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WEATHER GENERATOR TOOL FOR THE ASSESSMENT OF WATER RESOURCE PLANNING IN MEDITERRANEAN WATERSHEDS

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This work presents a Weather Generator (WG) tool to simulate annual sequences of rainfall events in Mediterranean watersheds based on Monte Carlo simulation and Bayesian techniques. Ground measurements of precipitations and synoptic maps are used to define cyclonic-front rainfall events in terms of duration and rainfall amount on a local (basin) basis. The resulting event series are statistically studied to develop empirical probability functions for every step in the Bayesian hierarchy ranging from annual precipitation and number of events to every event occurrence and its amount and duration, to build N equally-probable samples of V years of precipitation in a given watershed, each year consisting of M precipitation events of given duration/amount at the watershed scale, distributed within each year. The Weather Generator was applied to the Guadalfeo River Basin (Southern Spain), a 1360-km² coastal mountainous watershed with altitudes ranging from 3200 to 0 m.a.s.l. The synthetic samples of V years obtained through the WG tool were used to assess the current variability of climate in this area, the uncertainty of water resource availability in a 30-yr time horizon, and the uncertainty of extreme flood events in the main course of the river. These application examples are representative of the potential uses of the tool.

INTRODUCTION

Water resource planning requires the forecasting of precipitation at different time scales that are dependent on the planning horizon for decision-making. In Mediterranean areas, the uncertainty associated to precipitation occurrence and amount is very much linked to alternate sequences of highly variable dry and wet pluri-annual cycles, and the torrential character of some of the
rainfall events within the wet season. Moreover, most of the precipitation is associated to cyclonic fronts passing over the region, and their interaction with the regional and local topography. This variability supports the development of stochastic models to forecast hydrological variables for water resource planning (e.g. Beven [1], Krzysztofowicz [2], Yu et al. [3]), especially in a decision-making framework to identify the best alternative among different options of water–soil use. When risk analysis is to be performed, the stochastic forecasting is a requirement.

The occurrence of precipitation events acts as the main driver of runoff generation, filling of the hydrological systems, and flow routing throughout the watershed, whereas the dry periods between two consecutive events (no-events) determine the depletion of water storage in such systems and their initial state facing the next event to take place. Assuming this as the most significant source of uncertainty in the forecasting of hydrological variables, this work proposes a tool for the generation of precipitation event series within a year during a group of years. The resulting Bayesian model is used as the basis to assess the uncertainty of different hydrological variables in Mediterranean watersheds.

**METHODOLOGY**

Two different stages are identified, the characterization of the Bayesian structure of the Weather Generator and the obtention of derived hydrological variables. Firstly, the event/no-event series is built from the available daily precipitation dataset from the M weather stations in a given watershed. An “event” is defined as a period in which some point within the watershed has registered a cumulative precipitation higher than a given threshold, associated to the occurrence of a given cyclonic front. A “no-event” is, then, the period between two consecutive events. The event is characterized by its duration and its cumulative precipitation averaged over the watershed, together with the type of cyclonic-front that generates such event; this type is selected from a prior classification of the K significant synoptic patterns that are locally associated to rainfall occurrence. For forecasting purposes, two different hydrological seasons are identified in Mediterranean regions: wet (September 1 to May 31, 263 days) and dry (June 1 to August 31, 92 days) seasons. The event empirical sample obtained during a V years of historical rainfall data is then split into these two seasons. Figure 1 shows an example of the event (and no-event) identification for some years within the 1967-2007 period in the Guadalfeo River Basin (South Spain).

From this event and no-event series, the following Bayesian structure was identified from the analysis of the corresponding empirical probability functions (f), which is used as the cascade of the stochastic Weather Generator (WG) by Monte Carlo simulation under the hypothesis of independence of each year within the group of V years:

1. On an annual basis, the WG generates the number of events \( E_i \) (\( i=1..V \)), and the number of events in the wet season, \( E_{\text{wet},i} \), from \( f_{E_{\text{wet},i}|E_i} \) (\( E_{\text{dry},i} \) is determined from \( E_i = E_{\text{wet},i} + E_{\text{dry},i} \)); the number of \( E_{1,i} \) to \( E_{k,i} \) (\( k=1..K \), the types of cyclonic-fronts in the region) for both the wet and dry seasons from the conditional probability functions of type \( k+1 \) to type \( k \), and maintaining the sum of events of each type equal to \( E_{\text{wet},i} \) and \( E_{\text{dry},i} \), respectively; the number of rainfall days for the year \( i \), \( n_i \), and the number of rainfall days during the wet season, \( n_{\text{wet},i} \), from \( f_{n_{\text{wet},i}|n_i} \) (\( n_{\text{dry},i} \) is determined from \( n_i = n_{\text{wet},i} + n_{\text{dry},i} \)); finally, the total annual precipitation \( P_i \) is simulated, and the total precipitation during the wet season, \( P_{\text{wet},i} \), from \( f_{P_{\text{wet},i}|P_i} \) (\( P_{\text{dry},i} \) is determined from \( P_i = P_{\text{wet},i} + P_{\text{dry},i} \)).
2. On an event basis, for each event $E_{k,i}$ duration $D_{k,i}$ is generated; its cumulative precipitation $P_{k,i}$ is then generated from $f_{P_{k,i}/D_{k,i}}$. Every time one event is characterized for both duration and precipitation, the probability functions used for the simulations are truncated to maintain the annual variables previously associated; the final event for both the wet and dry season is estimated as the residue values of rainfall days and precipitation.

![Figure 1. Observed event series during 1985-1994 in the Guadalfeo River Basin; day of the year in the X-axis (starting September, 1), and averaged rainfall for each event (mm) in the Y-axis. Blue and red zones in the figure stand for the wet and dry season in this work, respectively.](image)

The WG produces $N$ replications of $V$ years consisting of $E_i$ events ($i=1..V$) and the corresponding variables as described in previous paragraphs, being $N$ the minimum number of replications that assures a given statistical significance of the simulation. Each replicated set of variables reproduces the probability functions of the observed variables at the annual and seasonal scales. Monthly trends were not included in the model and, thus, they cannot be analyzed from this approach.

**STUDY SITE**

The Guadalfeo River Basin is located 35 km north from the Mediterranean Sea in southeastern Spain. Elevations rise up to 3500 m.a.s.l. and thus, it is characterized by high altitudinal gradients and strong heterogeneity produced by a high mountain climate, with significant snowfall occurrence every year (Herrero et al. [4]), influenced by the surrounding Mediterranean climate downhill to the coast (Aguilar et al. [5], Aguilar and Polo [6]). The mean annual rainfall and temperature in the area ranges from 800 mm and 10 °C in the upper part of the watershed to 450 mm and 17 °C on the coast. The main part of the watershed, in terms of hydrology, is comprised of the southern hillside of Sierra Nevada, where global radiation is high throughout the year, even during winter, due to its southern orientation and lack of cloud.
In 2002, Rules Dam started to function as a flood control structure and water supply for the population on the coast (Figure 2). The reservoir covers an area of 309 ha and the fluvial discharge to it is gauged in the stretch upstream.

A potential relationship was identified between the annual precipitation averaged over the watershed and the annual maximum daily inflow to the reservoir by Polo and Losada [7].

RESULTS

The WG tool was implemented on a Visual C++ program for Windows called “SimClima” (Figure 3) which manages the data inputs to the Bayesian model described above structured as functions programmed in MatLab (these are command files .m; MatLab v.7.4 or superior is required to run the tool). Two main modules were structured in the program: input data analysis, and simulation definition.

Two applications of SimClima are included in this work as examples. Firstly, the intrinsic variability of extreme precipitation variables in the study site was analyzed from the results of
250 replications of the historical period 1967-2007. Figure 4 shows the cumulative distribution functions for two selected 40-yr extreme variables.

![Figure 4](image)

Figure 4. Simulated cumulative distribution functions (cdf) of the maximum $E_i$, and maximum $P_i$ in 40-yr at the study site (left and right, respectively).

These functions are two examples of the estimations of the intrinsic variability of rainfall variables at the study site. They can be used to assess the results of future scenarios of climate change in terms of their impact on the precipitation regime being significant or not.

The second example shows how the simulated rainfall regime can be used to assess the uncertainty of derived hydrological variables. The annual maximum instantaneous daily inflow, $Q_i$, to the reservoir was simulated from the simulated cdf in Figure 4-right and the potential relationship between the annual precipitation averaged over the watershed, $P_i$, and $Q_i$ (Figure 5).

![Figure 5](image)

Figure 5. Simulated cumulative distribution function (cdf) of the maximum $Q_i$ in 40-yr at the selected river stretch in the study site.

**CONCLUSIONS**
The WG implemented on SimClima is a simple-to-handle but efficient tool to forecast rainfall event regime associated to cyclonic-fronts in Mediterranean regions from daily rainfall datasets and synoptic information. This feature allows the inclusion of shifts in the significant types of cyclonic-fronts, the first and/or second order moments of the statistical distributions of the event variables, etcetera, acting on an area as climate change descriptors.

The combination of the WG results with a hydrological model allows the assessment of the uncertainty of variables different from precipitation, for which less monitoring points, with also shorter time series are usually available. This is especially useful for forecasting extreme events associated to threshold states to be surpassed (for erosive processes, floods, etc.).

The definition of event used in this work is especially useful in areas where high spatial variability is found for shorter time scales (daily, hourly). This approach has been further applied to develop spatial interpolation algorithms at the event scale, for which high spatial correlation is usually found. The inclusion of spatial patterns associated to the descriptor variables for each event will allow a distributed forecasting for integrated soil-water resource planning within the watershed. Moreover, easy characterization of the dry periods (no-events) can be performed.

REFERENCES