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A modified IHACRES rainfall-runoff model for predicting hydrologic response of a river basin system with a relevant groundwater component

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Introduction

A flow regime can be broadly categorized as perennial, intermittent, or ephemeral. In perennial systems, there is a permanent connection between the stream and groundwater, and good results can be obtained from rainfall-runoff models that do not explicitly represent the groundwater store.

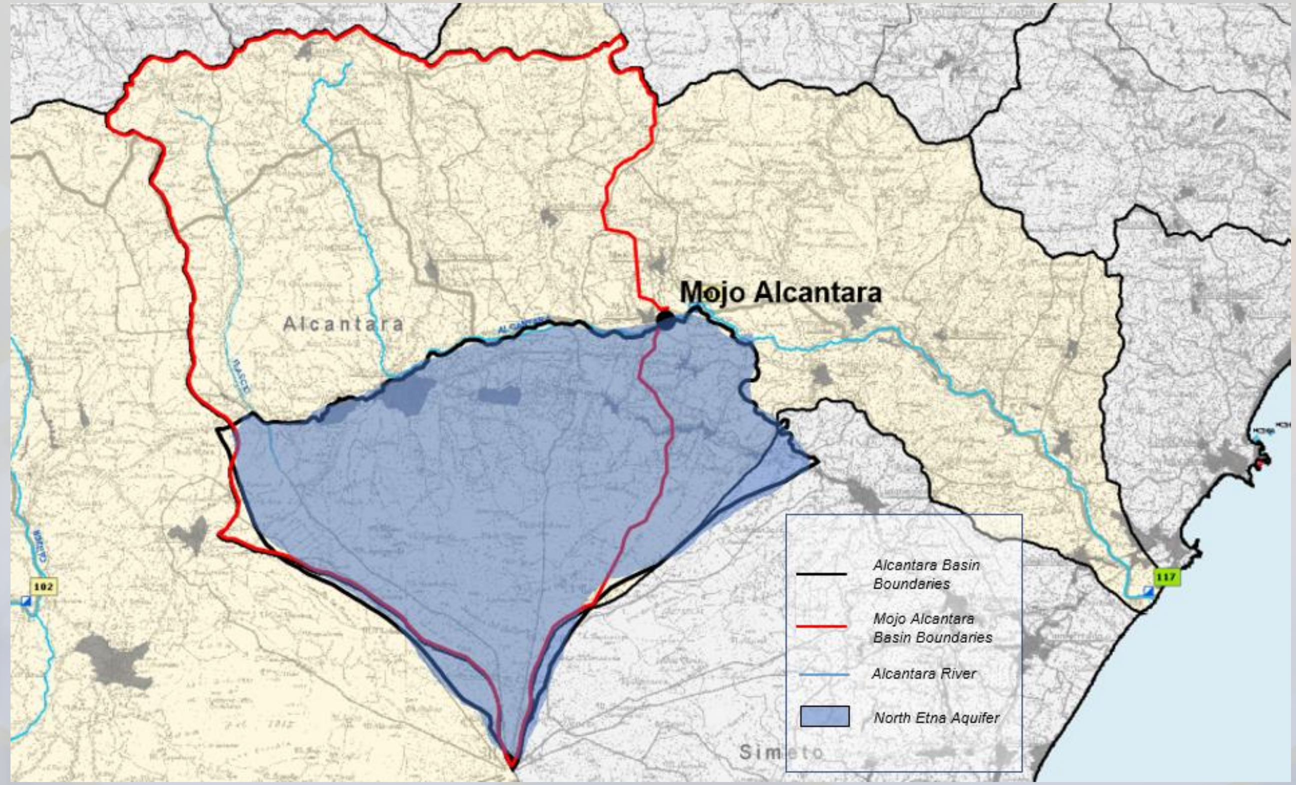
On the contrary, instead, rainfall-runoff models often fail to simulate the hydrologic connection between streams and **groundwater system** where it tends to be variable in time and space, as for the spatial intermittent streams.

This is the case of the **Alcantara river basin** in Sicily region (Italy), whose upstream is intermittent, while its middle valley is characterized by perennial surface flows enriched by spring water arising from the big aquifer of the Northern sector of the **Etna Volcano.**

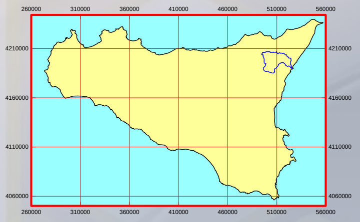
Etna Volcano, Sicily, Italy

Case Study

The Alcantara river catchment is located in North Eastern Sicily, encompassing the north side of Etna Mountain, the highest active volcano in Europe. The mountain area on the right side of the river is characterized by volcanic rocks with a very high infiltration capacity. Here, precipitation and snow melting supply a large aquifer whose groundwater springs at the mid/downstream of the river, mixing with surface water coming from the left side of the basin, whose contribution follows the rainfall annual variability typical of Mediterranean climate.



Groundwater resources are mainly used to supply all the municipalities located within the river catchment through local aqueducts, as well as the small towns along the Ionian coast; in addition: the Alcantara river also supplies some industries, farms and two hydroelectric power plants. This area is also a beautiful environmental reserve.



Alcantara River Basin and Mojo Alcantara Sub-Basin

Main Informations Table	Alcantara Basin	Mojo Alcantara Sub-Basin
Area (km^2)	603	342
Mean elevation (m)	531	1142
Max elevation (m)	3274	3274
Min elevation (m)	0	510

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Objectives of the Study

- Development and implementation of a model able to simulate the response of the system with its groundwater component explicitly modelled as well as interactions between aquifer and streamflow.

- Building up of a useful instrument for enhancement of water resources management in a complex groundwater fed catchment, the Alcantara river basin in Sicily, under different climatic and water demand scenarios.

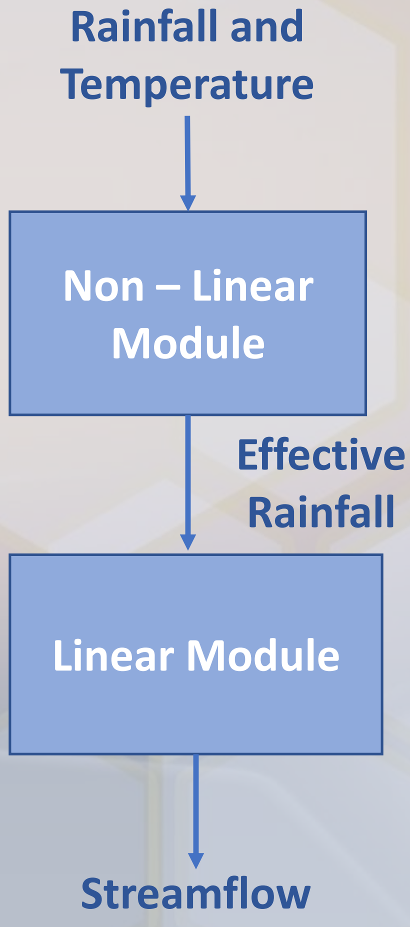
"Gole dell'Alcantara" – Alcantara Fluvial Park, Sicily, Italy

The IHACRES Model

In the **original version of IHACRES**, firstly described by Jakeman et al. (1990), the rainfall-runoff processes are represented by two modules: a **non-linear loss module** that transforms precipitation to effective rainfall considering the influence of the temperature, followed by a **linear module** based on the classical convolution between effective rainfall and the unit hydrograph to derive the streamflow.

Main advantages and capabilities of the model:

- It is simple, parametrically efficient and statistically rigorous
- Inputs data requirements are simple too, requiring only precipitation, temperature and streamflow
- The model provides a unique identification of system response even with only a few years of input data
- The model efficiently describes the dynamic response characteristics of catchments
- The model allows to obtain time series of interflow runoff with over-day storage, runoff from seasonal aquifers and catchment wetness index
- The model can be run on any size of catchment
- Simulation are quick and computational demand is low



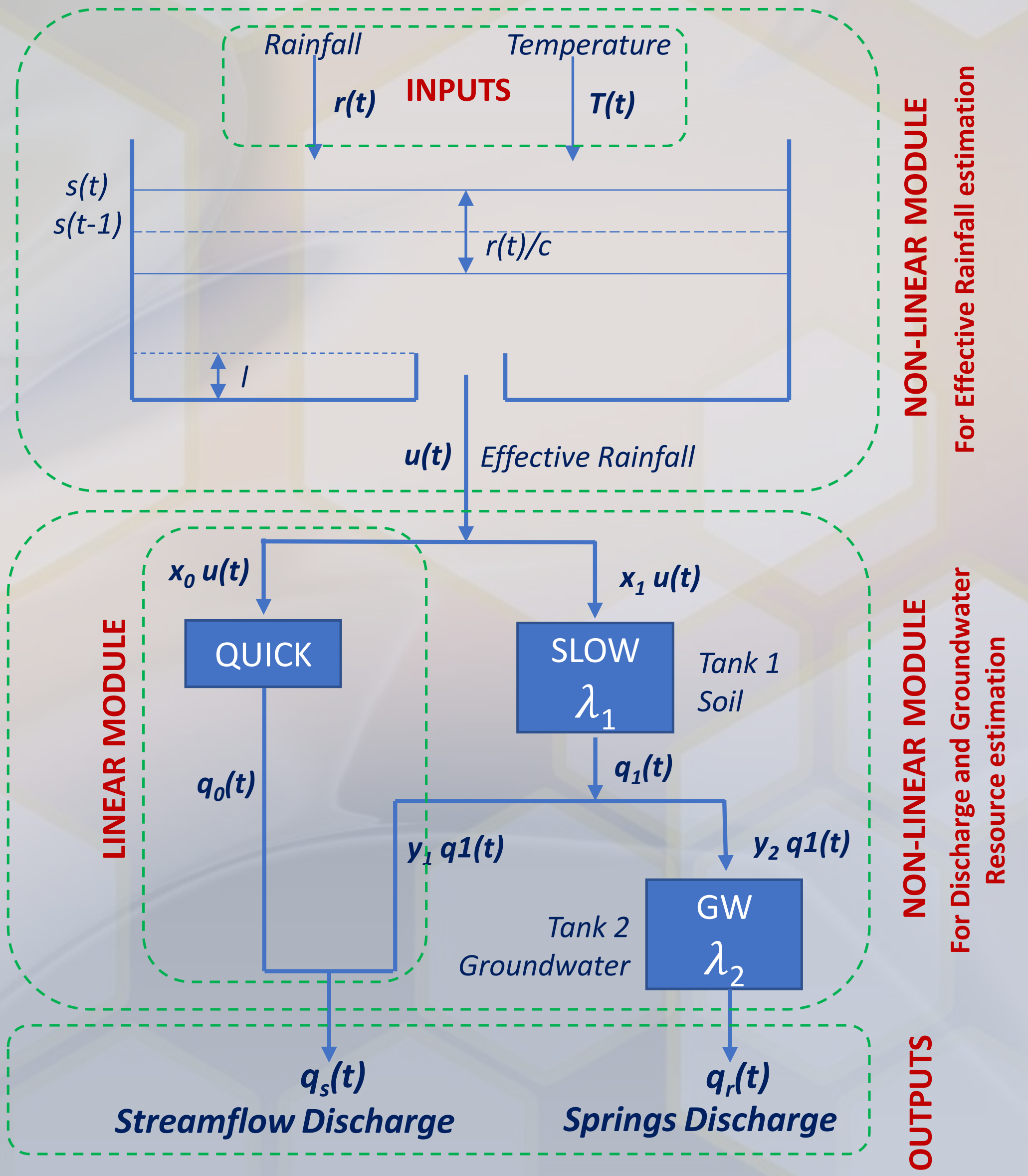
Generic Structure of IHACRES model (excerpted from Jakeman, 1990)

The Modified IHACRES Model

Hereafter a modified version of the above synthetically described IHACRES model is presented, able to better simulate the groundwater component of an aquifer system.

The structure of the modified IHACRES model includes three modules: **(1) a non linear loss module** that transforms precipitation to effective rainfall by considering the influence of temperature, after this **(2) a linear module** based on the classical convolution between effective rainfall and the unit hydrograph able to simulate the quick component of the runoff and **(3) another non linear module** that simulates the slow component of the runoff and that feeds the groundwater storage. From the sum of the quick and the slow components (except for groundwater losses that represents the aquifer recharge) the total streamflow is derived.

The need of this further non-linear module (3) arises from the necessity to properly describe the **groundwater component** of the aquifer system and to model and quantify spring discharges.



Structure of the modified IHACRES model

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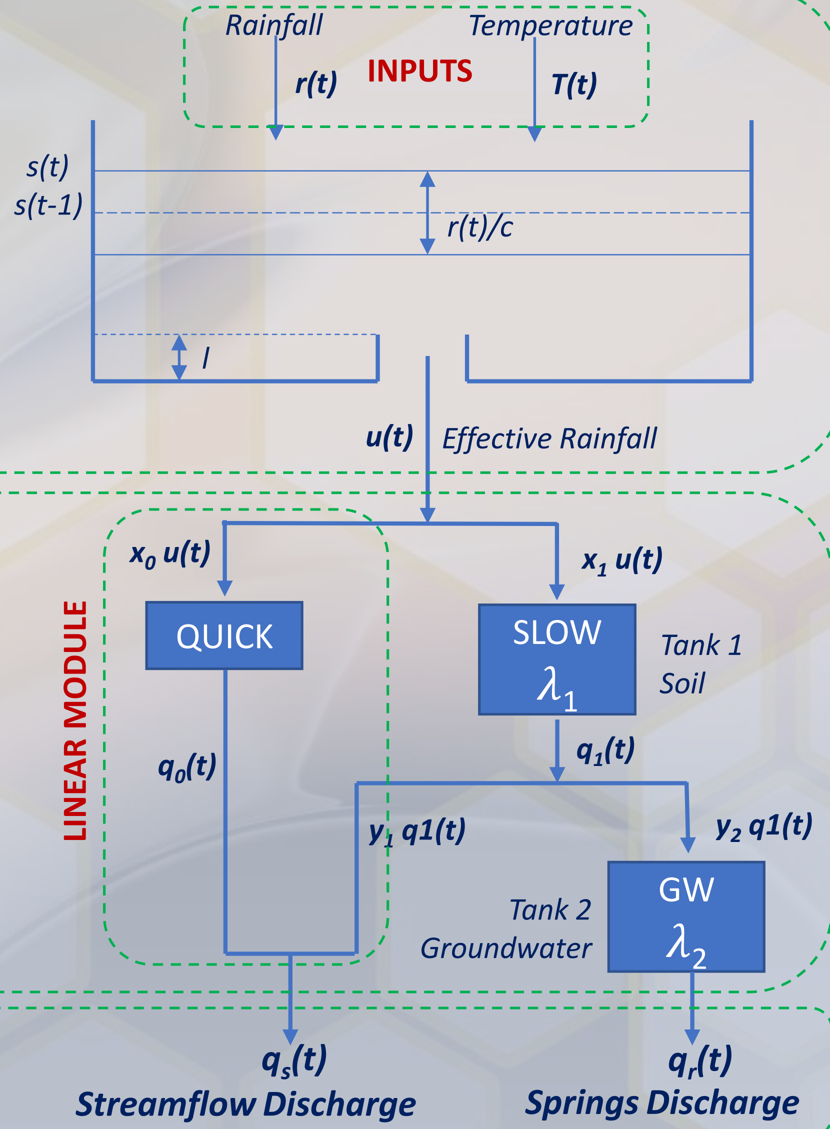
Structure of the Model and Equations

$$
\begin{cases}
\boldsymbol{u(t) = \left[\left(\frac{1}{2}[s(t)+s(t-1)]\right) - l\right]^{p} \cdot r(t)} & \text{If} \quad \frac{1}{2}[s(t)+s(t-1)] > l \\
\boldsymbol{u(t) = 0} & \text{otherwise}
\end{cases}
$$

Where:

$$
\begin{cases}
s(t) = \dfrac{r(t)}{c} + \left[1 - \dfrac{1}{\tau_w(T(t))}\right] \cdot s(t-1) \\
\tau_w(T(t)) = \tau_0 \cdot e^{[(20-T(t)) \cdot f]}
\end{cases}
$$



NON-LINEAR MODULE
For Effective Rainfall estimation

$$
\boldsymbol{q_0(t) = \frac{x_0}{t \cdot \Delta t} \cdot u(t) \cdot A \cdot \Delta t}
$$

$$
\boldsymbol{q_1(t) = \frac{x_1\left(1 - e^{-\frac{t\,\Delta t}{\lambda_1}}\right)}{t \cdot \Delta t} \cdot u(t) \cdot A \cdot \Delta t}
$$

Where:

$$
\begin{cases}
x_0 + x_1 = 1 \\
y_1 + y_2 = 1
\end{cases}
$$

NON-LINEAR MODULE
For Discharge and Groundwater Resource estimation

$$
\boldsymbol{q_s(t) = q_0(t) + q_1 y_1(t)}
$$

$$
\boldsymbol{q_r(t) = \frac{y_2 q_1(t)\left(1 - e^{-\frac{t\,\Delta t}{\lambda_2}}\right)}{t \cdot \Delta t} \cdot A \cdot \Delta t}
$$

OUTPUTS

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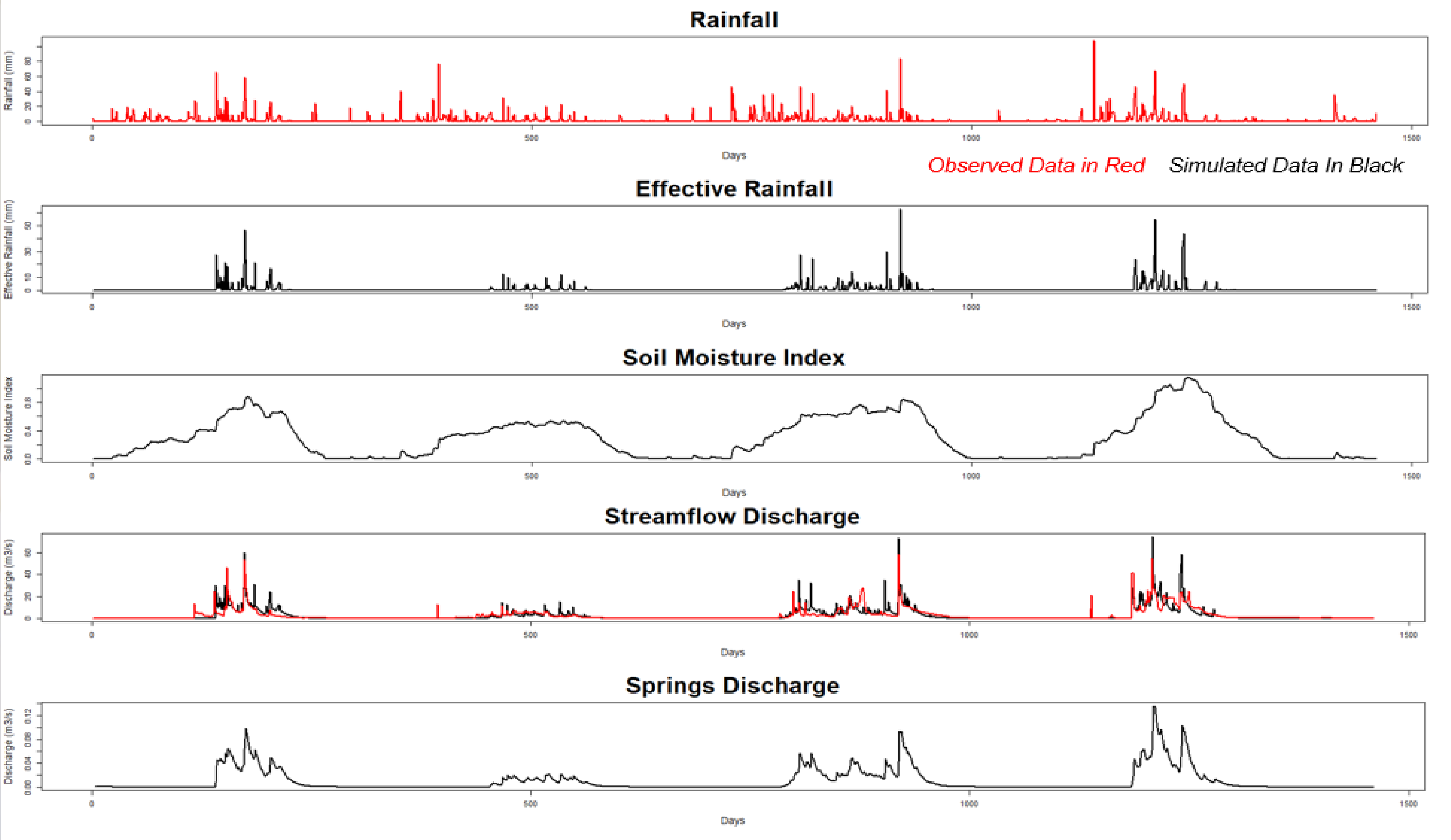
Calibration of the Model

The model has been calibrated on a 4-year daily streamflow discharge time series (1984-1986) at Mojo Alcantara hydrometric station.

For this case study, there are no spring discharge time series available, so to work around this issue, an **"A Priori"** condition has been used into the calibration process.

Model Calibration has been carried out in R-Studio Software using the packages ***"DEoptim"*** and ***"hydroGOF"*.**



Calibration of the Model (calibration period: 1984-1986)

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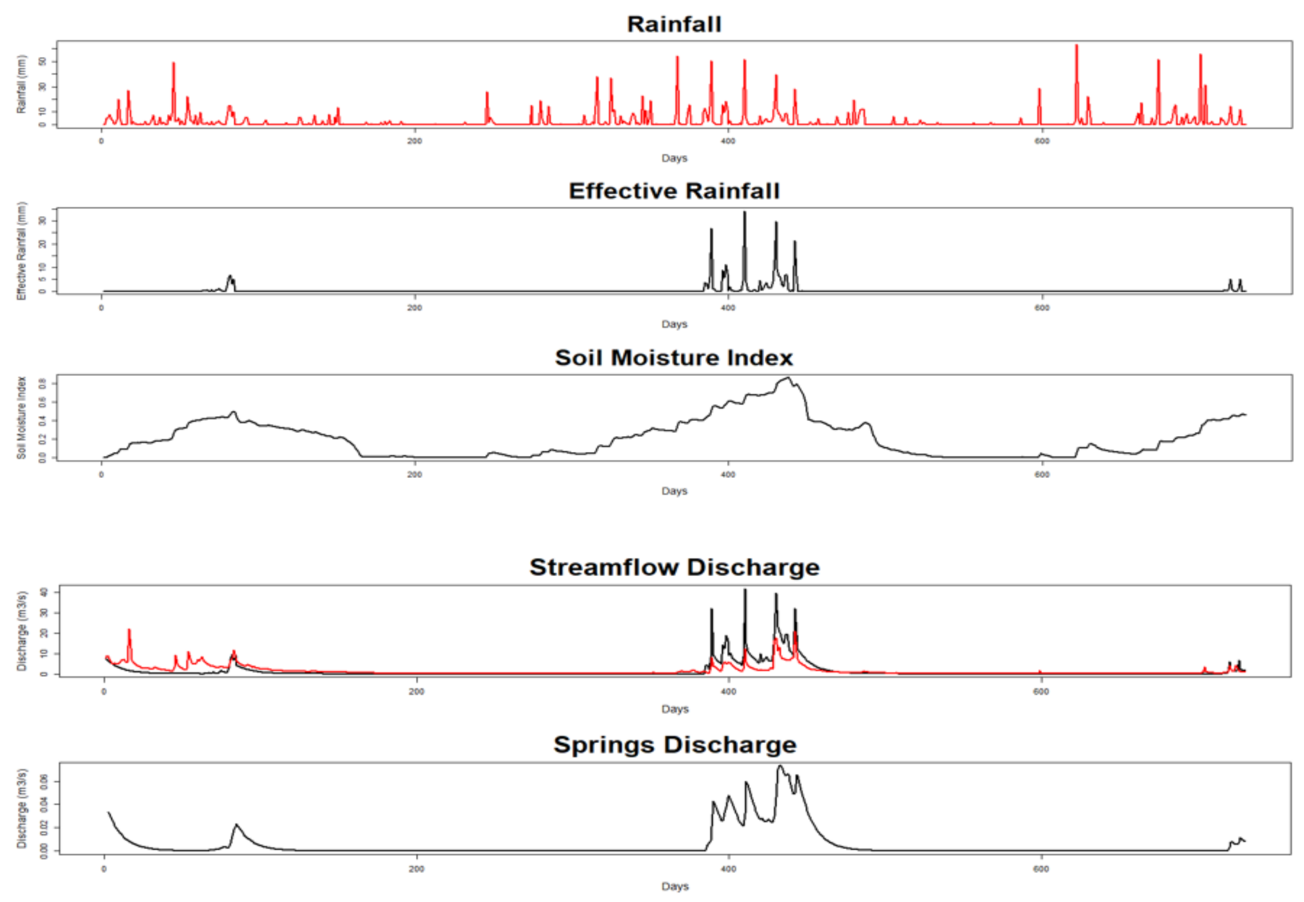
Validation of the Model

For the validation of the model, the daily streamflow discharge time series observed at Mojo Alcantara hydrometric station during the period 1987-1988 are used.

Moriasi et al. 2007 and Rittler et al. 2013 suggests that the efficiency of an hydrological model can be considered very satisfying when the Nash-Sutcliffe Efficiency value in validation is between 0,5 and 0,65.

Performance indicators of the calibration and validation of the model (Mean Square Error and Nash-Sutchliffe Efficency)

MSE (Calibration)	*NSE (Calibration)*	*MSE (Validation)*	*NSE (Validation)*
0,6789	*0,5169432*	*8,780084*	*0,483667*



Calibration of the Model (calibration period: 1984-1986)

Conclusions and Future Perspectives

The novelty of this modified IHACRES model lies in the fact that the **groundwater component and its interaction with the surface water through spring discharges are modeled** through a non-linear module whose equations involves the calibration of four parameters of easy interpretation.

Results show that the developed model is able to properly **reproduce the seasonality in the hydrological response** of the aquifer system in combination with the main streamflow.

In particular, the results of model validation can be considered satisfiying, with a Nash-Sutcliffe Efficiency value close to the optimal range suggested in literature by Moriasi et al. 2007 and Ritter et al 2013

Further researches will address **uncertainty and sensitivity analysis of the model and its parameters**. More specifically, a first order sensitivity anaylisis to better understand the influence of parameters on the performance of the model will be carried out, together with an uncertainty analysis based on the PLUE (Profiled Likelihood Uncertainty Estimation) approach.

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