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COUPLING STUDY OF THE VARIABLE INFILTRATION CAPACITY (VIC) MODEL WITH WEATHER RESEARCH AND FORECASTING (WRF) MODEL TO SIMULATE THE STREAMFLOW IN THE GUADALQUIVIR BASIN

M. GARCÍA-VALDECASAS-OJEDA, S. de FRANCISCIS, S.R. GÁMIZ-FORTIS,
Y. CASTRO-DÍEZ and M.J. ESTEBAN-PARRA

Applied Physics Department, University of Granada.

mvaldecasas@ugr.es

ABSTRACT

Variable Infiltration Capacity (VIC) model is a large-scale hydrologic model. Land surface is modeled as a grid of large and uniform cells with sub-grid heterogeneity (e.g. land cover), while water influx is local, only depending from the interaction between grid cell and local atmosphere environment. Water streamflow is obtained separately from the land surface simulation, using the Routing Model. The goal of this work consists into set an optimal hydrological and climate model to study the evolution of the streamflow of Guadalquivir Basin, with different future land use, land cover and climate scenarios, implemented with the regional Weather Research and Forecasting (WRF) model. In this work we present some results concerning the calibration of the most relevant parameters of VIC model, comparing the streamflow simulations obtained from the observational climate data SPAIN02 and WRF outputs databases, with the use of observational reservoirs and gauging stations daily streamflow time series, obtained from CEDEX database, in the time period 1988-1997.

Key words: Hydrological model, Guadalquivir streamflow, WRF model, VIC model.

RESUMEN

El modelo *Variable Infiltration Capacity* (VIC) es un modelo hidrológico de gran escala. La superficie terrestre es modelada considerando una gran rejilla de celdas uniformes que presentan heterogeneidad a escala de sub-rejilla (esto es, cubierta superficial), mientras que el flujo de agua es local, únicamente dependiente de la interacción entre celdas y el medio ambiente local. El caudal de agua se obtiene separadamente a partir de la simulación de la superficie terrestre usando el denominado modelo *Routing*. El objetivo de este trabajo consiste en calibrar un modelo hidrológico y climático de forma óptima con el fin de estudiar la evolución del caudal en la Cuenca del Guadalquivir, con diferentes posibles usos del suelo futuros, cobertura superficial y escenarios climáticos, implementado con el modelo regional *Weather Research and Forecasting* (WRF). En este trabajo se presentan resultados relativos a la calibración de los parámetros más relevantes del modelo VIC, comparando las simulaciones de caudal obtenidas por el mismo a partir de los datos climáticos observacionales de

SPAIN02 y de las salidas del modelo WRF, con los datos de caudal diario observacionales del CEDEX, para el periodo 1988-1997.

Palabras clave: Modelo hidrológico, caudal del Guadalquivir, modelo WRF, modelo VIC.

1. INTRODUCTION

Water plays a determinant role in the behavior of climate systems, because of the dependence of human activities on hydric resources. Studies of the alterations in hydrological cycles under the effect of climate change are very relevant in order to understand the anthropic effect on the climate and to evaluate their impacts at regional scale, involving many aspects of human welfare, from agricultural productivity to energy use, flood control, urban and industrial water supply and fisheries, flora and fauna management.

Water resources in the Iberian Peninsula, and particularly in Andalusia, have a considerable interest because of the large annual variability of temperature and precipitation in this region (Serrano *et al.*, 1999), with marked periods of drought. Moreover, there is an over-exploitation of water resources due to an increase in demand for water for agriculture, industry and tourism (Garrido and Gómez-Ramos, 2000). In fact, it has been shown that under a scenario of global warming, southern and western Europe could experience a decrease in agriculture yields of about 25% (PESETA project, 2009).

Streamflow variability plays an important role in the development and management of water resources in most regions of the world. In the last IPCC report it was stated that the entire Mediterranean region (including the Iberian sector) is currently presenting a broadly consistent decline in precipitation and flow rates (IPCC, 2013). The hydrological system acts as a spatial and temporal integrator of primary climate variables such as precipitation, temperature and evapotranspiration on a specific region, so the seasonal and annual streamflow variability in many basins is controlled by large-scale changes in atmospheric circulation patterns (Gámiz-Fortis *et al.*, 2008). The relationship between these climatic regimes and hydrological response has different degrees of complexity depending on the physical characteristics of the basin, integrating the climate forcings mentioned before. Additionally, the streamflow comes from naturally filtered precipitation, making it less prone to spatial and temporal noise effect (Gámiz-Fortis *et al.*, 2008). This justifies that studies about hydrological impacts of climate change should consider mainly the analysis of secondary variables such as river flows (Boé *et al.*, 2007).

The ultimate goal of our research line consists in the estimation of the projected Guadalquivir Basin streamflow by applying a hydrologic model that employs the input variables obtained from the climate change outputs projected by a regional model under different climate change scenarios.

For this purpose, we adopt the VIC hydrological model (<http://vic.readthedocs.io/en/vic.4.2.c/>), which is able to provide water and energy balances (Liang *et al.*, 1994).

2. METHODS

VIC model is a large-scale hydrologic model, where land surface is modeled as a grid of large and uniform cells with sub-grid heterogeneity, e.g. land cover.

The variability of land cover is represented by a classification of the grid cells according to types of vegetation or bare soil, and the soil layer is divided into three levels. Saturation excess resulting from runoff currents is parameterized through the variable infiltration curve provided by the Xinanjiang model (Wood *et al.*, 1992).

Grid cells have here a spatial resolution of 10km, with daily input/output temporal resolutions. The minimum meteorological forcing input data required by the model are daily precipitation and daily maximum and minimum temperatures. Other variables that can be further supplied to the model input are surface albedo, long-wave and shortwave radiation, specific humidity, zonal and meridional wind components, and/or atmospheric pressure. When these input variables are not provided, the model uses different calculation algorithms from the minimum variables required. Evapotranspiration is calculated using a modification of the Penman-Monteith equation (Shuttleworth, 1993) which allows the net radiation and other heat fluxes vary throughout the day.

The great computational performance of VIC model is due to the local water/energy influxes, i.e. they only depend from the interaction between soil and vegetation in the single grid cell and local atmosphere environment. In this way, each cell is an isolated system, whose dynamic is independent to the rest of the system. The main outputs of VIC, water runoff and baseflow, are used as the inputs for a spatial network based model, the Routing model (Lohmann *et al.*, 1998). In such a model the daily grid cell runoff/base flow are routed to the edges of grid cell, through the river network (defined by using the slopes in the elevation map), and finally reaching the observation point. The resulted hydrographs of routed daily flows can be then compared to the historical observational data.

2.1. Implementation of VIC model: input database

In order to run VIC, several sets of input data are necessary:

Soil Parameter File, composed by cell ID numbers, latitude/longitude, soil texture and other characteristics. We made use of the ISRIC-World Soil Information database (<http://soilgrids1km.isric.org>) to extract information on soil composition, i.e. bulk density, sand percent and clay percent. From these 3 quantities in union with the USGS digital elevation map (<https://lta.cr.usgs.gov/HYDRO1K>) and the average annual precipitation (calculated from SPAIN02 database, <http://www.meteo.unican.es/en/datasets/spain02>) we originated all the necessary variables to build the soil parameter file, e.g. field capacity, saturated hydrological conductivity, and wilting point. We chose to edit the soil file with 3 layers, initially set with width [0,-0.15 m], [-0.15,-0.6 m], and [-0.6, -2.0 m].

Vegetation Library File, which describes the available land cover types, and *Vegetation Parameter File*, which describes the land cover types and their properties, fractional areas, rooting depths, and seasonal leaf area index (LAIs) of the various land cover tiles within each grid cell. Vegetation library file is built from the re-gridding

of the NASA LDAS (Land Data Assimilation System) database (ldas.gsfc.nasa.gov/gldas/GLDASVegetation_GLDAS1.php), while the parameter file is the same used in NOAA Land Surface Model, downloadable from University Corporation for Atmospheric Research (UCAR)-National Center for Atmospheric Research (NCAR) (www.ral.ucar.edu/research/land/technology/lsm.php).

Meteorological Forcing Files. VIC takes daily time series of meteorological variables as inputs: precipitation, air temperature, wind speed, atmospheric pressure and density, vapor pressure (or vapor pressure deficit or relative humidity or specific humidity), incoming shortwave (solar) radiation, and incoming longwave (or thermal) radiation. However, VIC can estimate some of these quantities internally, so that the user need not supply all of them. The minimum set of variables that VIC requires are: daily total precipitation, and daily maximum and minimum temperatures.

2.2. VIC calibration algorithm and routine

VIC model has more than 20 parameters to be specified. Usually the calibration process consists in adjusting six of them (Nijssen *et al.*, 1997):

a) b_{inf} - [> 0 to ~ 0.4]. This parameter defines the shape of the Variable Infiltration Capacity curve. It describes the amount of available infiltration capacity as a function of relative saturated grid cell area. A higher value of b_{inf} gives lower infiltration and yields higher surface runoff. The infiltration parameter controls the transformation of rain (or snowmelt) in infiltration and direct runoff.

b) Soil Depth layers 2 and 3, D2 and D3 - [typically from 0.1 to 1.5 meters]. Soil depth affects many model variables. In general, for runoff considerations, thicker soil depths slow down (baseflow dominated) seasonal peak flows and increase the loss due to evapotranspiration. The depth of the topsoil (D1) is usually specified a priori.

c) Baseflow parameters: baseflow (D_{smax}) fraction of the maximum speed of the baseflow (D_s), and fraction of the maximum moisture content of soil in the third layer (W_s). These three parameters determine how quickly the water stored in the third layer of soil is evacuated as a baseflow (Liang *et al.*, 1994). D_{smax} is calculated from the slope of elevation map.

c.1) D_s - [>0 to 1]. This is the fraction of D_{smax} where non-linear (rapidly increasing) baseflow begins. With a higher value of D_s , the baseflow will be higher at lower water content in lowest soil layer.

c.2) W_s - [>0 to 1]. This is the fraction of the maximum soil moisture (of the lowest soil layer) where non-linear baseflow occurs. This is analogous to D_s . A higher value of W_s will raise the water content required for rapidly increasing, non-linear baseflow, which will tend to delay runoff peaks.

The model is calibrated similar to that described in Hurkmans *et al.* (2008). The parameters b_{inf} , D2, D3, D_s and W_s are calibrated using the SCE-UA algorithm shuffled complex evolution method developed at the University of Arizona (Duan *et al.*, 1994), with Nash-Sutcliffe efficiency as objective function (Hurkmans *et al.* 2009). This calibration is carried out for different areas or subareas separately, taking into account topographical, lithological and climatological criteria. Thus, a priori, in the

Guadalquivir Basin we distinguish between two sub-basins in high Guadalquivir River, two sub-basins corresponding to middle Guadalquivir and Genil sub-basins, one more in the low Guadalquivir, and the last one including the river mouth, see Figure 1.

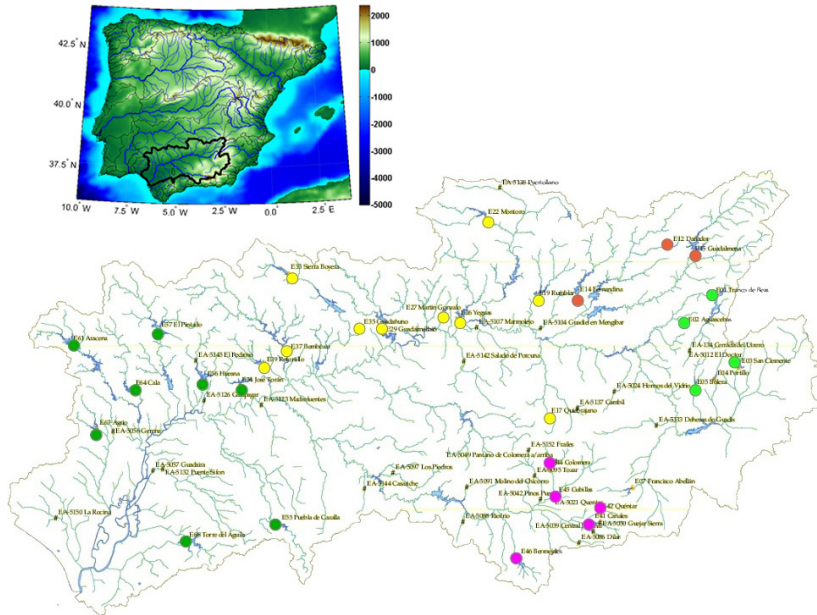


Figure 1: (up) Location of Guadalquivir Basin in the Iberian Peninsula. (bottom) Headwater reservoirs included in the CEDEX database. Colors corresponds to the reservoirs located in the different sub-basins: I-clear green and II-orange in the high Guadalquivir; III-yellow in the middle Guadalquivir; IV-violet for the Genil and V-dark green in the low Guadalquivir and river mouth.

3. VIC CALIBRATION STEP

Because the calibration process is computationally very demanding, the model was calibrated in a relatively short period: 1988-1997. The minimum set of forcing meteorological input used (daily total precipitation, daily maximum and minimum temperature) has been obtained from SPAIN02 database. In this time period, the SCE-UA algorithm compares the Routing model output streamflows with the daily time series of the observational headwater reservoir stations obtained from the Development Center for Hydrographic Studies (CEDEX, <http://ceh-flumen64.cedex.es/anuarioaforos/default.asp>, Figure 1), by means of the opposite Nash-Sutcliffe efficiency objective function:

$$E = \frac{\sum_{i=1}^N (\varrho_{run,i} - \varrho_{obs,i})^2}{\sum_{i=1}^N (\varrho_{obs,i} - \langle \varrho_{obs} \rangle)^2} - 1$$

where $Q_{run,i}$ and $Q_{obs,i}$ are the temporal datasets of simulated and observed streamflow at time i . Nash–Sutcliffe efficiency can range from -1 to ∞ . An efficiency of -1 corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data; whereas an efficiency more than zero ($E > 0$) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the numerator in the expression above), is larger than the data variance (described by the denominator). Essentially, the closer the model efficiency is to -1, the more accurate the model is. The efficiency coefficient is sensitive to extreme values and might yield sub-optimal results when the dataset contains large outliers in it (Nash and Sutcliffe, 1970).

In Table 1 we compare the Nash-Sutcliffe objective function in the case of VIC with calibrated (b_{inf} , D2, D3, Ds, Ws) in 6 sub-basins sets [E(B)] and with the suggested initial parameters set (b_{inf} , D2, D3, Ds, Ws) = (0.2, 0.45, 1.4, 0.001, 0.9) [E(O)], by the original VIC manual. Optimized VIC improves the adjust to observational data. In fact, the number of reservoir stations that improve their objective function, i.e. where $E(B) < E(O)$, or such that $E(B)$ deviates from $E(O)$ less than 0.1, are 26/31 (83%). In addition, the number of reservoir stations with $E(B) < 0.07$ (Hurkmans *et al.*, 2009) are 19/31 (61%).

#Station	Initial set (O)	Opt. set (B)	E(O)-E(B)	#Station	Initial set (O)	Opt. set (B)	E(O)-E(B)
Sub-basin 1				Sub-basin 4			
5001	0,110	0,113	-0,003	5020	-0,366	-0,471	0,104
5029	0,049	0,059	-0,010	5021	-0,185	-0,377	0,192
5045	-0,575	-0,574	-0,001	5038	-0,038	-0,392	0,355
5060	-0,483	-0,397	-0,086	5048	0,573	0,394	0,179
Sub-basin 2				5050	-0,078	-0,032	-0,047
5018	-0,431	-0,479	0,048	Sub-basin 5			
5044	-0,424	-0,430	0,006	5011	-0,009	-0,139	0,130
5052	-0,011	0,029	-0,040	5014	-0,034	-0,201	0,167
Sub-basin 3				5016	-0,066	-0,348	0,282
5005	0,009	0,030	-0,021	5022	-0,079	-0,276	0,197
5006	-0,159	-0,035	-0,123	5055	-0,439	-0,567	0,128
5012	-0,048	0,004	-0,052	5056	4,914	45,677	-40,763
5017	-0,058	0,007	-0,065	5061	-0,081	-0,373	0,292
5037	-0,100	-0,251	-0,075	5058	-0,323	-0,690	0,367
5039	-0,538	-0,366	-0,172				
5046	6,998	-0,072	7,070				
5047	-0,453	-0,190	-0,263				
5049	-0,502	-0,345	-0,157				
5052	-0,011	-0,004	-0,007				
5062	-0,102	-0,394	0,293				

Table 1: Nash-Sutcliffe objective function for VIC calibrated parameters, $E(B)$, and with the initial set, $E(O)$.

In Figure 2 some typical examples of streamflow outputs obtained from calibrated VIC compared with observational data are shown. As it can be seen, streamflows are accurately reproduced, although the very extreme high values tend to be subestimated by the model.

4. ROBUSTNESS ANALYSIS FOR WRF VARIABLES

Once we obtained the calibration of VIC, we test the robustness of the model and/or the goodness of Weather Research and Forecasting (WRF) model, by replacing or adding in the previously optimized VIC new meteorological input variables obtained by WRF model. We run the configurations with just one WRF variable (wind intensity and direction, shortwave radiation, specific humidity, atmospheric pressure) added to the SPAIN02 (precipitation, Tmax, Tmin) set (SPAIN02+X), and finally with adding all the new aforementioned WRF variables (SPAIN02+ALL).

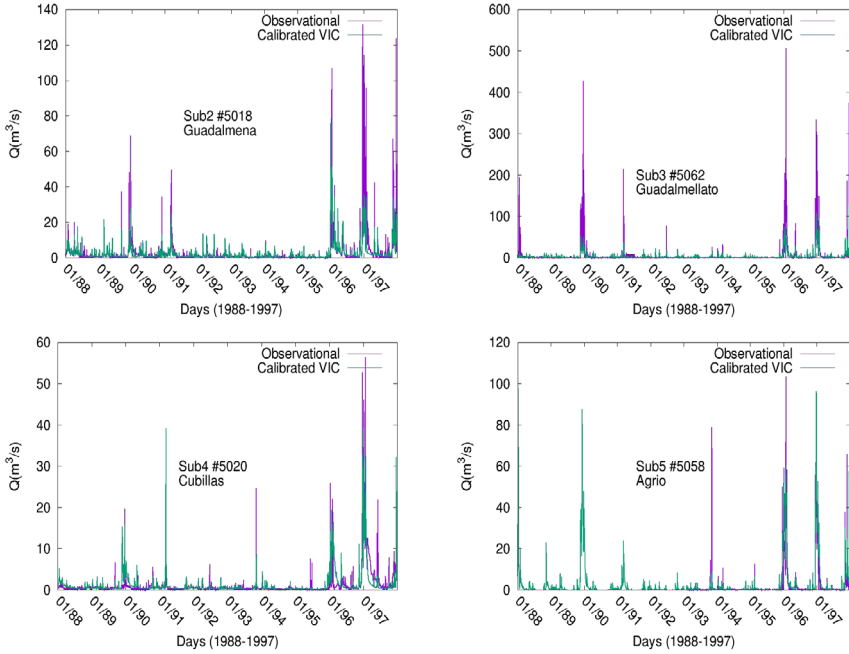


Figure 2: Some examples of streamflow outputs obtained from calibrated VIC (green) compared with observational data (violet).

Our analysis is focused on the evaluation, for each reservoir stations, of temporally “local” and “global” statistical observables, i.e. the Nash-Sutcliffe efficiency (E), the Relative Volume Error (RVE), the relative Root Mean Square Error ($RMSE_{rel}$), defined as:

$$RVE = \frac{\langle Q_{run} \rangle - \langle Q_{obs} \rangle}{\langle Q_{obs} \rangle} \quad RMSE_{rel} = \frac{\sqrt{\sum (Q_{run,i} - Q_{obs,i})^2 / N}}{\langle Q_{obs} \rangle}$$

For SPAIN02+WIND, RAD and HUM configurations the values of E , RVE and $RMSE_{rel}$ observables are improved, with respect to SPAIN02 case, in a number of reservoir stations from 19/30 (63%) to 22/30 (73%). In addition for all the statistical observables, there is a fixed set of 8 reservoir stations that worsen their value, all corresponding to the best ones calibrated.

Concerning atmospheric pressure, it seems to have a poor role in streamflows dynamic. For this case, E , RVE and $RMSE_{rel}$ values show (positive or negative) variations just in 6/30 (20%) of reservoir stations.

Analysis of the relative variation of observables f ,

$$Var(f, X) = \frac{f(SPAIN02) - f(SPAIN02 + X)}{f(SPAIN02)}$$

indicates that in all configurations there are a precise amount of the WRF meteorological variables concerning their strength of influence in the streamflow profiles, so that:

$$\begin{aligned} Var(E, ALL) &> Var(E, WIND) > Var(E, RAD) > Var(E, HUM) \\ Var(RVE, ALL) &> Var(RVE, WIND) > Var(RVE, RAD) > Var(RVE, HUM) \\ Var(RMSE_{rel}, ALL) &> Var(RMSE_{rel}, WIND) > Var(RMSE_{rel}, RAD) > Var(RMSE_{rel}, HUM) \end{aligned}$$

as it is shown in Table 2 for two chosen stations, with negative and positive variations, respectively.

#Station	Meteorological Input (SPAIN02+X)	Var(E,X) (%)	Var(RVE,X) (%)	Var(RMSE _{rel} ,X) (%)
#5020	SPAIN02+ALL	-2,523	-5,906	-0,801
	SPAIN02+WIND	-0,969	-2,926	-0,364
	SPAIN02+RAD	-0,457	-2,064	-0,186
	SPAIN02+HUM	-0,188	-0,947	-0,081
	SPAIN02+PRE	0,000	0,000	0,000
#5017	SPAIN02+ALL	4,627	0,042	0,016
	SPAIN02+WIND	1,931	0,013	0,007
	SPAIN02+RAD	1,096	0,008	0,004
	SPAIN02+HUM	0,223	0,001	0,001
	SPAIN02+PRE	0,000	0,000	0,000

Table 2: Relative variations in Nash-Sutcliffe efficiency (E), Relative Volume Error (RVE), and Relative Root Mean Square Error ($RMSE_{rel}$), between the simulated streamflows using different meteorological input variables (X) added to SPAIN02.

We attempt to explain the origin of such variation with the introduction of new WRF variables in the following way: original SPAIN02 output in general overestimates the null or almost null streamflow periods, while it underestimates the streamflow

peaks; each WRF variable increases the streamflow output with different strength, and with an accumulative effect, i.e. SPAIN02+*ALL* has always a greater effect than a single WRF variable, so that the positive or negative percentage of variation depends on the predominance of low activity period or peaks in the observational series. Figure 3 shows some samples of this behavior for two of the best calibrated stations.

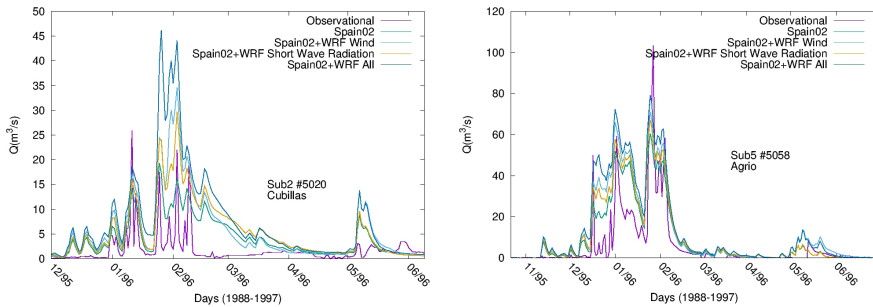


Figure 3: Example of the streamflow change in VIC model with the introduction of WRF variables for the reservoir stations #5020 and #5058

5. CONCLUSION

This work about Guadalquivir Basin streamflow shows that calibration of hydrological VIC model with the use of CEDEX historical observational reservoir data seems to be good enough compared with other studies about the VIC calibration for other basins (Hurkmans *et al.*, 2009). Moreover, it is important to consider the long observational period used, 1988-1997, and the joint optimization of several reservoirs datasets for each one of sub-basins, differently from several past works (Hurkmans *et al.*, 2008, 2009). Analysis of outputs with the addition of some WRF variables demonstrates the important role played by wind direction and speed as well as short-wave radiation. Thus, in future works will be relevant to include these variables in the calibration process, as far as possible extracted from robust observational data.

Recent works (Hurkmans *et al.*, 2009, 2010) have shown the greatest ability of this model to properly reproduce both the average and extreme streamflows compared to other models, and also its adequate use in climate impact assessment. VIC is less sensitive to parameter settings than the simpler water balance models (Hurkmans *et al.*, 2008). This is an important advantage, since it is questionable whether the parameters of certain conceptual models under current climatic conditions will be valid throughout the XXI century under a changing climate. So, VIC could be a valuable tool to study the climate change impacts on water resources.

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