PAPER • OPEN ACCESS

A comparison between lumped and distributed hydrological models for daily rainfall-runoff simulation

To cite this article: F Vilaseca *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **958** 012016

IOP Conf. Series: Earth and Environmental Science **958** (2022) 012016 doi:10.1088/1755-1315/958/1/012016

A comparison between lumped and distributed hydrological models for daily rainfall-runoff simulation

F Vilaseca[1], S Narbondo[1], C Chreties[1], A Castro[2,3] and A Gorgoglione[1,*]

[1]Department of Fluid Mechanics and Environmental Engineering, School of Engineering, Universidad de la República, 11300, Montevideo, Uruguay
[2]Department of Computer Science, School of Engineering, Universidad de la República, 11300, Montevideo, Uruguay
[3]Department of Electrical Engineering, School of Engineering, Universidad de la República, Montevideo, 11300, Uruguay

E-mail: agorgoglione@fing.edu.uy

Abstract. In Uruguay, the Santa Lucía Chico watershed has been studied in several hydrologic/hydraulic works due to its economic and social importance. However, few studies have been focused on water balance computation in this watershed. In this work, two daily rainfall-runoff models, a distributed (SWAT) and a lumped one (GR4J), were implemented at two subbasins of the Santa Lucía Chico watershed, with the aim of providing a thorough comparison for simulating daily hydrographs and identify possible scenarios in which each approach is more suitable than the other. Results showed that a distributed and complex model like SWAT performs better in watersheds characterized by anthropic interventions such as dams, which can be explicitly represented. On the other hand, for watersheds with no significant reservoirs, the use of a complex model may not be justified due to the higher effort required in modeling design, implementation, and computational cost, which is not reflected in a significant improvement of model performance.

1. Introduction

The Santa Lucía Chico watershed has been recognized by the Uruguayan government as a region characterized by rainfed agriculture, dairy and beef cattle farm, and potable water production, which are vital for economic and social development of the country [1]. Due to the importance of the water resource potential of this watershed, such area has been the pilot study of several projects[2-4]. In more than a decade, however, few studies have been focused on water balance computation in this watershed [5-6]. Each of these studies has used different hydrologic models and parameter estimation schemes to simulate hydrologic processes at watershed scale with a diverse frequency (daily, weekly, or monthly). Even though some efforts have been conducted towards this goal, there is not a modeling tool officially recognized and adopted by the local government for the water resource management of this catchment.

Various investigations have been conducted on distributed and lumped hydrologic models[7-9]. Refsgaard and Knudsen [7] made an in-depth comparison among conceptual, semi-distributed, and distributed models for several watersheds in Zimbabwe, but they could not defend the use of the distributed model over the others. Furthermore, in most of these works, it was stated that distributed models may or may not provide enhancments compared with conceptual models[7, 9].

Consequently, the central aim of this work is to return a thorough comparison between lumped and distributed models for simulating continuous daily streamflow at Santa Lucía Chico catchment. In particular, based on such comparison, we aim to identify possible scenarios for which we can state which the most suitable model is.

2. Materials

2.1 Study area

The study area is represented by the Santa Lucía Chico watershed, with closure at the outlet of the Paso Severino dam (Figure 1). It is located in the mid-south of the Uruguaian territory, an area characterized by temperate weather, with air temperature that ranges between 3 °C and 30 °C and total annual precipitation that varies between 1 m and 1.5 m [10]. The watershed's area is 2478 km^2, which is mainly covered by grassland and agriculture, making it a rural basin.

It is an area of intense agricultural activity and represents one of the major national sources of drinking water, making it a watershed important for the country. The Paso Severino dam was created as a reservoir for provisioning during dry periods the Aguas Corrientes' water treatment plant.

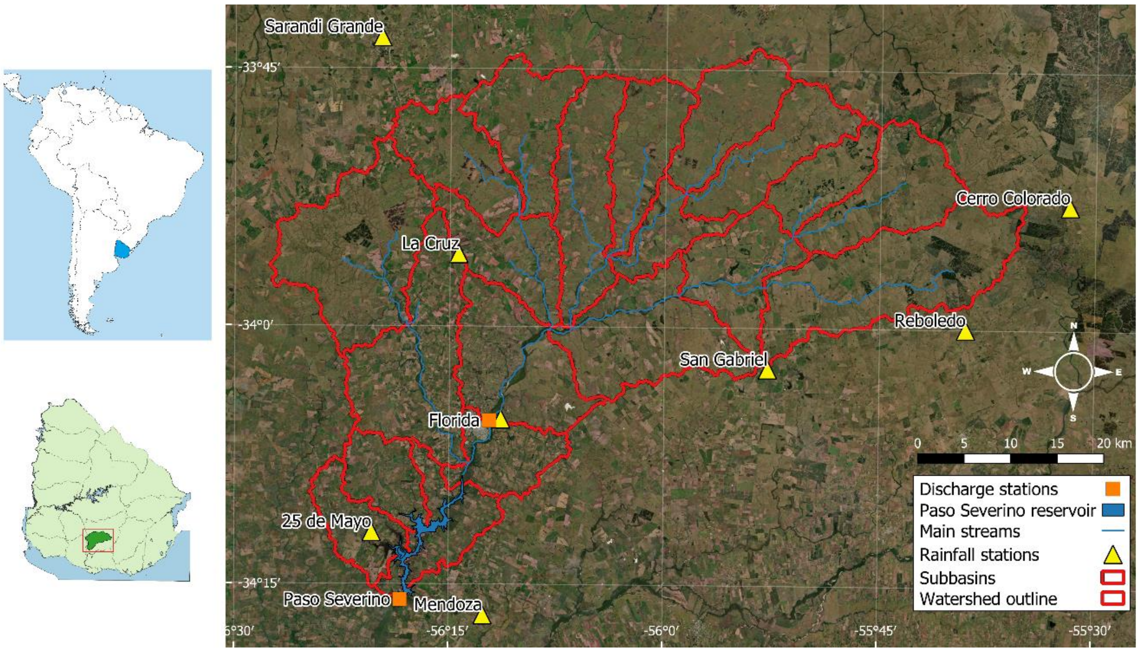

Figure 1. Up-left: Uruguay's placement in South America. Bottom-left: location of the Santa Lucía Chico catchment in Uruguay. Right: position of the discharge stations (orange squares) and rainfall stations (yellow triangles).

2.2 Data description

2.2.1. Streamflow data. Mean daily streamflow considered in this work corresponds to the period from 01/01/1990 to 12/31/2015. It was recorded at the station located in Florida city by the Uruguay National Water Board (DINAGUA). Furthermore, the mean daily discharge of the Paso Severino dam that covers the period 01/01/1990 - 12/31/2015 was exploited. The data was recorded and provided by the national company responsible for the dam management operations and the drinking water distribution (State Sanitary Infrastructures (OSE)).

2.2.2. Rainfall data. Accumulated daily rainfall records were recorded by the National Institute of Meteorology (INUMET). For this study, we considered precipitation registered at eight pluviometric stations located close to the catchment at Sarandí Grande, La Cruz, 25 de Mayo, San Gabriel, Cerro Colorado, Reboledo, Florida, and Mendoza (Figure 1). Florida is the only meteorological station with observations from 05/01/1989. The rest pluviometric stations have observations that cover the period 01/01/1980 - 06/30/2020.

2.2.3. Further climatic variables. Time series of Relative Humidity (RH), Wind Speed (WS), Solar Radiation (SR), minimum and maximum daily temperatures (Tmin and Tmax) were also considered (period from 01/01/1980 to 06/30/2020). Such variables were recorded by the National Institute of Agricultural Research (INIA). In particular, observations recorded at Las Brujas were adopted since such meteorological station was the closest to the site under study (Lat: -34.67, Lon: -56.34).

2.2.4. Spatial data. Topography, land use/land cover, and soil types are the spatial information considered for this study. The digital terrain model (DTM) was obtained from a national topographic map (scale 1:50000). Catchment slopes are low, with less than 5% for 77% of the region and more than 10% for only 2%. The current land use/land cover (LULC) map (year 2018) was obtained from the Ministry of Livestock, Agriculture, and Fisheries (MGAP) (scale 1:50000). Land uses include grassland, agriculture, forestry, dairy farming, urban areas, water bodies, and wetlands (respectively with the percentage 82.4%, 9.4%, 4.9%, 1.2%, 0.9%, 0.7%, and 0.5% of the watershed area). The soil classification considered by the soil map takes into account the CONEAT, that is the national productivity index. In the watershed under study, nineteen soil types can be found, mainly loamy soils that refers to the hydrological groups B and C.

3. Methods

3.1. SWAT model

3.1.1. Model setup. The Soil & Water Assessment Tool (SWAT) is a widely used distributed hydrological model proven to yield accurate results in representing the rainfall-runoff process for daily and monthly time steps. It has a complex calculation scheme since it considers the spatial distribution of soils, land uses, and topography and characterizes the rainfall-runoff process through more than 30 parameters. For this matter, the watershed's surface is divided into two scales: i) subbasins, which are determined based on the distribution of the channel network, and ii) hydrological response units (HRUs), which are a sub-division of the subbasin, determined by the intersection of land use, soil type, and slope maps (homogeneous HRU). Runoff calculations are made for each HRU, and the result is then aggregated for each subbasin and the entire watershed. Fuerthermore, it combines models for simulating nutrient and sediment source, mobilization, and delivery [11].

The QSWAT (QGIS-based tool) was used for model implementation. The final model setup consists of 20 subbasins (Figure 1) and 317 HRUs. SWAT comprises several methods to compute the hydrological processes. In this work, the daily surface-runoff calculation was based on the Soil Conservation Service (SCS) Curve Number (CN) method. To compute the evapotranspiration, we selected the Penman-Monteith option, and the Muskingum method was chosen to represent the delivery and transport from the sub-basins to the catchment's discharge point.

Land-use management information was recovered from a SWAT model previously implemented in the same watershed [6]. Meteorologic input data includes RH, SR, Tmax, Tmin, and WS from the INIA Las Brujas station and rainfall at the eight stations above mentioned (Figure 1). Paso Severino reservoir, located close to the basin's discharge point, was considered in the model as an uncontrolled reservoir with an average annual release rate.

3.1.2. Calibration and validation. The SWAT-CUP software was applied for the calibration and validation process. A set of 10 parameters was selected, which were optimized using the SUFI-2 algorithm [12], available in SWAT-CUP. Discharge at both Florida and Paso Severino was the response variable, and the Kling-Gupta Efficiency (KGE) was the objective function. The calibration period was from 01/17/1989 to 12/31/2008. Afterwards, using the best parameter ranges resulting from calibration, SWAT was validated with only one run for the period 01/01/2009 - 05/06/2016.

Model performance was evaluated using Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), and the ratio between root mean squared error and the standard deviation of observed data (RSR).

3.2. GR4J model

3.2.1. Model setup. The Génie Rural à 4 paramètres Journalier (GR4J) model is a rainfall-runoff model proposed by Perrin et al. [13]. The time step of the model is daily, the spatial aggregation is concentrated, and the main process is the soil moisture computation. It has two reservoirs: a production storage that computes the effective rainfall, and a routing storage that represents the routine in the basin. The model uses precipitation (P) and potential evapotranspiration (PET) as input data. First, it calculates the effective rainfall with a zero-capacity interception store, with a comparison between the P and the PET; then, the soil moisture storage exceedance and effective rainfall are split into two components, one routes 90% of effective rainfall with a unit hydrograph and a nonlinear routing storage, the other routes the remaining 10% with a second unit hydrograph. Finally, the model uses an inter-basin groundwater flow function to compute gains or losses deriving from the interaction between our watershed with the neighbour watersheds. The total flow rate at the discharge point is the sum of the above-mentioned components. Differently from SWAT, the spatial scale for GR4J is represented by the entire catchment (no sub-catchment or HRUs are computed). The model was implemented in MATLAB code.

3.2.2. Calibration and validation. The model calibration employed an iterative procedure by changing the parameters within their conventional range of variation and comparing (statistically and graphically) the simulated with the observed hydrograph. The calibration was performed until a good fit was obtained. The initial parameters were taken from [5]. As for the SWAT model, the KGE was considered as the objective function. The calibration period was the same used for the SWAT model (from 01/17/1989 to 12/31/2008). After the calibration process, the GR4J model was validated from 01/01/2009 to 05/06/2016, considering the best set of parameters selected during the calibration. Model performance was evaluated using NSE, PBIAS, and RSR, as we did for the SWAT model.

4. Results

Table 1 presents a comparison of the model performance based on the selected goodness-of-fit indicators. Figure 2 compares time-series graphs of SWAT and GR4J outcomes (simulations) with the observed discharge. Monthly flow frequency curves are presented in Figure 3.

Table 1. Numerical comparison of SWAT and GR4J performance in simulating discharge.

Model	Process	Location	KGE	NSE	PBIAS	RSR
SWAT	Calibration	P. Severino	0.73	0.58	-9.0	0.65
SWAT	Validation	P. Severino	0.72	0.45	6.0	0.74
SWAT	Calibration	Florida	0.68	0.62	-5.7	0.62
SWAT	Validation	Florida	0.68	0.66	10.7	0.59
GR4J	Calibration	P. Severino	0.71	0.56	6.35	0.66
GR4J	Validation	P. Severino	0.6	0.26	-8.01	0.81
GR4J	Calibration	Florida	0.71	0.65	11.64	0.59
GR4J	Validation	Florida	0.7	0.59	0.23	0.62

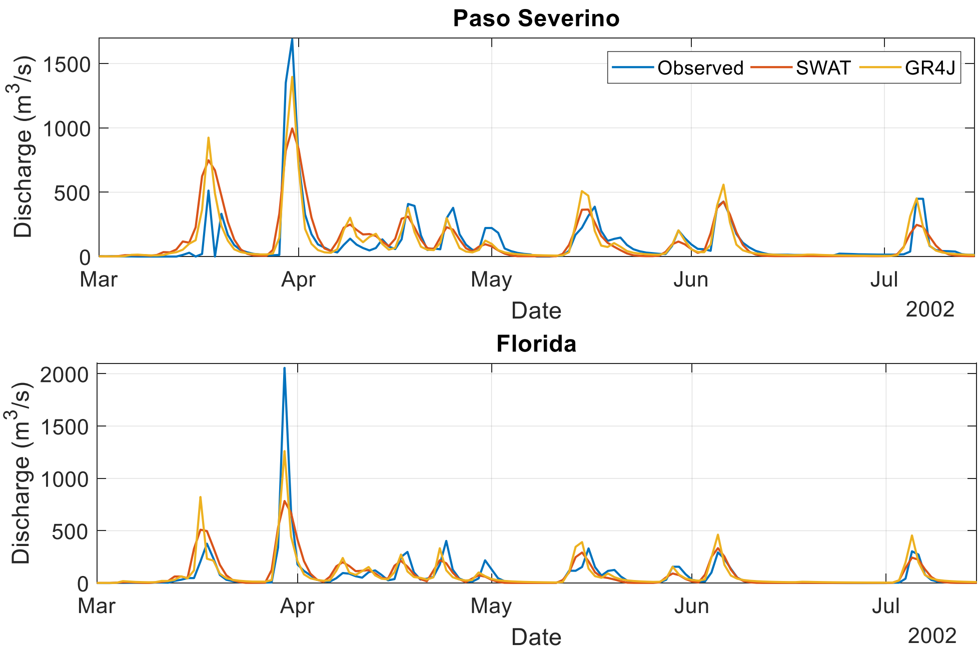

Figure 2. Comparative time series plot of observed and modeled discharge, period 3/1/2002 - 7/15/2002 at the Paso Severino and Florida stations.

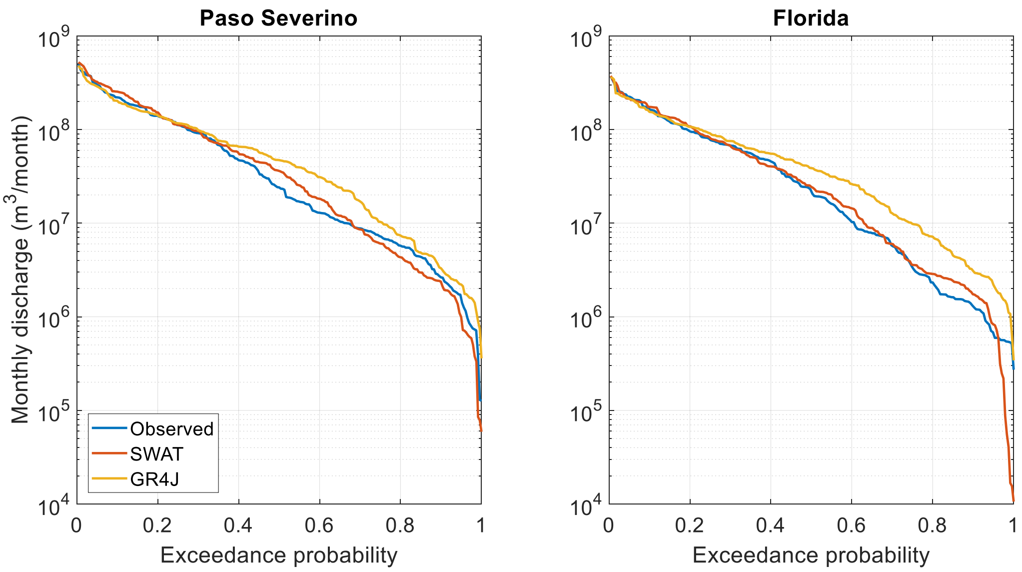

Figure 3. Comparison of monthly flow frequency curves for time series at Paso Severino and Florida.

5. Discussion

Taking into account metric references to evaluate model performance [14], simulations were considered satisfactory if NSE>0.50, RSR≤0.70, and |PBIAS|≤25%. With this criterion, from Table 1, we can see that the implementation of both models at Florida is considered satisfactory, while at Paso Severino only SWAT calibration can be considered equally satisfactory. It can also be noted that both models perform similarly at the Florida station, while, at Paso Severino, the SWAT model outperforms GR4J for the validation period. This is due to the fact that the Paso Severino reservoir (placed at the catchment's discharge point) was better represented by SWAT. In contrast, the lumped GR4J model does not have such capability. This result highlights an advantage of complex distributed models when simulating runoff in watersheds with significant anthropic interventions such as dams or reservoirs.

In Figure 2, time series plots show that the overall behavior of both models is adequate, as they correctly represent the observed base flow, raising, and falling limbs of hydrographs. Comparing both models, it can be seen that GR4J represents better high flow peaks than SWAT, which, in turn, underestimates such events and displays smoother hydrographs.

In the monthly flow frequency curve plots (Figure 3), it can be noted that the GR4J model overestimates middle and low flows. This pattern is particularly evident in Florida. On the other hand, SWAT seems to make an accurate representation of such flows. Both models correctly represent high flows.

Considering the overall performance and behavior of both models, it can be concluded that they both yield similar results, being SWAT more adequate at Paso Severino, where the influence of the dam over the water cycle is considerable. However, for watersheds with no significant reservoirs, such as the one with closure in Florida, the use of a model as complex as SWAT may not be justified. This is due to the higher effort required in terms of modeling design, implementation, and computational cost, which is not reflected in a significant improvement of model performance.

6. Conclusions

Daily rainfall-runoff modeling is a valuable and necessary tool for water management at agricultural watersheds such as the Santa Lucía Chico river. In this work, a distributed (SWAT) and a lumped model (GR4J) were implemented at two subbasins of such watershed to compare their capability in simulating daily hydrographs. Furthermore, we identified possible scenarios for which or which we can state which the most suitable model is.

Both models had satisfactory and very similar accuracy in Florida, while the SWAT model presented better results for Paso Severino, whose hydrologic cycle is influenced by the reservoir presence. Time series and flow frequency plots showed that GR4J better represents flow peaks, while SWAT better characterizes middle and low discharges.

In general terms, it can be concluded that SWAT better represents watersheds with anthropic interventions (such as dams). Furthermore, both models similarly perform in watersheds with no significant reservoirs. The increased complexity of implementation of SWAT does not seem to be justified for the single purpose of rainfall-runoff simulation.

References

[1] Secretaría Nacional de Ambiente, Agua y Cambio Climático (SNAACC) 2018 *Action plan for the protection of the environmental quality of the Santa Lucía river basin*

[2] Gorgoglione A, Alonso J, Chreties C and Fossati M 2020 Assessing temporal and spatial patterns of surface-water quality with a multivariate approach: A case study in Uruguay *IOP Conf. Series: Earth and Env. Sci.* **612** 012002

[3] Aubriot L, Delbene L, Haakonson S, Somma A, Hirsch F, Bonilla S 2017 Evolución de la eutrofización en el Río Santa Lucía: Influencia de la intensificación productiva y perspectivas *Innotec* **14** 7–17

[4] Rodríguez R, Pastorini M, Etcheverry L, Chreties C, Fossati M, Castro, A and Gorgoglione A 2021 Water-Quality Data Imputation with a High Percentage of Missing Values: A Machine Learning Approach *Sustainability* **13** 6318

[5] Narbondo S, Gorgoglione A, Crisci M and Chreties C 2020 Enhancing physical similarity approach to predict runoff in ungauged watersheds in sub-tropical regions *Water* **12** 528

[6] Mer F, Badano L, Neighbur N, Hastings F, Baethgen W, Alonso J, Navas R., Nervi E and Vervoort R W 2020 SWAT Subcuenca Santa Lucia https://doi.org/10.17605/OSF.IO/UQB5J

[7] Refsgaard J C and Knudsen J 1996 Operational validation and intercomparison of different types of hydrological models *Water Resour. Res*. **32** 2189-202

[8] Zhang Z Y, Koren V, Smith M, Reed S and Wang D 2004 Use of next generation weather radar

data and basin disaggregation to improve continuous hydrograph simulations. *J. Hydrol. Eng.* **9** 103-15

[9] Tegegne G, Park D K and Kim Y O 2017 Comparison of hydrological models for the assessment of water resources in a data-scarce region, the Upper Blue Nile River Basin *J. Hydrol.: Regional Studies* **14** 49-66

[10] Gorgoglione A, Gregorio J, Ríos A, Alonso J, Chreties C and Fossati M 2020 Influence of Land Use/Land Cover on Surface-Water Quality of Santa Lucía River, Uruguay *Sustainability* **12**(11) 4692

[11] Abbaspour K C, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J and Srinivasan R 2007 Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT *J. Hydrol.* **333** 413–30

[12] Abbaspour K C, Johnson C A and Genuchten M T 2004 Estimating Uncertain Flow and Transport Parameters Using a Sequential Uncertainty Fitting Procedure *Vadose Zone J.* **3** 1340–52

[13] Perrin C, Michel C and Andréassian V 2003 Improvement of a parsimonious model for streamflow simulation *J. Hydrol.* **279** 275–89

[14] Moriasi D N, Arnold J G, van Liew M.W, Bingner R L, Harmel R D and Veith T L 2007 Model evaluation guidelines for systematic quantification and accuracy in watershed simulations. *Transactions of the ASABE* **50**(3) 885-900