Research Paper

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

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Abstract: A flow regime can be broadly categorised as perennial, intermittent or ephemeral, in relation to the fact the stream flowing is continuous all year round or cheased for weeks or months each year. Various conceptual models are needed to capture the behaviour of these different flow regimes, which reflect the differences in stream-groundwater hydrologic connection. As the hydrologic connection becomes more transient and a catchment's runoff response more non-linear, such as for intermittent streams, the need for explicit representation of the groundwater increases. In the present study, we investigate the connection between Northern Etna groundwater system and the Alcantara River Basin in Sicily, which is intermittent in the upstream and perennial since the midstream due to groundwater resurgence. To this end, we apply a modified version of IHACRES rainfall-runoff model, whose input data are continuous series of concurrent daily streamflow, rainfall and temperature data. The structure of the model includes three different modules: (1) a non linear loss module that transforms precipitation to effective rainfall by considering the influence of temperature; (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) a second 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, representing the aquifer recharge), the total streamflow is derived. This model structure is applied separately to sub-basins showing different hydrology and land use. The model is calibrated at Mojo cross section, where daily streamflow data are available. Point rainfall and temperature data are spatially averaged with respect to the considered sub-basins. Model calibration and validation are carried out for the period 1984-1986 and 1987-1988 respectively.

Keywords: hydrologic response; groundwater-fed catchment; IHACRES rainfall-runoff model.

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1. Introduction

A flow regime can be broadly categorised 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. While ephemeral streams are defined as having short-lived flow after rainfall, intermittent streams become seasonally dry when the groundwater table drops below the elevation of the streambed during dry periods. A spatially intermittent stream may maintain flow over some sections even during dry periods due to locally elevated water tables.

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.

In a previous study, Aronica and Bonaccorso [1] investigated the impact of future climate change on the hydrological regime of the Alcantara River basin, by combining stochastic generators of daily rainfall and temperature with the IHACRES rainfall–runoff model under different climatic scenarios, to qualitative investigate modifications in the hydropower potential. In their study, some simplifications to the system configuration have been considered to disregard the contribution of the groundwater component, as the emphasys was on simulating surface runoff only.

In the present study, a modified IHACRES rainfall-runoff model is proposed to better describe the complex connection between Northern Etna groundwater system and the Alcantara river basin. The modeling approach adopted in the present study involves separated but coordinated analysis of linearity and non-linearity in the catchment response to rainfall, through a representation of catchment hydrological response into serial linear and non-linear modules. In particular, the modified version of IHACRES rainfall-runoff model, whose input are continuous series of concurrent daily streamflow, rainfall and temperature data, is calibrated and validated at one of the main cross sections of the Alcantara river basin, where daily streamflow data are available. The structure of the model also provides the opportunity for dealing with parameteres uncertainty when very short and poor quality data series are available for model calibration and validation (Wagener et al. [2]).

2. Model description

The IHACRES model (acronym of *"Identification of unit Hydrograph And Component flows from Rainfall, Evapotranspiration and Streamflow"*) is a simple model designed to perform the identification of hydrographs and component flows purely from rainfall, evaporation and streamflow data.

2.1. The IHACRES Model

In the original version of IHACRES, firstly described by Jakeman et al. (1990) [3], the rainfall-runoff processes are represented by two modules (see Fig. 1): 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.

In literature, several studies on IHACRES development and application (Jakeman et al. 1990 [3], 1993a [4], 1993b [5], 1994a [6], 1994b [7]; Jakeman and Hornberger 1993 [8], Ye et al. 1997 [9]) have demonstrated the following advantages and capabilities:

- 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

Figure 1. Generic structure of the original IHACRES model, showing the conversion of climate time series data to effective rainfall using the Non-linear Module, and the Linear Module converting effective rainfall to streamflow time series (excerpted from Jakeman 1990 [3])

2.2. The Modified IHACRES Model

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

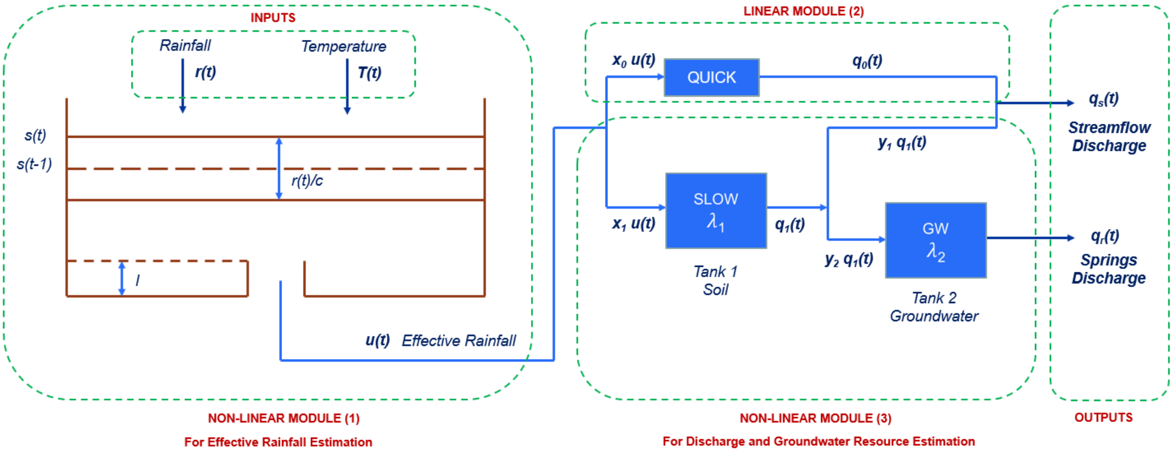

Figure 2. Structure of the Modified IHACRES Rainfall-Runoff model. A Non-Linear Module (1) for Effective Rainfall Estimation, a Linear Module (2) and another Non-Linear Module (3) for Discharge Estimation.

The structure of the modified IHACRES model shown in Figure 2, 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.

The non linear loss module (1) involves calculation of an index of catchment storage ***s(t)*** based upon an exponentially decreasing weighting of precipitation and temperature conditions:

$$s(t) = \frac{r(t)}{c} + \left[1 - \frac{1}{\tau_w\big(T(t)\big)}\right] \cdot s(t-1) \tag{1}$$

$$\tau_w\big(T(t)\big) = \tau_0 \cdot e^{[(20-T(t))\cdot f]} \tag{2}$$

where ***s(t)*** is the catchment storage index, or catchment wetness/soil mosisture index at time t, varing between 0 and 1, $\boldsymbol{\tau_w\big(T(t)\big)}$ is a time constant which is inversely related to the temperature declining rate, $\boldsymbol{\tau_0}$ is the value of $\tau_w\big(T(t)\big)$ for a reference temperature fixed to a nominal value depending on the climate and usually equal to 20°C for warmer climates (Jakeman et al 1994a [6]), ***c [mm]*** is a conceptual total storage volume chosen to constrain the volume of effective rainfall to equal runoff, ***f* [1/°C]** is a temperature modulation factor. The effective rainfall ***u(t)*** is calculated as the product of total rainfall ***r(t)*** and the storage index ***s(t)*** taking into account the two parameters ***p*** (an exponent of a power-law used to describe the non-linearity) and ***l*** (that represents a threshold parameter) introduced by Ye et al. (1998) [10] for low-yielding catchments, in order to better describe the strong non-linearity caused by the impact of long dry periods on the soil surface:

$$u(t) = \left[\left(\frac{1}{2}[s(t)+s(t-1)]\right) - l\right]^{p} \cdot r(t)\ ;\ \ if\ \ \frac{1}{2}[s(t)+s(t-1)] > l \tag{3a}$$

$$u(t) = 0\ ;\ \ otherwise \tag{3b}$$

The effective rainfall feeds the two component of the outflow: the *quick* component $\boldsymbol{q_0(t)}$ in the linear module (2) and the *slow* component $\boldsymbol{q_1(t)}$ in the non-linear module (3) that represents the soil response, conceptualized as a reservoir with storage constant λ_1.

The quick and slow components, respectively, are represented as:

$$q_0(t) = \frac{x_0}{t\cdot\Delta t}\cdot u(t)\cdot A\cdot\Delta t \tag{4}$$

$$q_1(t) = \frac{x_1\left(1-e^{-\frac{t\,\Delta t}{\lambda_1}}\right)}{t\cdot\Delta t}\cdot u(t)\cdot A\cdot\Delta t \tag{5}$$

with

$$x_0 + x_1 = 1 \tag{6}$$

where x_0 and x_1 represent the two share-out parameters of the effective rainfall *u(t).*

The sum of the quick component $q_0(t)$ calculated by the linear module and an aliquot of the slow component $y_1 q_1(t)$, gives as results the *streamflow discharge* $\boldsymbol{q_s(t)}$:

$$q_s(t) = q_0(t) + q_1 y_1(t) \tag{7}$$

The other aliquot $\boldsymbol{y_2 q_1(t)}$ of the slow component, instead, feeds the reservoir that represents groundwater with storage constant λ_2. The output of the groundwater reservoir is $\boldsymbol{q_r(t)}$ that represents *spring discharges*:

$$q_r(t) = \frac{y_2 q_1(t)\left(1-e^{-\frac{t\,\Delta t}{\lambda_2}}\right)}{t\cdot\Delta t}\cdot A\cdot\Delta t \tag{8}$$

with

$$y_2 = 1 - y1 \tag{9}$$

3. Case Study

In the presented work, the above described model is applied to the Alcantara River Basin, that is located in North Eastern Sicily (the largest Italian island), encompassing the north side of Etna Mountain, the tallest active volcano in Europe. The river basin has an extension of about 603 km^2. The headwater of the river is at 1400 m a.s.l in the Nebrodi Mountains, while the outlet in the Ionian sea is reached after 50 km (Figure 3).

The mountain area on the right-hand side of the river is characterized by volcanic rocks with a very high infiltration capacity. Here, precipitation and snow melting supply a big aquifer whose groundwater springs at the mid/downstream of the river, mixing with surface water and contributing to feed the river flow also during the dry season. The left side of the basin is characterized by sedimentary soils and gives a seasonal contribution to the river flow, as it 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.

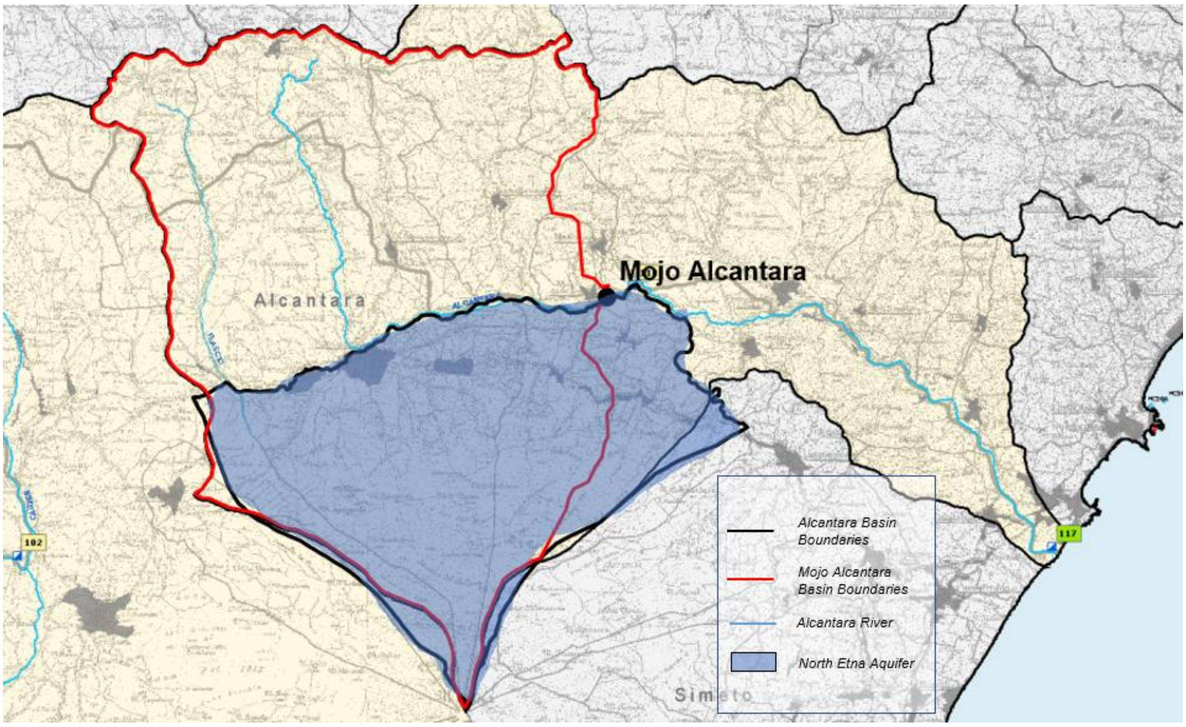

Figure 3. Alcantara River Basin and Alcantara at Mojo cross-section Sub-Basin (in red). The Northern Etna groundwater aquifer is also indicated (light blue).

4. Calibration and Validation of the Model

The modified IHACRES rainfall-runoff model above described has a total number of eleven parameters: five parameters in the effective rainfall estimation module (τ_0, f, c, l, p) and six in the discharge estimation module (x_0, x_1, y_1, y_2, λ_1, λ_2) but only nine need to be calibrated.

The input data used for running the model are daily point rainfall and temperature data spatially averaged over the considered area. The model has been calibrated on a 4-year daily streamflow discharge time series (1984-1986) at Mojo Alcantara hydrometric station (Figure 3, Table 1).

Table 1. Main characteristics of the Alcantara Basin and Mojo Alcantara Sub-Basin

	Alcantara Basin	**Mojo Alcantara Sub- Basin**
Area (km^2)	603	342
Mean elevation (m a.s.l.)	531	1142
Max elevation (m a.s.l.)	3274	3274
Min elevation (m a.s.l.)	0	510
Main river length (km)	54,67	34,66
Medium river slope	0,059	0,08

For this case study, there are no spring discharge time series available, so to work around this issue, an “A Prior” condition has been used into the calibration process, that is: the mean annual aquifer recharge value simulated into the model has to be similar to the mean annual aquifer recharge value estimated in other studies (Sogesid, Piano di Tutela delle Acque Sicilia – PTA, Palermo 2007), that is about 115 Mm³/year. Model Calibration has been carried out in R-Studio Software using the packages "*DEoptim*" and "*hydroGOF*"**.** In Figure 4 results of calibration are shown.

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 (Figure 5).

Moriasi et al. 2007 [11] and Rittler et al. 2013 [12] 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 are shown in Table 2.

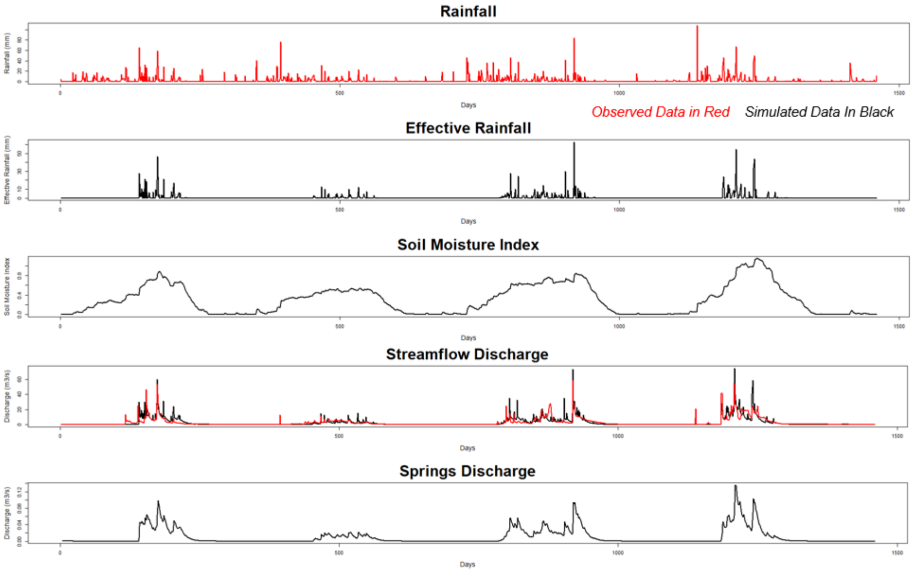

Figure 4. Calibration of the model (calibration period: 1984-1986)

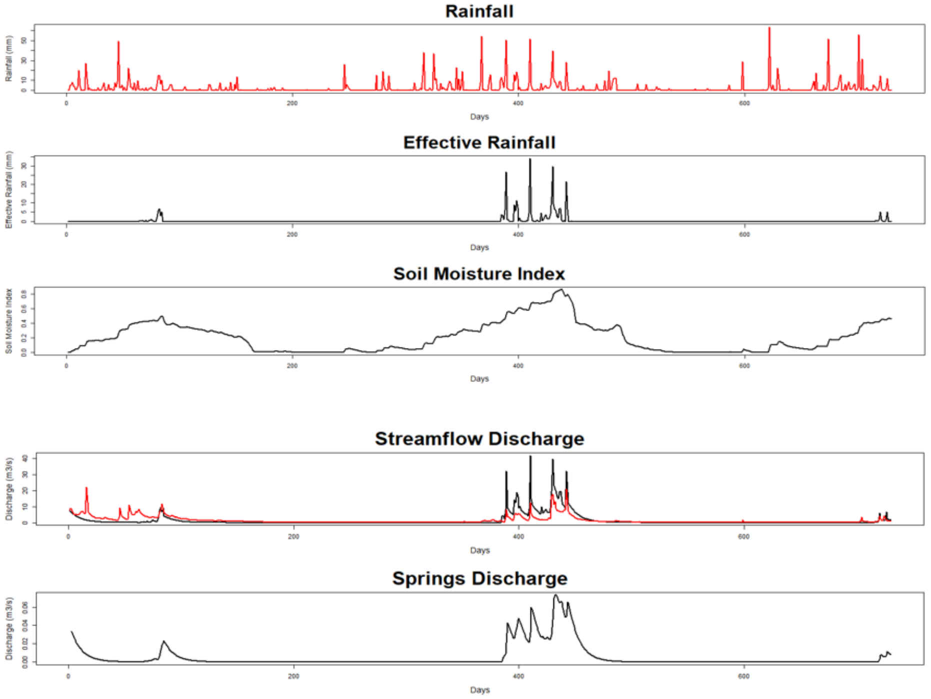

Figure 5. Validation of the model (validation period: 1987-1988)

Table 2. 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

5. Conclusions and Future Perspectives

An hydrological conceptual rainfall-runoff model has been proposed to simulate the stream-aquifer interactions of the Alcantara at Mojo river basin in Sicily (Italy). The proposed modelling approach involves a compound analysis of linearity and non linearity in the catchment response to rainfall, through a serial combination of linear and non-linear modules.

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 Ritter et al 2013 [11].

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.

References

1. Aronica G.T., Bonaccorso B.; Climate Change Effects on Hydropower Potential in the Alcantara River Basin in Sicily (Italy), Earth interactions, Volume 17 (2013). Paper No. 19
2. Wagener T., Wheater H.S., Gupta H.V.; Rainfall-Runoff modelling in gauged and ungauged catchments, Imperial college press, London, 2004
3. Jakeman A.J., Littlewood I.G., Whitehead P.G.; Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments, Journal of Hydrology, 117, pp. 275-300, 1990
4. Jakeman A.J., Chen T.H., Post D.A., Hornberger G.M., Littlewood I.G., Whitehead P.G.; Assessing uncertainties in hydrological response to climate at large scale, IAHS Publ. 214, edited by W.B. Wilkinson, pp. 37-47, Institute of Hydrology, Wallingford, England, 1993a
5. Jakeman A.J., Littlewood I.G., Whitehead P.G., An assessment of the dynamic response characteristics of streamflow in the Balquhidder catchments, Journal of Hydrology, 145, 337-355, 1993b
6. Jakeman A.J., Post D.A., Beck M.B, From data and theory to environmental model: the case of rainfall-runoff, Environmetrics, 5, pp. 297-314, 1994a
7. Jakeman A.J. Post D.A., Schreider S.Y., Ye W.; Modelling environmental systems: Partitioning the water balance at different catchment scales, Computer Techniques in Environmental Studies V, vol. 2, Environmental System, Edited by P. Zannetti, Comput. Mech., Southampton, England, pp. 157-170, 1994b
8. Jakeman A.J., Hornberger G.M., How much complexity is warranted in a rainfall-runoff model?, Water Resources Research, 29, pp 2637-2649, 1993
9. Ye W., Bates B.C., Viney N.R., Sivapalan M., Jakeman A.J.; Performance of conceptual rainfall-runoff models in low-yielding ephemeral catchments, Water Resources Research, 33(1), pp. 153-166, 1997
10. Ye W., Jakeman A.J., Young P.C., Identification of improved rainfall-runoff models for an ephemeral low-yielding Australian catchment, Environmental modelling & software, 3, pp. 59-74, 1998
11. Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50(3), 885-900. 2007
12. Ritter, A.; Muñoz-Carpena, R.; Performance evaluation of hydrological models: statistical significance for reducing subjectivity in goodness-of-fit assessments". Journal of Hydrology. 2013