .

### 3.2 A statistic representing the respective place of each model

The pdfs of each model can be compared by pair, and we can summarize the results of such a comparison in a table as follows (Table 1).

**Table 1.** record of the respective location of the probability density functions.  $P(M_i > M_j)$  corresponds to the frequency with which elements of  $M_i$  are larger than elements of  $M_j$ .

larger than → ↑	M1	M2	M3	M4
M1		$p(M1 > M2)$	$p(M1 > M3)$	$p(M1 > M4)$
M2			$p(M2 > M3)$	$p(M2 > M4)$
M3				$p(M3 > M4)$
M4				

If  $H_0$  is true,  $p(M_i > M_j) = 0.5$ , for any  $i$  different from  $j$ . We can thus propose the following statistic to characterize synthetically the respective layout of the pdfs:

$$S = \sum_{\substack{i=1, n-1 \\ j=i+1, n}} (x_{i,j} - 0.5) \quad \text{Equation 1}$$

where  $x_{i,j} = p(M_i > M_j)$

For the first case of Figure 2 the absolute value of  $S$  will be *small*, but for the second case, the absolute value of  $S$  will be *large*. Let us now define by simulation the *small* and the *large* adjectives.

### 3.3 Simulation of likely situations under $H_0$

The simplest solution to simulate equiprobable situations under  $H_0$  consists in inverting the chronological order of the models (i.e. of their pdfs). If  $n$  is the number of periods, there are  $n!$  possible combinations, which are all equally likely under  $H_0$ . If we compute  $S$  for all these combinations, we can draw an experimental distribution of the  $S$  statistic and identify thresholds for the 5% larger values and the 5% smaller ones. We will accept  $H_0$  if the observed value of  $S$  is between these thresholds, reject it otherwise.

## 4. TEST OF THE METHOD ON AN EXPERIMENTAL WATERSHED

### 4.1 Coshocton experimental watershed

The North Appalachian Experimental Watershed (NAEW) is located in Coshocton, Ohio, in the USA. This experimental watershed has been managed by the Agricultural Research Service since 1935. One of the sub-watersheds of the NAEW, watershed 172 (0.18 km<sup>2</sup>), was reforested in 1938. The forest plantation was thinned only 30 years later, in 1967-70 [McGuinness and Harrold, 1971]. Evolution of hydrological behaviour over the period 1938-1966 was documented by Langford and McGuinness [1976], and rainfall and runoff records are available over the period 1939-1999, with a short interruption between 1972 and 1975.

### 4.2 Rainfall-Runoff model used: GR4J

We used GR4J, a simple, reliable, continuous lumped rainfall-runoff model at daily time step,

having just four parameters [Edijatno et al., 1999; Perrin, 2000].

There are two reasons why we chose such a parsimonious model for simulation:

- first of all, we consider that the present state of hydrological knowledge does not allow us to use the so-called “physically-based” models, for which the required data are quite never available, and that need the calibration of “effective” parameters. As soon as calibration is required, we believe that the number of parameters must be kept at the lowest possible level. Twenty years of research led by Claude Michel at Cemagref, Antony, resulted in a four-parameter model to represent the rainfall-runoff relationship at the daily time step. Perrin et al. [2001] showed that this model yielded the same performances as the best existing models, which used a larger number of parameters (see Perrin [2000] for a description of a parsimonious model’s development approach).
- second, it is clear that the approach presented in section 3 needs a model with well-defined parameters, that remain relatively independent from each other (if not, the simulation of equiprobable parameter sets loses its hydrological meaning). This can only be achieved by a parsimonious model.

A detailed discussion of the model structure is outside the scope of this paper, but its structure is shown in Figure 3, and a list of its parameters is given in Table 2.

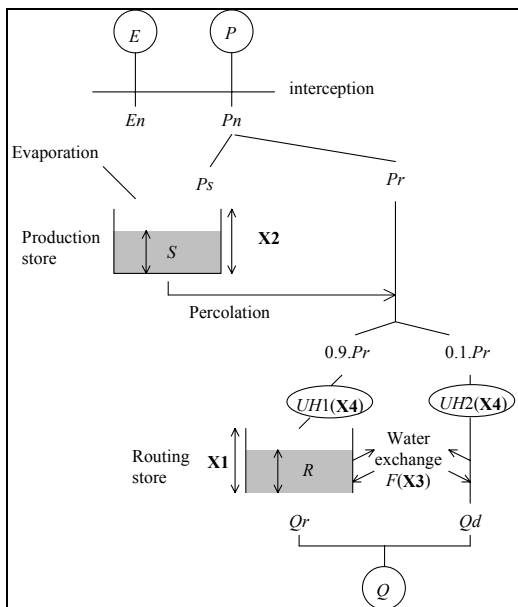
The structure of the GR4J model was developed by following an empirical approach and by testing it on a large sample of catchments. GR4J (or slightly different versions) was successfully applied in several countries and used by different authors in various hydrological studies [Servat and Dezetter, 1993; Yang and Parent, 1996; Kuczera and Parent, 1998; Yang and Michel, 2000].

The GR4J model structure is simple, with a soil moisture accounting reservoir and a water exchange function in the production module, and two unit hydrographs and a non-linear routing store in the transfer part of the model. The model showed satisfactory versatility and robustness in the comparative study proposed by Perrin et al. [2001], which comes partly from its extreme parsimony with only four parameters to be optimised. The four model parameters accounts for water balance (X2: capacity of production store; X3: water exchange coefficient) and water transfer (X1: capacity of the non-linear routing store; X4: unit hydrograph time base).

Given GR4J low number of parameters, it can be calibrated with simple techniques. Here model calibration was performed by a local optimisation algorithm called the ‘step-by-step’ method. The principle of the method is detailed by Edijatno et al. [1999]. Starting from average parameter values, the procedure searches an optimum parameter set in the parameter space by maximising an objective function.

**Table 2.** List of parameters of GR4J

Parameter	Parameter signification
X1	Capacity of the non-linear routing reservoir (mm)
X2	Capacity of the production reservoir (mm)
X3	Water exchange coefficient (mm)
X4	Unit hydrograph time base (day)



**Figure 3.** Diagram of GR4J model

### 4.3 Results

We applied our methodology on watershed 172 at Coshocton over three periods (Table 3). For the first period (1938-1967), a period of rapid forest growth that had been identified by Langford and McGuinness [1976] as a period of non-stationarity, our test confirmed the strong negative trend for total runoff, with a p-value of 0.9 %. This confirms results of the hydrological literature on the diminution of total runoff following afforestation [Bosch and Hewlett, 1982].

**Table 3.** results of the non-stationarity test for Coshocton over 3 different periods

Period of test	trend	sign	p-value
1938-67	yes	-	0.9 %
1976-99	no		19.5 %
1938-99	no		31.6 %

For the period 1976-99, no trend can be detected, and we should conclude that the watershed behaviour has stabilized after 40 years of forest growth.

Last, it is interesting to look at test results over a mixed period (non-stationary period followed by a stationary period). Over 1938-99, no trend can be detected by the test. This shows that a test like the one we presented cannot be applied blindly, and requires some hydrological thinking beforehand.

## 5. CONCLUSION

In this paper, we presented a new methodology to detect non-stationarities in watershed behaviour using a parsimonious 4-parameter rainfall-runoff model (GR4J). We divided the study period in sub-periods and defined for each of them a model of watershed behaviour, characterized by the distribution of a hydrological variable (here, total runoff). The non-parametric statistical test proposed here was able to identify the non-stationarity of hydrological behaviour on a reforested watershed, during the first 30 years following reforestation. No trend was apparent during the last 30 years of the rainfall-runoff series, suggesting that the watershed had reached equilibrium under its new land-cover.

## 6. ACKNOWLEDGEMENTS

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