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Articles

Estimation of water budget and management using simulation models: case of the Cabe river basin

Estimación del balance hídrico y gestión usando modelos de simulación: caso cuenca del río Cabe

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Abstract

Currently, there are mathematical methods and models for the calculation and simulation of the hydrological cycle, which is a fundamental stage for the correct accounting of water resources in a basin. The objective of this work is to carry out a new assembly of hydrological simulation and water resources management models, as well as to evaluate their performance by contrasting the results with the official data reported in the current Hydrological Plan, for the Cabe river sub-basin, in Galicia, Spain. The results of the hydrological simulations obtained were compared with two similar studies in the region to verify their validity. Finally, in the water resources management simulation stage, it was found that the results of this study present a greater approximation to the observed data compared to the results reported in the current Hydrological Plan. In this way, it is considered that the assembly of methods and models proposed in this work is a contribution to obtain quality results that help to improve the situations of the current management of resources in the Cabe river region, as well as to face the impacts of climate change on water resources.

Keywords: Water budget, management, simulation, Cabe River, Visual-Balan, AQUATOOL.

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Resumen

Actualmente se cuenta con métodos y modelos matemáticos para el cálculo y la simulación del ciclo hidrológico, que es una etapa fundamental para la correcta contabilización de los recursos hídricos en una cuenca. El objetivo de este trabajo es el de realizar un nuevo ensamble de modelos de simulación hidrológica y de gestión de recursos hídricos, así como evaluar su desempeño contrastando los resultados con los datos oficiales reportados en el actual Plan Hidrológico para la subcuenca del río Cabe, en Galicia, España. Los resultados de las simulaciones hidrológicas obtenidos se compararon con dos estudios similares en la región para verificar su validez. Finalmente, en la etapa de simulaciones de la gestión de recursos hídricos se encontró que los resultados de este estudio presentan una mayor aproximación a los datos observados en comparación con los resultados reportados en el Plan Hidrológico vigente. Por lo tanto, se considera que el ensamble de métodos y modelos propuestos en este trabajo es una contribución para obtener resultados de calidad que ayuden a mejorar las situaciones de la gestión actual de recursos en la región del río Cabe, así como para hacer frente a los impactos del cambio climático en los recursos hídricos.

Palabras clave: balance hídrico, gestión, simulación, río Cabe, Visual-Balan, AQUATOOL.

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Introduction

The definition of "water resources" refers to the amounts of water that are used for the activities of human societies. The human being is not the only user of water resources, since all ecosystems, together with their biotic-abiotic elements, need water for their functioning and interactions. The United Nations Organization (ONU, 2018) establishes that: "Water is a precondition for human existence and for the sustainability of the planet".

In order to use and manage water resources sustainably, it is necessary to be able to quantify them accurately. According to Diamond (2005), ever since civilizations such as the Egyptians, Greeks, Romans, and Mayans have been known and up to the present, their survival has been marked by the way in which they managed their natural resources. Diamond shows in his research how the incorrect management of resources led to the extinction or displacement of entire civilizations. Currently and with greater intensity since the Kyoto Protocol in 1997, the monitoring and study of water resources has intensified, to the extent that today there are mathematical techniques assisted by specialized programs that facilitate analysis-research of water resources from the basin level to the level of cities or towns.

Addressing water resource management challenges generally requires responses in two key areas: responses that address structural issues, including generation and acquisition of data and information, infrastructure, operations, maintenance and institutional responses that encompass issues such as policy and pricing (GWP & INBO, 2009). On the other hand, an approach proposed by the Food and Agriculture Organization of the United Nations (FAO, 2019), is called Water Accounting and Auditing (WA&A). One of the perspectives of Water Accounting is based on hydrology. This hydrological perspective is firmly based on the understanding of the physical process that governs the volumes and rates of change in water flow, as well as stocks in different territories and/or under different climatic conditions or management regimes. Another critical aspect of Water Accounting is that both supply and demand for water supply systems must be considered and evaluated. On the supply side, it is important to know as precisely as possible the availability in space and time of rainfall, surface water, groundwater and unconventional water sources. On the demand side, knowledge of user demand is essential, how they are satisfied, consumptive and non-consumptive usage patterns, the level of service that is experienced by users, and its benefits (Batchelor, Hoogeveen, Faures, & Peiser, 2017).

Hydrological simulation models are the tools used to investigate hydrological processes, ranging from small catchments to global models. Each model has its own unique features and respective applications. Some of them are complete and use the physics of the underlying hydrological processes and are distributed in space and time. Also, each model has various drawbacks such as lack of ease of use, large data requirements, lack of clear statements of its limitations, etcetera (Gayathri, Ganasri, & Dwarakish, 2015). Sorooshian, Sharma and Wheater (2008) classified the models as continuous and event-based models. The first ones produce information only for specific time periods, while the latter produces continuous information. One of the most important classifications is the empirical model, the conceptual models and the physically based models.

According to Islam (2011), in summary, models for water resource management can be classified as: 1) optimization models based on maximization of economic benefits; 2) optimization models based on minimization of flow costs, and 3) water resource management models based on dynamic systems. Mayer and Muñoz-Hernández (2009) state that simulation and optimization are the two main approaches for watershed modeling. In simulation, the behavior of water resources is simulated based on a set of rules that govern water allocations and the operation of the infrastructure, while in optimization, allocations are optimized based on an objective function and associated restrictions.

The integrated management of a socio-economic and environmental water resources system has attracted considerable attention and has proven to be more suitable for the sustainable management of water resources. Computer programs designed for Decision Support (Decision Support Systems, DSS), involve total water resources and water consumption, with complex content and wide coverage. Currently, DSSs that have already been developed mainly include optimization techniques, conflict resolution techniques, and complex adaptive systems (Fan, Xu, Chen, Li, & Tian, 2020).

DSS tools provide operational solutions to help policymakers address complex socio-ecosystem environmental issues at various scales. In addition to core functions targeting decision analysis, they generally include capabilities for modeling and, in some cases, also for participatory process management. These DSS tools can provide the operational framework for the integration of simulation modeling, participatory planning, and decision analysis methodologies and approaches (Giupponi & Sgobbi, 2013).

In the northwest of Spain (Galicia) there are some studies in similar basins that serve as a reference for this work. Specifically, the works of Samper *et al*. (2005); Raposo, Molinero and Dafonte (2012) in Galicia Costa, and Samper and Pisani (2013) in the Valiñas River sub-basin are discussed. The difference in the results is possibly due to the fact that there is a different geological composition between the Vilasouto and Ponte Pena sub-basins, where almost half (47 %) belong to the group of "quartzites, slates, sandstones and siltstones", unlike the Vilasouto sub-basin, where this same group has only 13.79 %, which highlights the appearance of limestone, since this modifies the hydrogeological parameters of the aquifer.

The objective of this work was to propose a methodology through the assembly of Visual-Balan and AQUATOOL mathematical and computer models, to estimate the water balance in the upper sub-basin of the Cabe River and evaluate the supply guarantees in its water demands. Although there is currently hydrological planning in this study area, official reports still show a bias with the reality of water flows by overestimating the quantities of water resources.

Materials y methods

Study area

In the northwest of Spain, in the Autonomous Community of Galicia, within the municipality of Lugo, is the Cabe Exploitation System (SEC), which refers to the resulting use of the Cabe River sub-basin, which is part of the Demarcation Hydrographic of the Miño-Sil (DHMS). The surface of the SEC basin is 735.18 km^2. During its route of 54.94 km it receives tributaries, being important the Mao with 49.47 km in length, Cinsa and Carabelos with 15.69 and 11.35 km in length respectively. In the entire SEC there are 200.65 km of water masses and 925.05 km of channels (MAGRAMA, 2015). One of the important elements for the management of water resources within the SEC is the Vilasouto reservoir, which has a capacity of 21 Hm^3, located in the upper part of the sub-basin. Figure 1 shows the location of the SEC within the DHMS and its junction point with the Sil River.

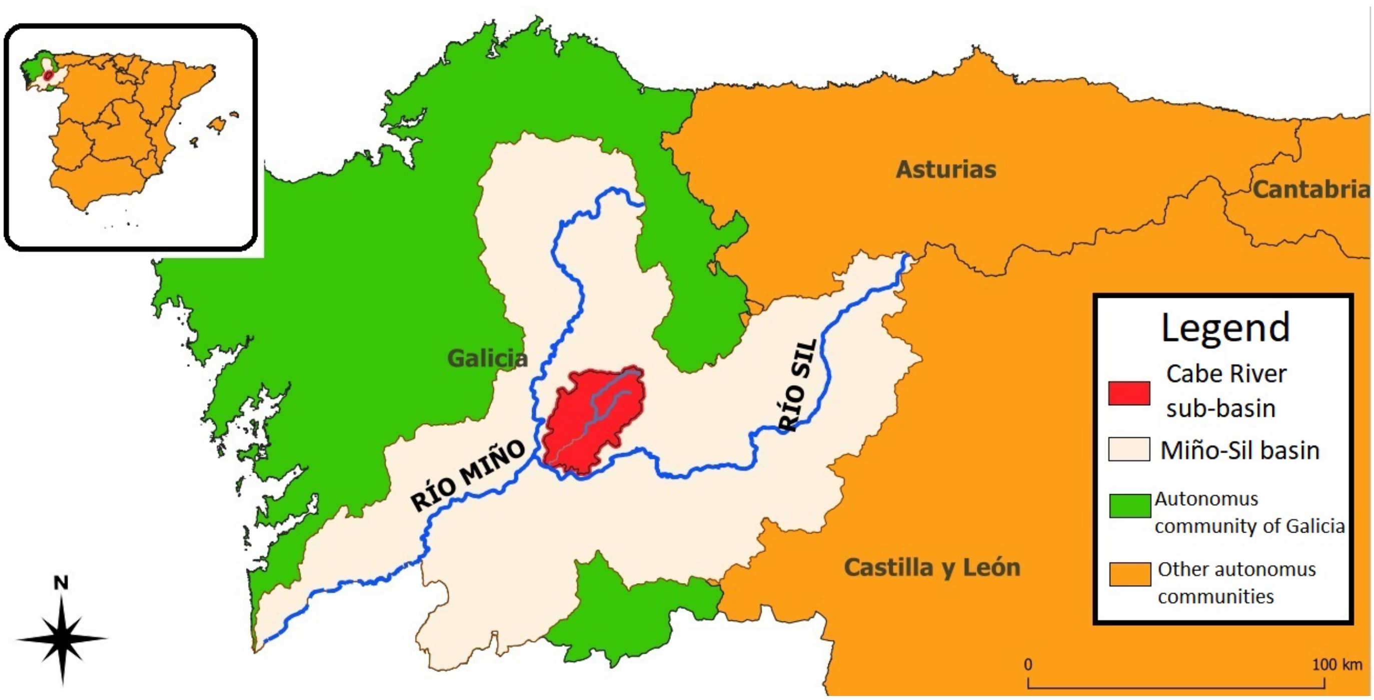

Figure 1. Location of the Cabe River sub-basin within the Miño-Sil Hydrographic Demarcation.

The hydrological simulation model used in the current Hydrological Plan (HP) is the conceptual and almost distributed model SIMPA (Integrated System for Modeling the Precipitation Contribution process), updated by the Center for Hydrographic Studies of the Center for Studies and Experimentation of Public Works (Cedex), from Spain. Table 1 shows the basic statistical data of the hydrological variables as reported by the CHMS in the current PH. The average annual precipitation is 1041.59 mm and an average annual contribution of 386.42 hm^3/year, while other hydrological variables for the SEC are potential evapotranspiration of 604.1 mm/year, real evapotranspiration 518.33 mm/year, aquifer recharge 158.66 hm^3/ year, surface flow 226.60 hm^3/year and underground flow 159.82 hm^3/year, total flow 386.42 hm^3/year.

Table 1. Basic average precipitation and contribution statistics for the SEC, series 1980/81-2011/12. Source: CHMS (2015).

Annual data	Precipitation (mm/year)	Year of occurrence	Annual contribution (hm^3/year)	Year of occurrence
Minimum value	638.9	2011/2012	140.22	2011/2012
Average value	1041.59		386.42	
Maximum value	1751.33	2000/2001	841.86	2000/2001
Var. Coef.	0.23		0.40	
Bias Coef.	0.81		0.86	
Autocorrelation	-0.19		-0.22	

In the information reported in the PH, the uses of water are divided by "Demand Units" of urban type (includes domestic, industrial, municipal, commercial and tourism), agricultural, livestock and recreational. Table 2 shows the amounts of water that are extracted from the various sources to satisfy the 17.78 hm^3 per year of all the demands in the SEC estimated for 2012. Most of the water is obtained from surface sources, due to natural availability of water in the region.

Table 2. Origin of supply in the SEC. Adapted from CHMS (2015).

Exploitation system	Origin of water in the Exploitation System			
	Superficial (hm^3/year)	Underground (hm^3/ year)	Spring source (hm^3/ year)	Vol. Total (hm^3/ year)
Cabe	14.13	2.43	1.22	17.78

Upper Sub-basin of the Cabe River

The specific study area for this research work is actually a simplification or reduction of the SEC (of 735.18 km^2), which is the Upper Sub-basin of the Cabe River (SARC, by his acronym in Spanish) with an area of 426.34 km^2, which is approximately half of the SEC. The delimitation point (outlet) of the SARC is within the city of Monforte de Lemos, Lugo. The study area has been established at this point because the last gauging station (EA1765) is located 4 km upstream on the outskirts of the city of Monforte de Lemos. Consequently, it is not possible to calibrate a hydrological model after the gauging station, and carrying out a hydrological simulation in uncalibrated areas would generate results with high uncertainty that cannot be contrasted with any reality. With this foundation and because Monforte de Lemos is a city with relevance in the area, the starting point of the SARC was established at latitude 42°31'16.23"N and longitude 7°30'56.48"W. The demand for water resources for each type in the SARC is shown in Figure 2, information that has been extracted and adapted from the current PH. It can be seen that the urban demand unit (UDU) is 4.2 hm^3, which represents 24 % of the total and remains relatively stable throughout the year. The same is observed for livestock demands (UDG) recreational demand (UDP 10) that represent the minimum of the demand being 3 % each. The agricultural demand unit (UDA) that represents 70 % with 12.1 hm^3 and has the highest consumption in the months of May to September and zero consumption from November to February.

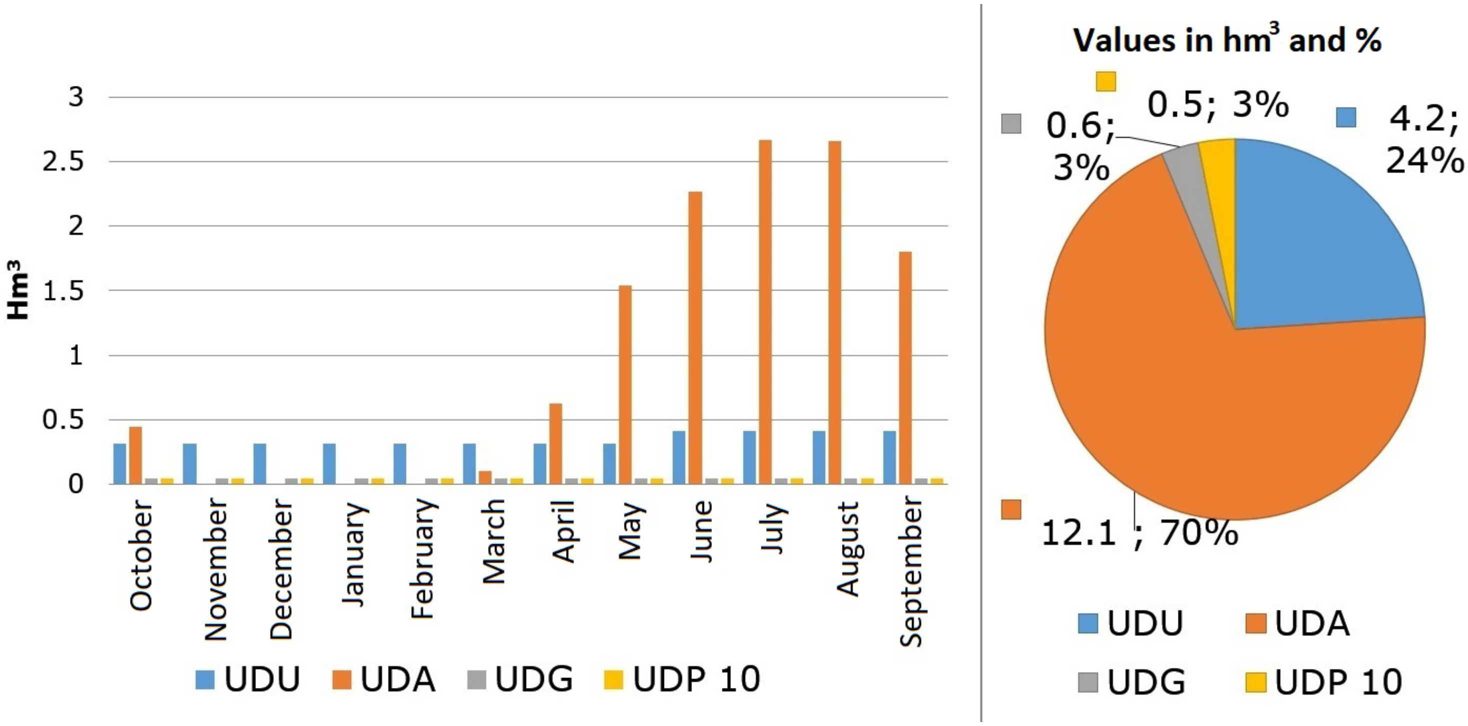

Figure 2. Uses of water resources for each unit of demand in the SARC. Adapted from CHMS (2015).

Methodology

The methodology consists of an assembly of mathematical methods and specialized software for the simulation of processes of the hydrological cycle and management of water resources. Figure 3 shows the beginning of the process and the order in which the assembly of models is carried out to reach the partial and final results of the purpose of this work, where each phase is differentiated in a different shade of blue. The steps outlined in red represent the input information obtained from various sources considered official; those framed in black refer to software, in yellow to mathematical models and the green boxes represent results that are considered relevant for the purpose of this research work. The process in Figure 3 begins with the definition of the sub-basins within the study area, continuing with obtaining the complete series of meteorological parameters required by the hydrological modeling software, then dealing with the hydrological simulation with the software Visual-Balan, which feeds on the information from the two previous phases, in addition to all the physical parameters of the basin and the data from the gauging stations. In this way, Visual-Balan performs a first validation of the hydrological simulation which, if the criteria are not met, will require a recalibration of the physical parameters of the basin, until an acceptable validation is obtained. To evaluate the behavior of models, Moriasi *et al*. (2007) recommend the efficiency number of Nash and Sutcliffe (2003), the coefficient of determination (R^2) and the root mean square error (RMSE). As a result, the series of data on the contribution of water resources for each sub-basin in the study area are obtained. The part that corresponds to the simulations with the AQUATOOL software requires information on the water flows within the system, such as demands, returns, pumping, distribution network, among other aspects, to later generate the water flow network. for the studio stage. According to

Andreu, Solera, Capilla and Ferrer (2007), AQUATOOL's SIMGES module is fed from the flow network and input data series, performing the management simulation to supply the demands within the system. The storage elements (such as reservoirs and reservoirs) within the flow system serve as control points to assess the correct functioning of the model, in order to be able to compare the simulated levels in the reservoir with those measured. As a final result, an overview of the accounting of water resources is obtained from before their use, to the distribution and evaluation of the supply of the demands, for the period of time evaluated.

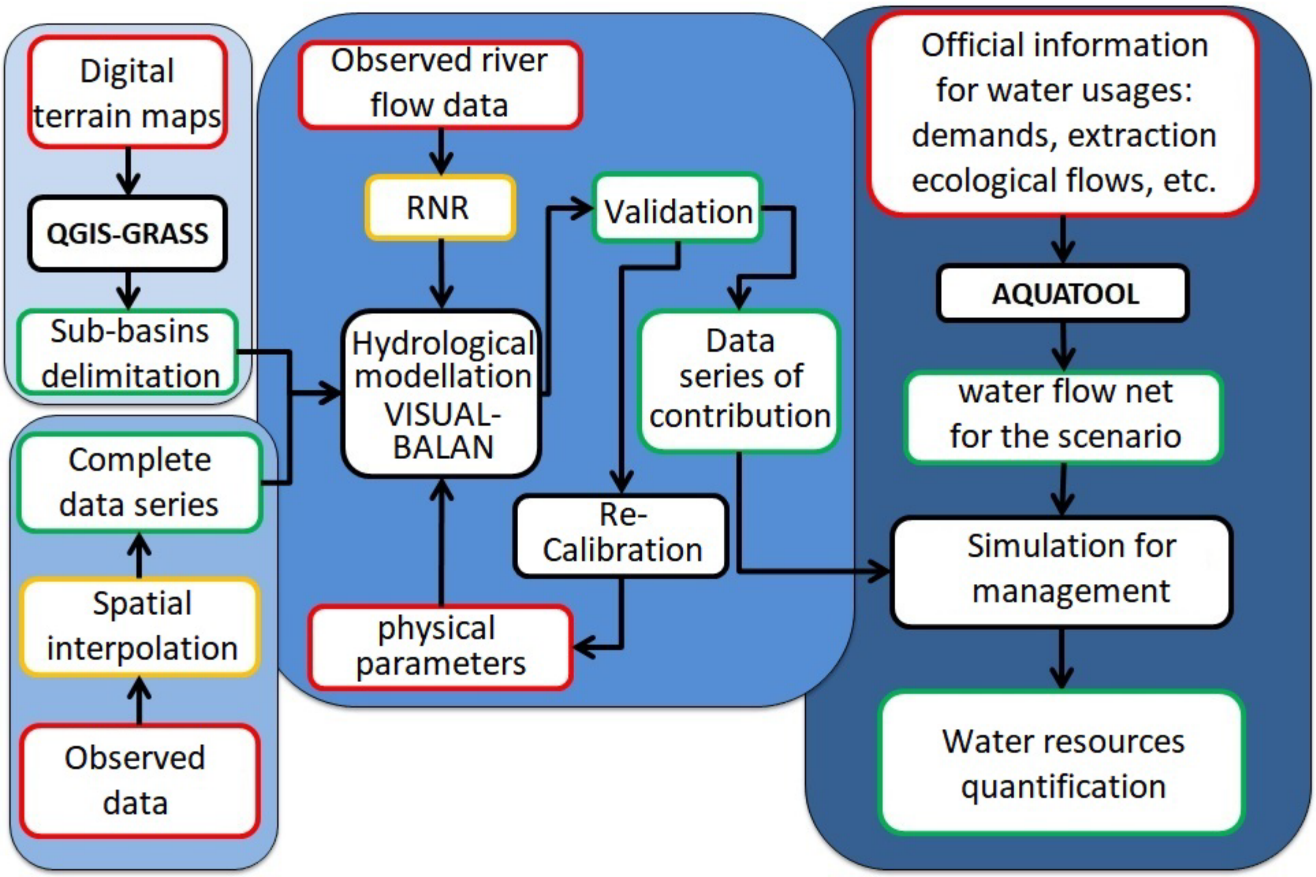

Figure 3. Assembly process of the methodology.

For the definition of the sub-basins in the study area, geo-spatial information was required from the National Geographic Institute (IGN) of Spain and from the QGIS software to process and obtain the delimitation maps of the sub-basins in the study area. With the information from the digital terrain models (DTM) they were worked with the geographic information software QGIS and the GRASS tools. Through the IGN, the information of the maps with the Reference Coordinate System (SCR)

ETRS89, of MDT05 LIDAR (Digital Terrain Model and Laser Imaging Detection and Ranging) and BTN25 (National Topographic Base) were obtained from the download center.

Within the QGIS plugins that were used in this work, there are the utilities and tools of GDAL (Geospatial data abstraction library), GRASS-PROJECT (Geographic resource analysis support system).

Regarding the daily meteorological data series of mean temperature (mean T), precipitation (Pr.) and reference evapotranspiration (ET_0) for the SARC, they are obtained according to the results of the work by Rangel-Parra (2019), where the calculations of the estimation by spatial interpolation for the climatic variables mentioned.

The physical parameters of the soil in the study area were obtained from the interactive maps of soil properties in Galicia from the Department of Edaphology and Agricultural Chemistry of the University of Santiago de Compostela (USC, 2018). The physical parameters that have not been possible to obtain from the literature were adjusted using the automatic calibration tool offered by Visual-Balan.

The gauging data observed in the Mao (main tributary) and Cabe rivers were obtained from the Cedex yearbook (Cedex, 2018) for the stations of Ribas Altas, Ponte Pena and Vilasouto reservoir. For the Ponte Pena station they correspond to the entire period of 2007-2017, while for the station in Ribas Altas, only the winter flows of 2006-2017 (when the irrigation activity is not carried out) were used, since during the summer extractions are made for irrigation that are not duly registered, so it would be possible to apply the restitution to the natural regime. Finally, in the case of the Vilasouto reservoir, it was possible and necessary to apply an restitution to the natural regime by having daily data on the level of the reservoir.

According to Lopez-Garcia (1993), to calculate the flow with restitution to the natural regime (RNR), the general equation has the following approach:

$$N = S + T + B - V - Q - R + E \pm A \qquad (1)$$

Where *N* is the flow of a river in the natural regime for the period, S is the measured flow; *T* is the flow derived or transferred by intakes upstream (out of the basin); *B* is the flow withdrawn by pumping in aquifers connected, V is the flow discharged by upstream uses; *Q* is the flow transferred from other basins (into the basin); *R* is the flow contributed by additional recharge in aquifers; *E* is the evaporated flow in reservoirs and new water masses , and *A* is the flow stored or released by reservoirs.

For this particular work and applied to the Vilasouto reservoir, the equation has been modified to adapt it to the particular case, being as follows. The total flow with RNR at the outlet point of the reservoir is calculated with the following water balance equation for storage:

$$A_i = A_{i-1} + P + N - Evap. - Q_{Out} \quad (2)$$

Or for the total flow:

$$N = (A_i - A_{i-1}) + Evap. + Q_{Out} - P \quad (3)$$

Where for day i, A_i is the storage in the reservoir for a certain day and $A_{i\text{-}1}$ is the storage of the previous day in units of volume/time corresponding to day i; Evap. is the evaporation on the surface of the reservoir; Q_{out} is the outflow from the reservoir and P is the precipitation that falls on the reservoir area (multiplied by the reservoir area). The evaporation (*Evap.)* of the Vilasouto reservoir was estimated as a fraction of the reference evapotranspiration (ET_0) calculated by spatial interpolation for the center of the reservoir. The equation reported by the American Association of Civil Engineers (ASCE, 1996) is:

$$ET_c = K_c ET_0 \quad (4)$$

Additionally, the area of the reservoir must be added to have the volume of all the evaporation in the reservoir for the corresponding day.

$$K_c(ET_0 * A) = Evap. \quad (5)$$

Where the K_c value is 0.75 as reported by ASCE for open surface water. It is considered that ET_c would correspond to the evaporation of the water surface (*ET_c = Evap.),* A is the area of the reservoir and $\mathbf{ET_0}$ is the reference evapotranspiration in the reservoir.

The Visual-Balan software performs water balances in the edaphic soil, in the unsaturated zone and in the aquifer using an interactive environment for data entry and post-processing of results. The fundamental terms of the balance are the inputs due to precipitation and irrigation, the outputs due to surface runoff, evapotranspiration, interception, hypodermic flow and underground flow, the variation of the moisture content of the soil, of the unsaturated zone and of the water level in the aquifer. These results can be compared with available data on levels and capacity (Samper, 1999).

The criteria used by AQUATOOL to evaluate failures in supply guarantees have been those of the Instruction for Hydrological Planning (IPH, 2008) of the Spanish government for urban and agricultural demands (UTAH DWR criteria): For urban demand, Failure is considered when the deficit in a month is greater than 10 % of the monthly demand. For agricultural demand, failure is considered when the deficit in a year is greater than 50 % of the annual demand (D.A.). It is considered a failure when in two consecutive years the sum of the deficit is greater than 75 % of the D.A., and it is considered a failure when in ten consecutive years the sum of the deficit is greater than 100 % of the D.A. (Solera-Solera, Paredes-Arquiola, & Andreu-Álvarez, 2015).

Results

Figure 4 shows the result of the map generated in QGIS, where the Upper Sub-basin of the Cabe River (SARC) is represented with the red border with 426.34 km^2, as well as the three internal sub-basins, Ribas Altas 350.79 km^2, Ponte Pena 35.24 km^2 and Vilasouto 49.24 km^2. The sub-basins were established in reference to the available gauging stations. The shaded part of the map corresponds to the Lower Sub-basin of the Cabe River (308.84 km^2 not included in this work), which joins the Sil River to the south. The WGS84 geographic coordinates of its centroids are SARC 42º36'13''N and 7º25'2.9” W, Ribas Altas 42º37'40''N and 7º23'40” W, Vilasouto Reservoir 42º41'10” N and 7º21'12” W. Finally, Ponte Pena 42º39'10''N and 7º18'37” W, with projection ETRS89/UTM zone 29 (EPSG:25829).

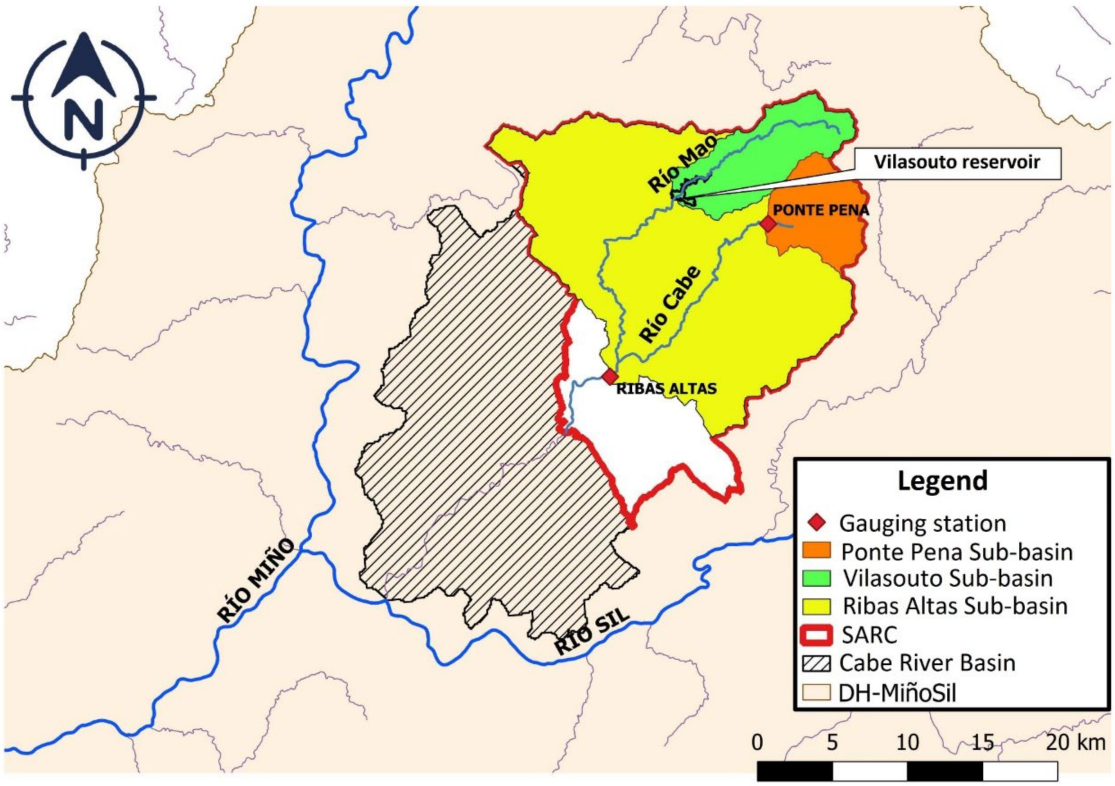

Figure 4. Result of the generation of sub-basins within the Cabe river sub-basin within.

Regarding the calculation of the Restitution to the Natural Regime (RNR), Figure 5 shows the average daily outflow in the restituted Vilasouto reservoir. When plotting this flow with RNR, it was observed that after 06/20/2013 of the 11 hydrological years, there was a negative irregular behavior in the flows (indicated circles), which is due to the error in the estimation of the outflows. and in their records and validation. For this reason, only the data prior to this irregularity date, which corresponds to 10/01/2006 to 06/19/2013, were used as a reference to calibrate the Visual-Balan hydrological model (blue points in Figure 6) in this sub-basin.

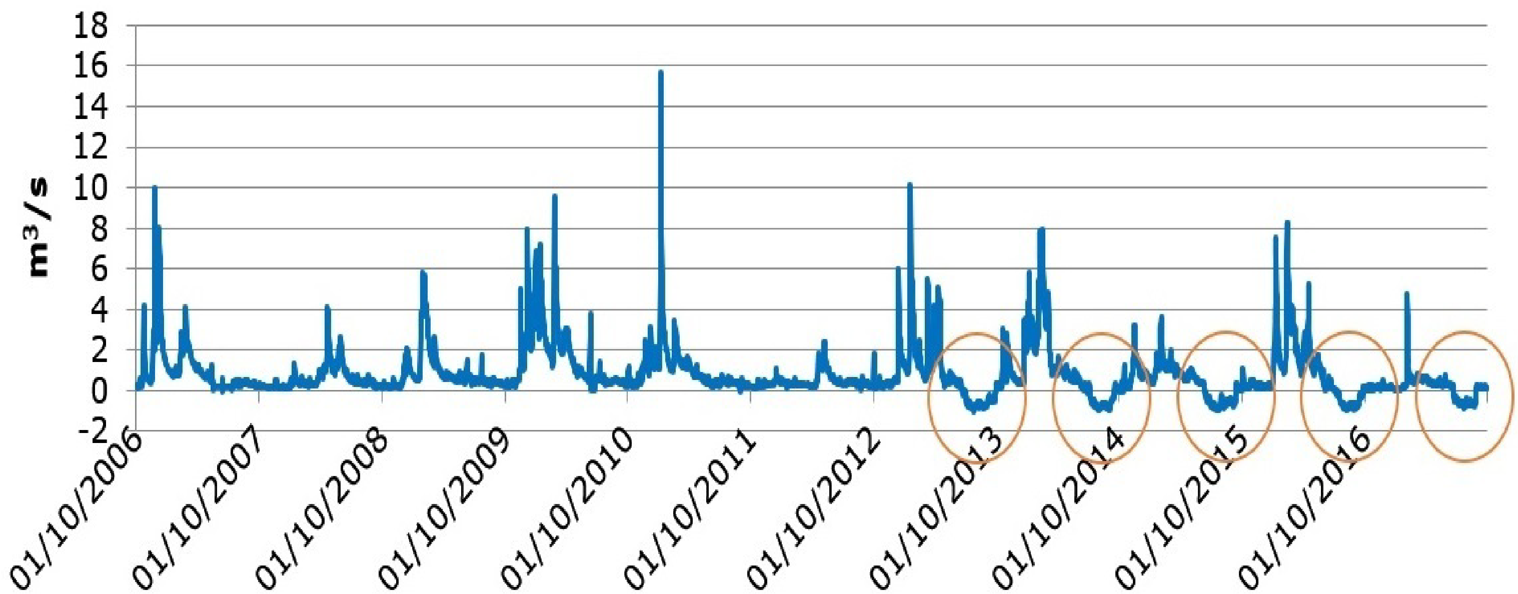

Figure 5. Result of the Restitution to the Natural Regime in the Vilasouto reservoir, average flow per day.

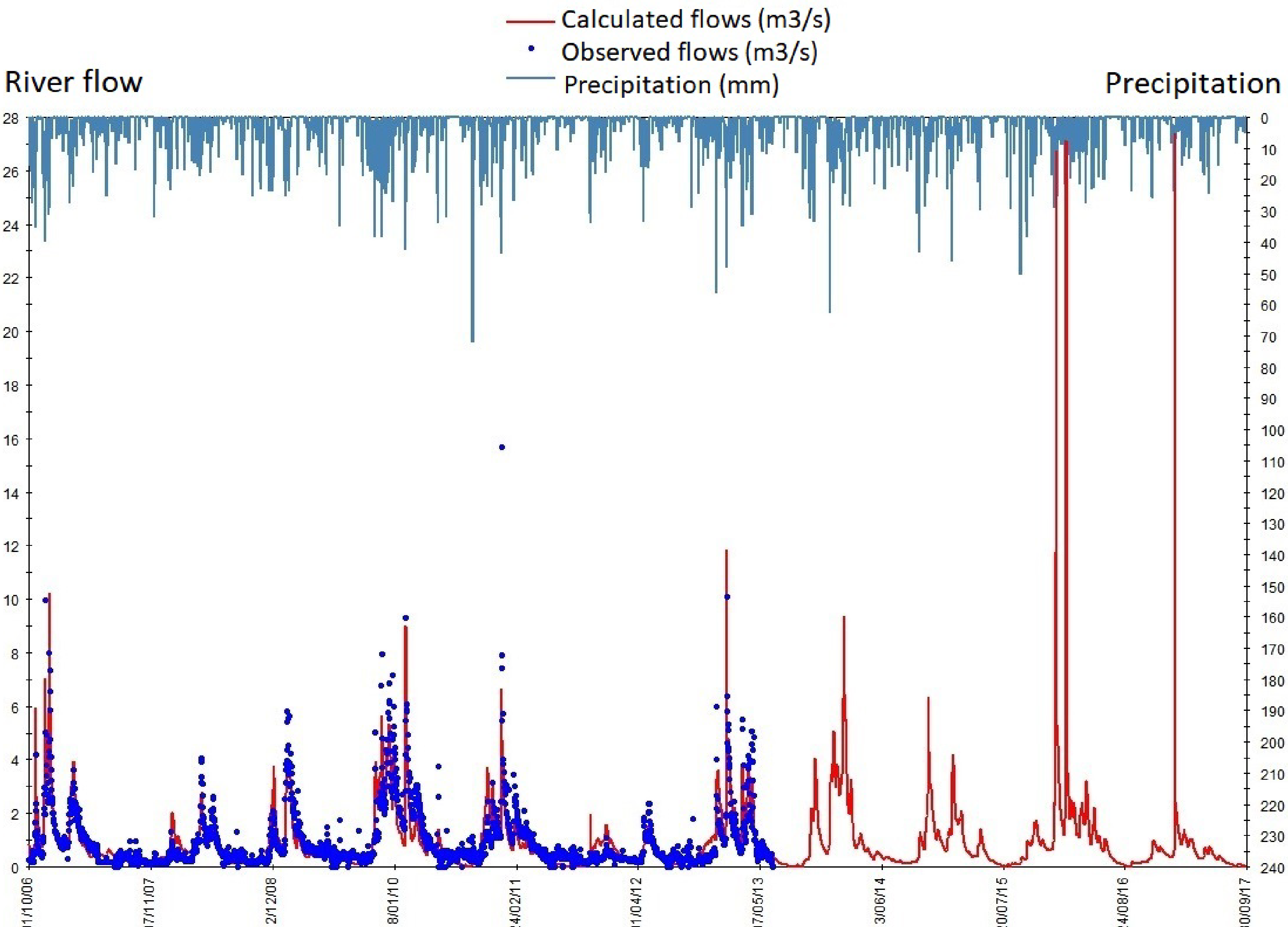

Figure 6. Comparison of the calibration in Vilasouto with the observed and simulated flows.

Figure 6 shows the result of the calibration in the Vilasouto sub-basin, comparing the observed and simulated flows after having eliminated the period with negative flows explained in Figure 5.

Table 3 shows the result of the average annual contributions by sub-basin in the SARC for the period 2006-2017; the Vilasouto sub-basin 29.71 hm^3/year (12 %); Ponte Pena 24.26 hm^3/year (8 %); Ribas Altas 132.32 hm^3/year (62 %), and the remaining area between Ribas Altas and the SARC exit point contributes 29.88 hm^3/year (18 %), for a grand total of 216.36 hm^3/year. As reported by the CHMS, the entire SEC contributes 386 hm^3/year, for the 216.36 estimated in this work for the SARC, they represent 56 % of the estimate for the SEC.

Table 3. Contribution of water resources by SARC sub-basin.

Sub-basin	**Annual contribution (hm^3/year)**	**%**
Vilasouto	29.71	12
Ponte Pena	24.26	8
Ribas Altas	132.32	62
Remainder SARC	29.88	18
Total in SARC	216.36	100

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After estimating the flow with RNR, the hydrological simulation was carried out with Visual-Balan in the Vilasouto sub-basin iteratively and recalibrating the physical parameters of the soil, using the help of the tools included in Visual-Balan for sensitivity and auto analysis. - calibration. The physical parameters of the soil in the study area were obtained from the interactive maps of soil properties in Galicia from the Department of Edaphology and Agricultural Chemistry of the University of Santiago de Compostela (USC, 2018). Figure 6 shows the flows simulated with the calibrated model and the flows observed from the Cedex yearbook database, where a Nash-Sutcliffe-Efficiency (NSE) coefficient value of 0.69 was obtained. The simulated flows are well adjusted to the magnitude and trends of the observed data. On the other hand, the result of the hydrological simulation for Ribas Altas, obtained a validation of NS of 0.82 and for the Ponte Pena sub-basin, a value of NS of 0.38 was obtained. Moriasi *et al*. (2007) in their publication gave an interpretation classification to the NSE values, which are shown in the following Table 4.

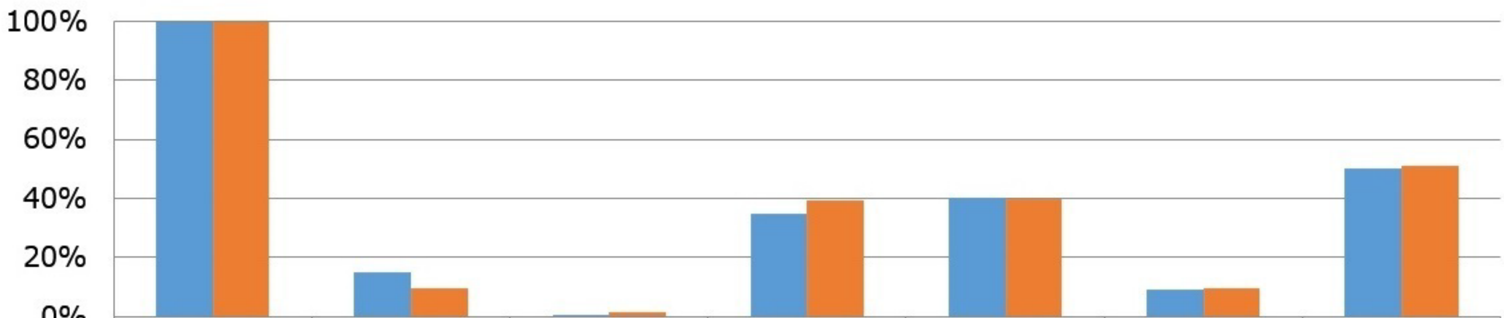
Table 4. Interpretation of the values of the Nash-Sutcliffe-Efficiency criterion.

Performance rating	NSE
Very Good	0.75 < NSE > 1
Good	0.65 < NSE > 0.75
Satisfactory	0.5 < NSE > 0.65
Unsatisfactory	NSE =< 0.5

The NSE obtained in the Ponte Pena sub-basin is the lowest of the three simulated sub-basins, however, it only represents 8 % of the contributions of the study area, as shown in Table 3. On the other hand, no detailed information on geological parameters and groundwater flows to improve the validation of the simulation in Ponte Pena. To increase the consistency of the calibration obtained for the SARC (and observe the impact of the result obtained in Ponte Pena), the distribution of flows was contrasted with two other hydrological studies within the Galician area (Raposo *et al*., 2012) for the Hydrographic Demarcation and for the Valiñas River (Samper & Pisani, 2013). Table 5 shows the similarity in the importance of the hydrological components. Additionally, Figure 7 shows the graphic distribution between the two flow results of the case of the Valiñas River and the SARC. The coincidence of such comparisons supports the results obtained for the study area of this work and the representativeness in the calibration obtained with Visual-Balan.

Table 5. Comparison of the results of Visual-Balan for SARC with two studies in the same area of Galicia.

Hydrological parameters (annual values)	Valiñas River, Samper & Pisani (2013)		Galicia Costa, Raposo et al. (2012)		SARC	
Precipitation (mm)	1 081	100 %	1545.44	100 %	994.32	100 %
Interception (mm)	163	15.08 %	118.8	7.69 %	93.21	9.68 %
Superficial runoff (mm)	5	0.46 %	92.7	6 %	16.82	1.69 %
ET_0 (mm)	928	-	-	-	997.00	-
ETR (mm)	376	34.78 %	357.8	23.2 %	391.02	39.3 %
Underground transit recharge (mm)	536	-	-	-	490.28	-
hypodermic flow (mm)	437	40.43 %	592.3	38.3 %	396.17	39.8 %
Aquifer recharge (mm)	99	-	385	24.9 %	94.38	-
underground flow (mm)	98	9.07 %	-	-	94.38	9.49 %
Total flow (mm)	541	50.05 %	-	-	507.37	51.0 %



	Precipitation (mm)	Interception (mm)	Superficial runoff (mm)	ETR (mm)	Hipodermic flow (mm)	Underground flow (mm)	Total flow (mm)
Valiñas river	100.00%	15.08%	0.46%	34.78%	40.43%	9.07%	50.05%
SARC	100.00%	9.68%	1.69%	39.33%	39.84%	9.49%	51.03%

Figure 7. Comparison of the results of the hydrological variables of the SARC and the Valiñas River sub-basin.

One of the features of Visual-Balan is the ability to perform a double calibration against surface flows and piezometric levels. However, with regard to groundwater resources, there is no information on piezometric level data in the area, information that is essential to improve the calibration results of the hydrological-geological model. Raposo *et al*. (2012), and Samper and Pisani (2013), coincide in their works with the challenge of calibrating the hydrological model when working in a study area with variations in the geology of the basin and the heterogeneity of the characteristics of storage and transmission of water. underground in crystalline type rocks.

For the management simulation in AQUATOOL, the contributions calculated in Visual-Balan for each sub-basin are considered as the input information of water resources. The flow scheme developed in AQUATOOL for the SARC in Figure 8 is the corresponding adaptation of the existing one in the PH 2016-2021 for the SEC. Additionally, the ecological flow was added (also established in the PH for this sub-basin) in the form of demand for water resources and thus it was possible to evaluate its guarantee of compliance.

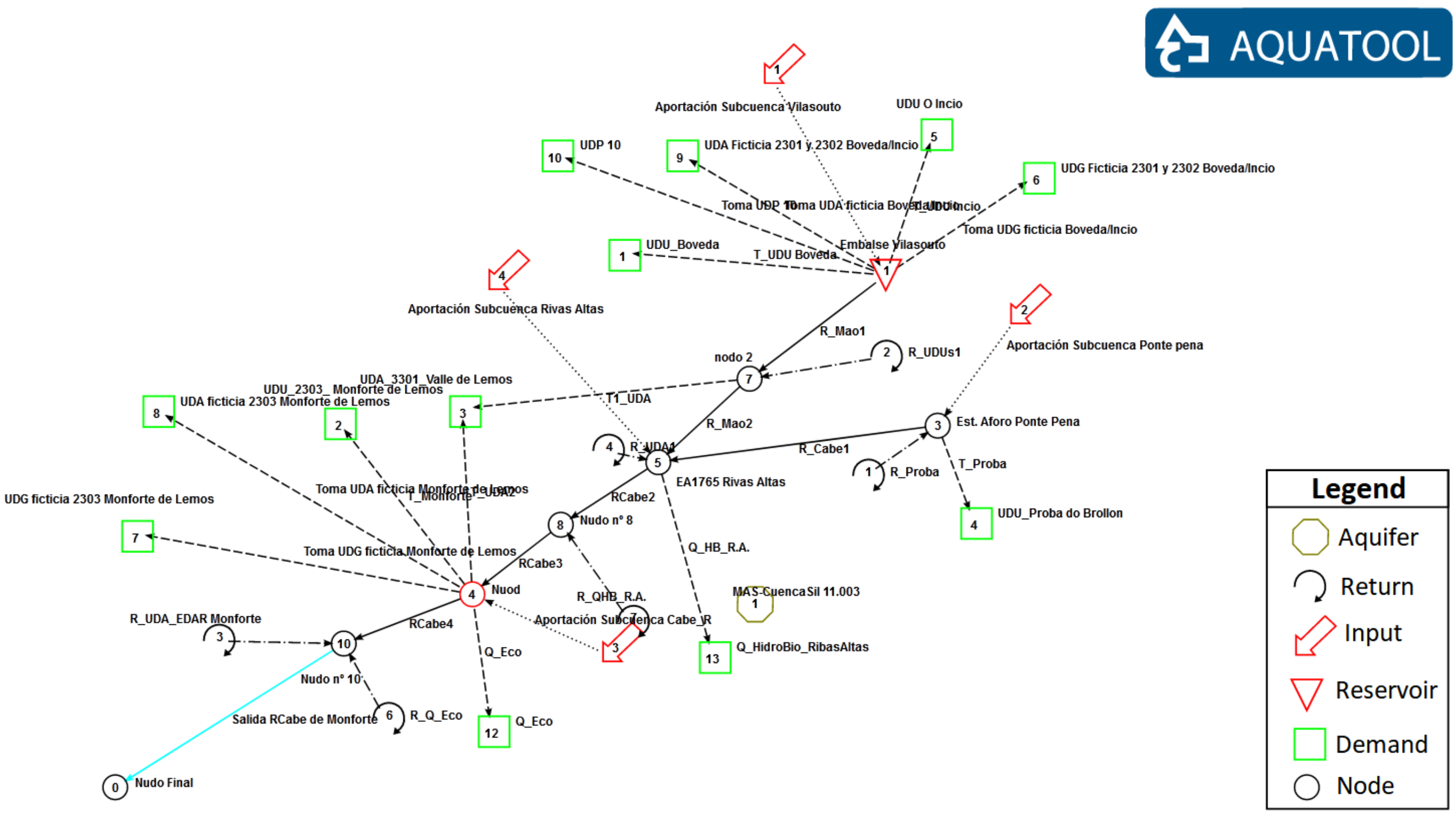


Figure 8. Scheme of water flows in AQUATOOL for the SARC.

The reserve level observed in the Vilasouto reservoir was considered the reference point to evaluate the AQUATOOL flow simulation against the real behavior of the system. Figure 9 shows the graphs between the levels observed and simulated by AQUATOOL for the SARC, as well as the levels of the simulation carried out and reported by the CHMS in the current PH. A clear better approximation to the reality of the results of this work can be observed than those reported in the PH.

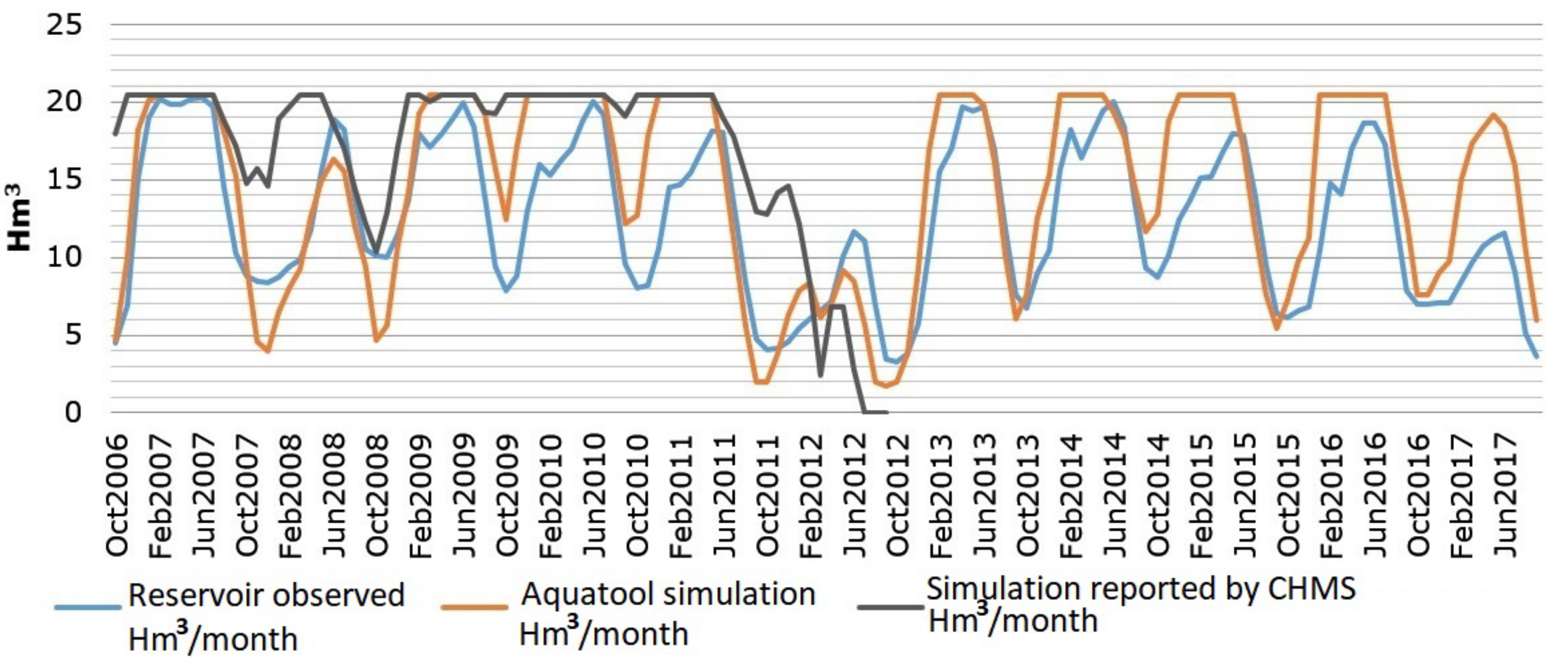


Figure 9. Comparison between the levels of the Vilasouto reservoir simulated with AQUATOOL and observed levels.

The difference found between the results of the CHMS and those of this work lies in the estimates of the contribution of water resources. While the data used by the CHMS was generated by the SIMPA software, in this work the information of the meteorological parameters reported in Rangel-Parra (2019) derived from the MeteoGalicia data was used. The hydrological simulation in Visual-Balan implies a more complex process than the SIMPA model, so the contributions generated by SIMPA are overestimated and when simulated in AQUATOOL, they result in an absence of failures in the guarantees.

Finally, for failures in the guarantee of supply, the IPH criteria pre-established in AQUATOOL were used. Table 6 shows the summary of the results of the failures for the simulated period of 2006-2017. A total of 10 failures are found for the demands, with the ecological flow being the one with the highest number with 3, the livestock demand in Bóveda presents 2 and finally those that present 1 failure were the agricultural demand of the Lemos Valley, the livestock demand in Monforte, the agricultural demand in Monforte, the agricultural demand in Bóveda and the recreational demand UDP10. For the urban ones (UDU) there is no failure. It is important to point out that the UDUs have been given priority over the rest of the demands. Despite the failures found by the IPH criteria, the guarantee in volumetric percentage remains above 99 %. The dates of the failures coincide with the periods with the lowest reserve level in the Vilasouto reservoir.

Table 6. Failures in the guarantee of supply for the demands of the SARC in the simulation with AQUATOOL.

Demand	No. Failures	Guarantee (%)	Guarantee Vol. (%)	Max. Deficit one month (hm^3)	Max. Deficit 2 months (hm^3)
UDA_3301_Valle de Lemos	1	99.2	99.1	0.034	0.034
UDG Ficticia 2301 y 2302 Bóveda	2	98.5	99.4	0.021	0.023
UDG ficticia 2303 Monforte de Lemos	1	99.2	99.4	0.012	0.012
UDA ficticia 2303 Monforte de Lemos	1	99.2	99.0	0.011	0.011
UDA Ficticia 2301 y 2302 Bóveda	1	99.2	99.3	0.045	0.045
UDP 10	1	99.2	99.5	0.032	0.032
Caudal Ecológico	3	97.7	99.3	1.857	2.073

Conclusions

The joint application of the flow results obtained with the Visual-Balan hydrological model and the AQUATOOL decision support model produces values closer to the values recorded in the Vilasouto reservoir than those reported in the current Hydrological Plan for the river. Therefore, the improvement in the simulation of the hydrological cycle of this work is considered a contribution to future Hydrological Plans in the Miño-Sil Hydrographic Demarcation.

The coincidence in magnitude and distribution of the flows of the hydrological components with two other studies in the same region, supports the results of the calibration of the Visual-Balan hydrological model.

In the simulation with AQUATOOL it was found that there are failures in the supply guarantees for some water demands that are not identified in the Hydrological Plan. These failures coincide with the low levels in the Vilasouto reservoir. The report in the Hydrological Plan is affected by the overvaluation of the water resources of the SIMPA model, which are reflected in the reservoir with levels higher than the real ones, resulting in a lower estimate of failures in the supply of water demands.

The absence of data on piezometric levels is a limitation when calibrating hydrological models, especially in an area such as Galicia and its hydrogeological nature. However, with currently available data it is possible to achieve a functional calibration to simulate surface water flows.

Having this ensemble of Visual-Balan & AQUATOOL models calibrated and validated opens the possibility of extending research in the Upper Sub-basin of the Cabe River to evaluate the possible effects of climate change on water resources. With the help of the assembly carried out in this work, any issue in the management of water resources and supply for water demands can be addressed with greater emphasis.

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References

Andreu, J., Solera, A., Capilla, J., & Ferrer, J. (2007). Modelo SIMGES de Simulación de la Gestión de Recursos Hídricos, incluyendo Utilización Conjunta. Versión 3.00. Manual del Usuario. Valencia, España: Universidad Politécnica de Valencia.

ASCE, American Society of Civil Engineers. (1996). Hydrology Handbook (2nd ed.). New York, USA: Library of Congress Catalog.

Batchelor, C., Hoogeveen, J., Faures, J., & Peiser, L. (2017). Water accounting and auditing. A sourcebook. Rome, Italy: Food and Agriculture Organization of the United Nations.

Cedex, Centro de Estudios y Experimentación de Obras Públicas. (20 de 03 de 2018). Anuario de aforos. Modalidades de consulta. Madrid, España: Centro de Estudios y Experimentación de Obras Públicas. Recovered from http://ceh-flumen64.cedex.es/anuarioaforos/default.asp

CHMS, Confederación Hidrográfica del Miño-Sil. (2015). Plan hidrológico del ciclo 2015-2021. Madrid, España: Confederación Hidrográfica del Miño-Sil.

Diamond, J. (2005). Collapse: How societies choose to fail or succeed. New York, USA: Viking.

Fan, M., Xu, J., Chen, Y., Li, D., & Tian, S. (2020). How to sustainably use water resources. A case study for decision support on the water utilization of Xinjiang, China. Water, 12, 3564. DOI: 10.3390/w12123564

FAO, Food and Agriculture Organization of the United Nations. (2019). Water accounting and auditing. Recovered from http://www.fao.org/land-water/water/water-management/water-accounting/en/

Gayathri, K. D., Ganasri, B. P., & Dwarakish, G. S. (2015). A review on hydrological models. Aquatic Procedia, (4), 1001-1007.

Giupponi, C., & Sgobbi, A. (2013). Decision support systems for water resources management in developing countries: Learning from experiences in Africa. Water, 798-818. DOI: 10.3390/w5020798

GWP & INBO, Global Water Partnership & International Network of Basin Organization. (2009). Manual para la gestión integrada de recursos hídricos en cuencas. Londres, Reino Unido: Global Water Partnership, International Network of Basin Organization.

IPH, Instrucción para la Planificación Hidrológica. (2008). Orden ARM/2656/2008, de 10 de septiembre, por la que se aprueba la instrucción de planificación hidrológica. Madrid, España: Boletín Oficial del Estado.

Islam, Z. (2011). Literature review on water resources modeling. Alberta, Canada: Department of Civil and Environmental Engineering, University of Alberta.

Lopez-Garcia, J. (1993). Restitución de datos de aforo al régimen natural. En: Andreu, J. (ed.). Conceptos y métodos para la planificación hidrológica (pp. 69-74). Barcelona, España: Centro Internacional de Métodos Numéricos en Ingeniería.

MAGRAMA. (2015). Plan Hidrológico de la parte española de la Demarcación Hidrográfica del Miño-Sil (2015-2021), Capítulo 4. Ourense, España: Confederación Hidrográfica del Miño-Sil, Ministerio de Agricultura, Alimentación y Medio Ambiente, de España.

Mayer, A., & Muñoz-Hernández, A. (2009). Integrated water resources optimization models: An assessment of a multidisciplinary tool for sustainable water resources management strategies. Geography Compass, 3(3), 1176-1195.

Moriasi, D., Arnold, J., Van Liew, M., Bingner, R., Harmel, R., & Veith, T. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50(3), 885-900

Nash, J., & Sutcliffe, J. (2003). River flow forecasting through conceptual models part I — A discussion of principles. Journal of Hydrology, 10(3), 282-290. DOI: 10.1016/0022-1694(70)90255-6

ONU, Organización de las Naciones Unidas. (2018). UN Water. Recovered from http://www.unwater.org/water-facts/

Rangel-Parra, R. (2019). Determinación de la cantidad de recursos hídricos para la gestión a nivel de cuenca por modelación. Estudio de aplicación a las cuencas de río Cabe (Lugo) y río Colorado (B.C., México). Lugo, España: Universidad de Santiago de Compostela.

Raposo, J., Molinero, J., & Dafonte, J. (2012). Parameterization and quantification of recharge in crystalline fractured bedrocks in Galicia-Costa (NW Spain). Hydrology and Earth System Sciences, (16), 1667-1683.

Samper, J. (1999). Manual del usuario del programa Visual Balan 2.0. Coruña, España: Universidade da Coruña.

Samper, J., & Pisani, B. (2013). Balance hidrometeorológico e hidroquímico para el estudio de los recursos hídricos y la evolución de la calidad química del agua en pequeñas cuencas de Galicia. Estudios en la Zona No Saturada del Suelo, XI. La Coruña, España. Recovered from http://zonanosaturada.com/zns13/publications_files/5.4.pdf

Samper, J., García-Vera, M., Pisani, B., Alvares, D., Varela, A., & Losada, J. (2005). Modelos hidrológicos y sistemas de información geográfica para la estimación de los recursos hídricos: aplicación de GIS-Balan a varias cuencas españolas. Estudios de la Zona No Saturada del Suelo, VII. La Coruña, España. Recovered from http://soda.ustadistancia.edu.co/enlinea/eduvirtual/Cuencas/maestria/docs/seminv/Lec-3Samperetal.pdf

Solera-Solera, A., Paredes-Arquiola, J., & Andreu-Álvarez, J. (2015). AQUATOOL+, Manual de usuario. Valencia, España: Universidad Politécnica de Valencia.

Sorooshian, S., Sharma, K., & Wheater, H. (2008). Hydrological modelling in arid and semi-arid areas. New York, USA: Cambridge University Press.

USC, Universidad de Santiago de Compostela. (25 de febrero, 2018). Propiedades dos Solos Galicia. Santiago de Compostela, España: Universidad de Santiago de Compostela. Recovered from http://rgis.cesga.es/index.html