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Authors: Molina, Julian, Sillero-Medina, José Antonio, and Ruiz-Sinoga, Jose Damian

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Julian Molina, José Antonio Sillero-Medina
and Jose Damian Ruiz-Sinoga

University of Malaga, Spain.

ABSTRACT: In areas with scarce water resources, it is so important to analyze the connection between the different elements of a river basin and the water collected by the basin's reservoir, to determine and predict the spatial and temporal variability of water on it. In this paper, we use the basic principles of hydrological modelling to develop a model for the exploitation of rainfall in reservoir basins in the province of Malaga, Spain. The monthly water input data of the seven reservoirs in the province of Malaga, provided by the Hidrosur Network of the Automatic Hydrological Information System (SAIH), as well as the precipitation and daily temperature of the stations of the State Meteorological Agency (AEMET) associated with the basins of each of these reservoirs were used. We assume that the entrance to a reservoir in a given month must depend on the precipitation produced in its watershed (both the amount of rain and the intensity with which it fell), the precipitation collected from the previous months (and the way in which it was produced) and the evapotranspiration produced during that period. For each reservoir, we propose a model with nine parameters to simulate the arrival of rainfall to the reservoir, covering aspects from the amount and intensity of rain, past and present, to the level of evapotranspiration on a given area for a given date. These nine parameters are optimally adjusted through an artificial intelligence algorithm to maximize the correlation between real and simulated contributions. The results show how this model, adjusted for each reservoir, will let us predict how changes in the rainfall and temperature patterns, predicted, for example, by the IPCC models, will affect the future water levels at the studied reservoirs.

KEYWORDS: Reservoirs, exploitation, soil hydrology, useful water, artificial intelligence, parametric adjustment

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CORRESPONDING AUTHOR: José Antonio Sillero-Medina, Habitat, Territory and Digitalization Institute. University of Malaga, Arquitecto Francisco Peñalosa Street, 18, Malaga 29071, Spain. Email: jasillero@uma.es

Introduction

The IPCC (2021) report predicts a reduction in water resources availability in the Mediterranean region as a result of rising temperatures and changing rainfall dynamics. Thus, the risks associated with water will be one of the most notable problems in Mediterranean society (Garcıa-Ruiz et al., 2011; IPCC, 2014, 2021) and will generate great concern in the population and among researchers (Coscarelli & Caloiero, 2012; De Luis et al., 2011; Guijarro Pastor, 2002; Katz et al., 2005; Lemus-Canovas & López-Bustins, 2016; Negri et al., 2005; Olcina Cantos, 2017). Under these considerations, the availability of water in the Mediterranean area is considered one of the most relevant aspects in the context of global change, especially because of the strong climate dependence of economic sectors and activities such as agriculture (Fader et al., 2016; Spain is the EU country with the largest irrigated area) and tourism (Pulido-Velázquez et al., 2020; Tapiador et al., 2021). The remarkable spatiotemporal mismatch between the availability of and demand for water resources has led to the extensive development of hydraulic infrastructures throughout Spain (Pulido-Velázquez et al., 2020). The important agricultural tradition and its hydroelectric dependence have played a key role in the construction of a large number of reservoirs (Iglesias et al., 2005), which generate an enormous requirement in terms of water use. Reservoirs are, therefore, key elements for the management of water resources given that controlling their volume is a fundamental practice for agricultural, energy, industrial, and municipal water planning, as well as for controlling ecological requirements and protecting against floods (Habets et al., 2018; Jiang et al., 2019). However, climate change is profoundly influencing these water reserves, jeopardizing their current potential and exploitation capacity (Garrote et al., 1999; Rocha et al., 2020). Thus, reservoirs, despite their specific location, can be modeled to elucidate the water situation of larger geographical areas of basin or sub-basin scales. These models depend on the climatic and landscape characteristics of each eco-geomorphological system, which will function as explanatory factors of its hydrological conductivity (Bracken & Croke, 2007; Zhao et al., 2020).

The elaboration of predictions of the availability and variations of water in the territory of these water reserves is of great interest (Qin et al., 2020), especially within a paradigm of climate, energy, and food crises (Ehsani et al., 2017; Li et al., 2010; Mashaly & Fernald, 2020; SPANCOLD, 2013). Water security is a key issue on the agenda of many nations and international institutions (Marcal et al., 2021). However, in general, these studies related to hydrological connectivity are not usually considered until the occurrence of problems associated with water quantity and quality (Zhang et al., 2021).

The methodologies of such predictions offer illuminating results that enable appropriate planning and management of the territory from the perspective of sustainability and in congruence with the objectives and goals of sustainable development promoted by the United Nations in their 2030 Agenda (Vörösmarty et al., 2018).

Table 1. General Features of the Selected Reservoirs.

RESERVOIR NAME	TOTAL CAPACITY (HM³)	ANNUAL AVERAGE RAINFALL (MM)	AVERAGE MAXIMUM TEMPERATURES (°C)	AVERAGE MINIMUM TEMPERATURES (°C)
Concepción	57.54	618.45	21.61	14.75
Casasola	21.72	526.52	22.42	15.66
Limonero	22.34	477.52	23.13	13.71
Guadalteba	153.30	479.95	21.75	11.74
Guadalhorce	125.72	477.91	21.75	11.74
Conde de Guadalhorce	66.49	494.25	21.75	11.74
Viñuela	164.37	451.95	23.92	13.20

Mathematical modeling based on simulation and optimization systems is considered a fundamental tool for analyzing hydrological dynamics and describing the management of water resources (Mashaly, & Fernald, 2020; Mereu et al., 2016; Recio et al., 2016), especially when the range of parameters based on territorial experience is restricted, reducing uncertainty and regulating modeling behavior (Gharari et al., 2021; Hrachowitz et al., 2014).

On the basis of these climatic modifications and given the recent increase in attention to changes in the pattern and dynamics of rainfall and the current concern about water risks and water availability, the present study aims to study the relationship between the level of precipitation and the contribution to reservoirs in the province of Malaga, Spain. The objective is to develop a model that clarifies how each reservoir receives the rain falling in its basin, thereby enabling a determination of which episodes and intensities of precipitation have a better response at the level of each reservoir in the province of Malaga.

Materials and Methods

Study area

The study area corresponds to the province of Malaga, located on the Mediterranean coast, at the south of the Iberian Peninsula between latitude 37°14´N to 36°18´N and longitude 5°36´W to 3°44´W, occupying an area of 7,307.5 km^2 (Figure 1). This area has a Mediterranean climate, with typical characteristics of subtropical latitudes in terms of variability of precipitation and temperature (Michaelides et al., 2018). In addition, the physiographic characteristics of the province of Malaga have been identified as a fundamental aspect affecting this high variability, causing great spatiotemporal contrasts of the main climatic elements (Lionello et al., 2012). The area of study, from this climatic approach, is cataloged as a critical point of great sensitivity in the context of global change (Giorgi, 2006; IPCC, 2021). Thus, several authors and studies (Barcena-Martin et al., 2019; Ruiz-Sinoga et al., 2011, 2012; Sillero-Medina, Martínez-Murillo, Ruiz-Sinoga, 2021, Sillero-Medina, Rodrigo-Comino, Ruiz-Sinoga, 2021) agree that the western Mediterranean is a particularly sensitive area in the context of Climate Change, which has recently been endorsed by the latest IPCC (2021) report. From a hydrological point of view, this area in Spain corresponds to a "comb-shaped drainage pattern" composed of a whole series of hydrological basins that are arranged along it.

Data source

The information on the reservoirs was obtained from the Sistema Automático de Información Hidrológica (SAIH) Network (http://www.redhidrosurmedioambiente.es), for a total of seven reservoirs in the province of Malaga. Each one of them has different climate conditions and capacities, as described in Table 1. Data series have different starting points, depending on the reservoir, but all end in 2020 (Table 2). The data include the aggregated contributions received each month by each of the seven reservoirs in the province of Malaga, in cubic hectometers.

The precipitation and temperature data were obtained from the state meteorological agency, Agencia Estatal de Meteorología (AEMET), on a daily scale. Based on its location and the length of the data series, each reservoir has been associated with meteorological observations of a temperature station (the closest to the reservoir) and a number of precipitation stations falling in its basin (Table 2).

Data normalization

Data of the monthly aggregated water contributions to the reservoirs ($Contr_i$) are given in cubic hectometers; rainfall (p_i) is measured in milimeters and temperature (tmP_i and tmL_i) in degrees Celsius. Thus, as a preliminary step, all the values were normalized to be used in a common model. To be used with this model, data of the contribution to the reservoirs were normalized in the range [0,1], with 1 being the maximum contribution and 0 the minimum contribution. These normalized contributions for each month are labeled as $ContrN_i$, and the normalization procedure is expressed as:

$$ContrN_i = \frac{(Contr_i - min)}{(max - min)} \quad (1)$$

Table 2. Reservoirs in the Province of Malaga, Weather Stations, and Time Period of the Data.

RESERVOIR ID	RESERVOIR NAME	PERIOD	NUMBER OF PREC STATIONS	TEMP STATION NAME	PERIOD
1	Concepción	1970–2020	3	Marbella (Puerto Banús)	1970–2021
2	Casasola	2004–2020	5	Málaga-Carmelitas	1986–2021
3	Limonero	1983–2020	6	Málaga-Aeropuerto	1942–2021
4	Guadalteba	1974–2020	11	Pantano de Guadalhorce	1964–2021
5	Guadalhorce	1974–2020	23	Pantano de Guadalhorce	1964–2021
6	Conde de Guadalhorce	1974–2020	2	Pantano de Guadalhorce	1964–2021
7	Viñuela	1992–2020	6	Vélez-Málaga (Clause)	1991–2021

where max and min represent the maximum and minimum contributions in the reservoir during the complete time horizon, respectively. The daily precipitation data associated with the basin of each reservoir were normalized in the range [0,1], with 1 being the maximum amount of precipitation and 0 the minimum amount of precipitation. The normalized precipitation on a given day is represented as pN_i, and the normalization procedure is expressed as

$$pN_i = \frac{\left(p_i - min\right)}{\left(max - min\right)} \tag{2}$$

where max and min represent the maximum and minimum daily precipitation in the precipitation stations of the reservoir during the complete time horizon, respectively.

Regarding temperature, two sources were considered: (i) the global temperature of the province, tmP_i, and (ii) the specific temperature of the station associated with each reservoir, referred to as the local temperature, tmL_i. These two sources were considered using a single station near the reservoir and therefore might not correctly represent what occurs in the basin of attraction of the reservoir; thus, two temperatures (local and global) were used, leaving the calibration algorithm to determine which combination of local and global temperatures is more convenient. Temperatures, both local and global, were normalized between 0 and 1 using the maximum and minimum of the set of temperatures throughout the study horizon:

$$tmPN_i = \frac{\left(tmP_i - min\right)}{\left(max - min\right)} \tag{3}$$

$$tmLN_i = \frac{\left(tmL_i - min\right)}{\left(max - min\right)} \tag{4}$$

We must specify that for precipitation we consider all the precipitation stations on the reservoir's basin, due to the fact that rain on the basin of a reservoir does not imply (similar) rain in other basins, even being geographically close. So, for each reservoir we consider the set of precipitation stations on its basin. In this sense, Table 2 is including the number of precipitation stations considered for each reservoir.

The situation with the temperature is different, as temperature is a more uniform phenomenon, and the number of temperature stations is quite scarcer. So, to measure the temperature in the basin of each reservoir we consider it is a weighted average of the temperature in the closest temperature station to the reservoir (specified for each reservoir in Table 2) and the average temperature of the province. As we know that the weight for this weighted average could depend on the reservoir, it is considered a parameter and adjusted to its optimal value in the calibration process.

Mathematical Model

To describe the mathematical model developed for the optimal simulation of precipitation in reservoirs, which is the subject of the present study, we first describe the parameters and factors used.

First, the parameters adjusted by the model were *TL, TU, EL, EN, EU, WeightEvapo*, R_{-1}, α (*PowerDelay*), and β (*WeightTempGlob). TL* and *TU* are the lower and upper thresholds for rainfall type, respectively. *EL, EN*, and *EU* are the exploitation factors for each type of rain (lower, normal, and upper, respectively). *WeightEvapo* is the evapotranspiration factor. β (*WeightTempGlobal*) is the importance of the global temperature of the province in this reservoir with respect to the local temperature of the associated station. R_{-1} and α (*PowerDelay*) are used to measure the influence of the precipitation in the months before the moment under investigation.

To calibrate the model, we need to find the optimal values of these nine parameters for each reservoir, which will enable us to calculate $ContrSimulated_i$ such that the corresponding correlation with the known real value of $ContrN_i$ is optimal. That is, we will attempt to find values of these nine parameters that maximize the correlation between the simulated contribution using the model and the real value of the contribution.

As mentioned, the normalized value of the contribution to the reservoir is $ContrN_i$, $i = 1, \ldots, NumObsRes$. Each observation corresponds to 1 month and 1 year of the time horizon of the study, which has been assigned a global average temperature of the province in that month, $tmPN_i$, and a local average temperature of the nearest station, $tmLN_i$. Finally, the number of normalized observations of precipitation related to a reservoir in a given month and year is defined as n_i.

Taking into account all the aforementioned parameters, we propose the following model:

(i) The levels of exploitation of each reservoir are first set: lower exploitation or weak rain (*EL*), normal exploitation or average rainfall (*EN*), and upper exploitation or heavy rain (*EU*). These levels fall between two rainfall-type thresholds: the lower threshold (*TL*) and the upper threshold (*TU*). Both the rainfall thresholds and the different levels of exploitation must be adjusted and are thus the first five parameters adjusted.

"Weak rain" is any rain below the lower threshold (*TL*), "normal rain" is any rain above the lower threshold (*TL*) and below the upper threshold (*TU*), and "heavy rain" is any rain above the upper threshold (*TU*). In percentage terms, for this model, the reservoir receives an *EL*% of weak rainfall, an *EN*% of normal rainfall, and an *EU*% of heavy rainfall. Given our time horizon, for a given month, the simulated contribution is

$$ContrSimulated_i = \sum_{k=1}^{n_i} Factor_k * pN_k \quad \text{, where}$$

$$Factor_k = \begin{cases} EL \text{ if } p_k < TL \\ EN \text{ if } p_k \geq TL \text{ and } p_k \leq TU \\ EU \text{ if } p_k > TU \end{cases} \tag{5}$$

(ii) We next consider the precipitation losses caused by evapotranspiration, which increases when the average temperature of the reservoir in the month under consideration is increasing. To this aim, we use parameter β (*GlobalTempWeight*), which measures the relative importance of the global temperature and the local temperature of the reservoir. If this parameter is 1, the only temperature to consider is the global temperature; if this parameter is 0, the only temperature to consider is the local temperature. For intermediate values, the temperature used will be a combination of local and global temperatures. Thus, the temperature that we consider for a reservoir in any month will be a convex linear combination of both temperatures according to parameter β:

$$Temp_j = \left(tmPN_j * \beta\right) + \left(\left(1-\beta\right) * \left(tmLN_j\right)\right) \tag{6}$$

(iii) Once this temperature has been calculated, the weight of the evapotranspiration level of the reservoir to temperature and its subsequent loss of precipitation is represented by *WeightEvapo*, which is the sixth parameter to adjust. *WeightEvapo* takes a value between 0 and 1 and is used to measure the amount of precipitation lost by evapotranspiration according to the formula

$$\begin{aligned} ContrSimulated_i = {} & ContrSimulated_i \\ & - WeightEvapo * Temp_j \end{aligned}$$

(iv) The previous state of soil moisture plays a critical role in determining the contributions that finally reach the reservoir because the soil moisture caused by the rainfall in the previous months allows a humid soil to better exploit the current precipitation.

In this sense, the model considers the current precipitation exploitation as a function not only of the precipitation in the current month but also that in the previous 5 months according to some factors to be adjusted, R_{-i}, $i = 1, \ldots, 5$, and the formula

$$\begin{aligned} ContrSimulated_i = {} & ContrSimulated_i \\ & + \sum_{k=1}^{5} R_{-k} * ContrSimulated_{i-k} \end{aligned} \tag{7}$$

In the adjustment of these five parameters, R_{-i} is assumed to follow a decreasing trend under the logic that the rain that will most strongly influence the exploitation is the most recent, followed by the second-most recent, and so on, in progressively smaller contributions. In this case, the model considers R_{-i} calculated as

$$R_{-1} = \gamma, R_{-i} = (R_{-i+1})^{\alpha}, i = 2, \ldots, 5 \tag{8}$$

Each R_{-i} from R_{-2} is calculated as the previous R_{-i} raised to a power α of the previous one, enabling us to calculate all the R_{-i} by adjusting only two parameters, R_{-1} (γ) and α.

(Figure 2) is summarizing the whole procedure from the precipitation to the final water contribution to the reservoir.

In short, under this mathematical model, the nine parameters described in this section must be adjusted for each reservoir so that the contribution simulated by the model correlates best with the real contribution.

Local Search Algorithm for the Parameters of Calibration

In this section, we first establish the optimization problem to be solved in order to obtain the optimal values of the parameters and propose a local search method to solve it. Relating the problem to be solved, once the simulated contribution model has been defined based on the previously described parameters, we need to find the parameters' values that maximize the correlation between the simulated contribution (obtained with some values for these parameters) and the real contribution. This is, we intend to find the values for these nine parameters of the model so that the obtained simulated contributions

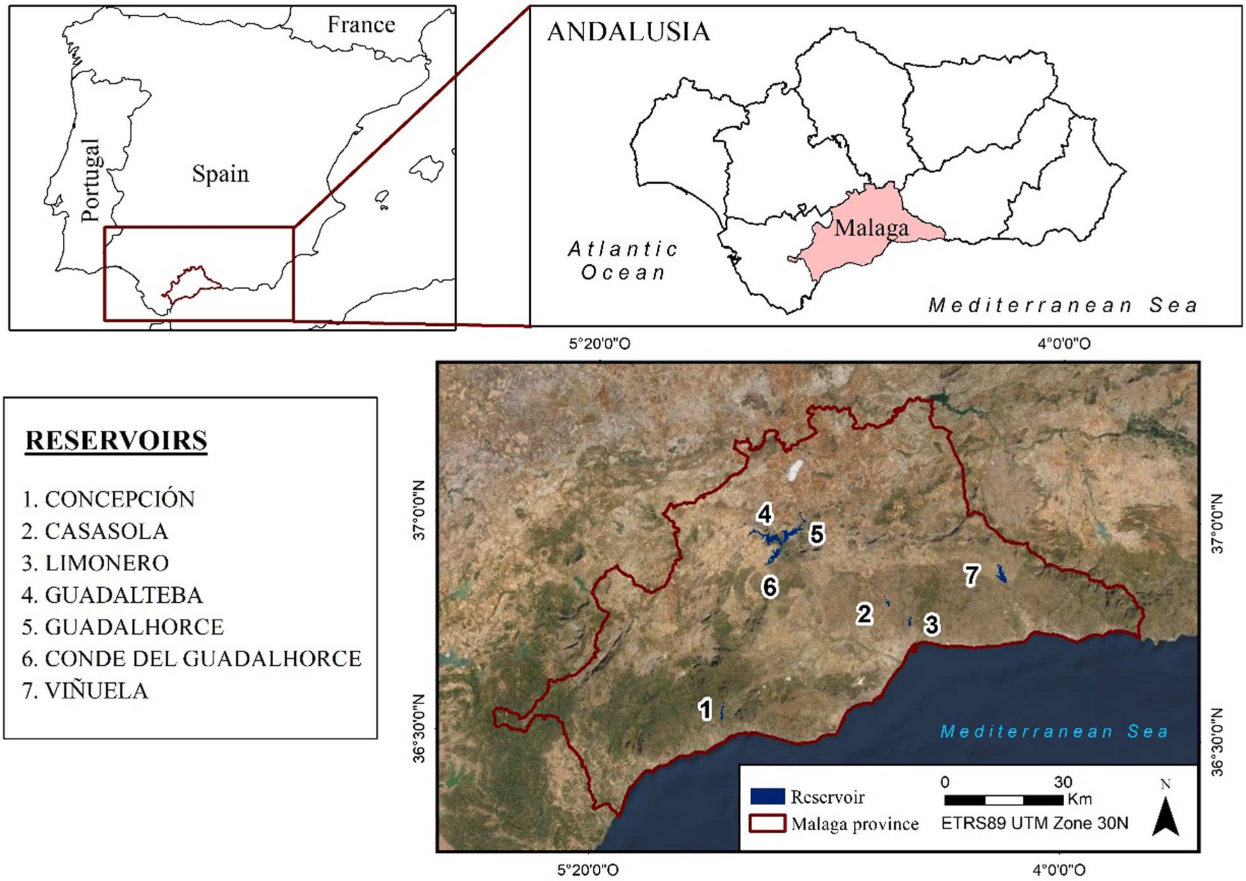

Figure 1. Location map. Selected study area and reservoirs.

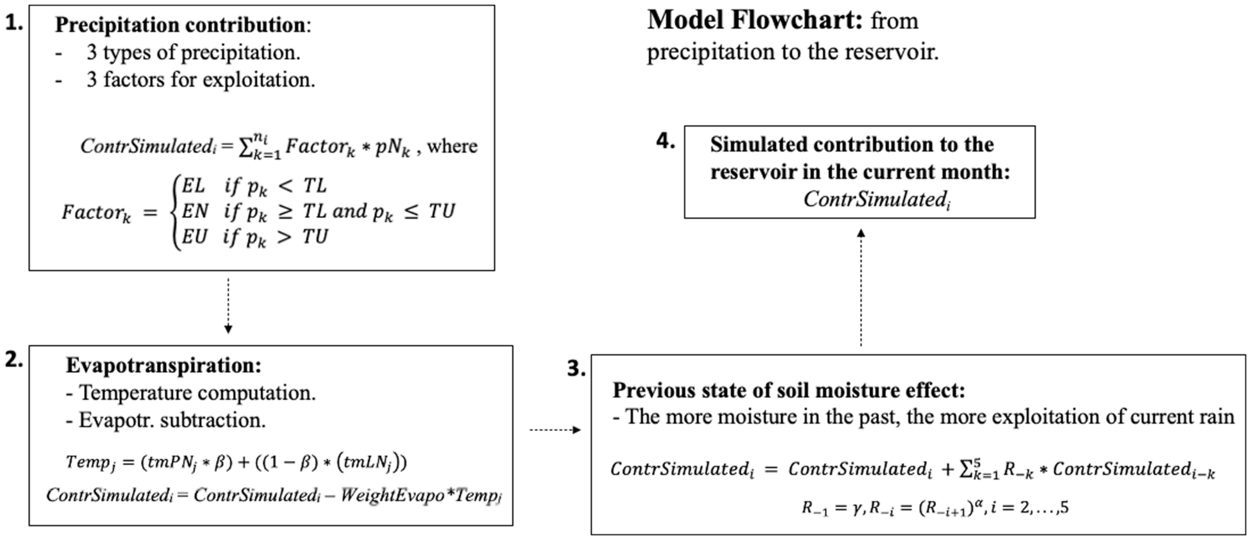

Figure 2. Model flowchart.

correlate the most with the real ones. Besides, the optimal value of the correlation coefficient obtained will validate the model significance.

To solve this problem, we propose a local search method, a heuristic method that is widely used to find approximate solutions to a variety of hard optimization problems. The main idea behind a local search algorithm is to start from a random initial solution and then iteratively apply small changes to get a better solution, moving from one solution to a better one until a stopping criterion is met. Typically, this criterion is when there are no further improvements, or a predefined number of iterations is achieved. The solution obtained in the last iteration approximates the optimal solution to the problem. Usually, the whole procedure is repeated with a number of different random initial

Table 3. Analysed Periods for Each of the Selected Reservoirs in the Province of Malaga.

RESERVOIR NAME	FULL PERIOD	PRESENT	PAST
La Concepción	1970–2020	2000–2020	1970–1999
Casasola	2004–2020		
El Limonero	1983–2020	2000–2020	1983–1999
Guadalteba	1974–2020	2000–2020	1974–1999
Guadalhorce	1974–2020	2000–2020	1974–1999
Conde de Guadalhorce	1974–2020	2000–2020	1974–1999
La Viñuela	1992–2020	1992–2005	2006–2020

solutions, and the best of the final solutions obtained is considered the optimum.

In our case, our mehtod is restarted using 20 different initial solutions or "seeds." The procedure for producing each seed is to simply generating all the values of the parameters randomly in their corresponding ranges. Starting from each seed, we launch the improving procedure, consisting of two phases based on the generation of what we refer to as "neighbors" (i.e. the small changes to the current solution), which will be evaluated to check if they represent an improvement of the current solution. These neighbors are created in two different ways:

- Phase 1: One of the nine variables is randomly chosen, and a new random value is generated for that variable, which will result in a small variation in the solution. This neighbor is then evaluated and, if the correlation of the resultant simulated contribution with the vector of real contributions is higher, then the neighbor replaces the original point and the same procedure is repeated. If its correlation is worse, a new neighbor is generated until 100 consecutive neighbors are generated without any improvement of the current solution.
- Phase 2: One of the nine variables is randomly chosen, and its value is increased and decreased by a small and prefixed amount, ε, generating two neighbors. These neighbors are then evaluated and, if one of them results in better correlation with the resulting simulated contribution with the vector of real contributions, it replaces the original point and the same procedure is repeated. If their correlations are worse, two new neighbors are generated through the same procedure until 100 consecutive neighbors are generated without any improvement of the current solution.

This method was implemented in Python and applied to each of the selected reservoirs, first for the complete time horizon and then with the time horizon divided into two periods to identify a possible time evolution (Table 3). In the case of the Casasola reservoir, the time horizon was not divided because it was already too short.

Results

Dynamics of the contribution of the reservoirs throughout the time horizon

According to the analysis of the use of the different selected reservoirs, the results for the available time horizon show contrasting features (Table 4). In this table we can find all the optimal parameters found for all the reservoirs as well as some measures on the distribution of rain on the three main categories (upper, normal, and low rain) and the final performance of the reservoir, this is, the percentage of the precipitation that finally achieves the reservoir (Av. Exploitation). All this results are described and analyzed in detail below.

- **Optimal value of the correlation (*ROpt*):** This variable represents the final value of the correlation after the optimal adjustment of the parameters. We observe that all values are sufficiently high for the model to be meaningful. The *ROpt* values for Concepción, Casasola, and Viñuela reservoirs exceed 0.8. Those for the Limonero, Guadalteba, and Guadalhorce reservoirs exceed 0.7. The *ROpt* for the Conde de Guadalhorce, which required the greatest adjustment, exceeds 0.6.
- ***WeightEvapo***: The greater this value, the more water is lost by evapotranspiration. The Guadalteba and Concepción reservoirs stand out, with *WeightEvapo* values significantly higher than the corresponding values of the other reservoirs. The Guadalteba and Concepción reservoirs therefore exhibit greater sensitivity to increases in temperature than the other reservoirs.
- **Upper, normal, and lower exploitation factors (*EU, EN, EL*)**: These parameters represent the percentage of each type of rain reaching the reservoir. Greater values indicate a greater percentage of precipitation in the type of rain exploited.

Table 4. Results for all the Reservoirs for the Whole Time Horizon.

TIME HORIZON	1970–2020	2004–2020	1983–2020	1974–2020	1974–2020	1974–2020	1992–2020
Parameters	CONCEPCIÓN	CASASOLA	LIMONERO	GUADALTEBA	GUADALHORCE	CONDE GUAD	VIÑUELA
ROpt	0.8286	0.8566	0.7983	0.7309	0.7449	0.6758	0.8457
WeightEvapo	1.5789	0.9244	0.6812	2.6257	1.0209	0.2907	0.9216
EU	0.1130	0.0556	0.5494	0.5906	0.6775	1.0000	0.5874
EN	0.8173	0.6917	0.1914	0.0902	0.0315	0.6442	0.1188
EL	0.1688	0.1177	0.0663	0.0000	0.2252	0.3785	0.0255
TU	187.60	136.33	111.33	306.40	130.81	77.37	148.03
TL	48.31	78.72	67.46	14.85	20.73	22.37	12.19
R-1 (%)	68.7	42.4	58.0	72.9	78.4	60.8	54.1
R-2 (%)	15.3	18.0	33.6	20.5	37.8	37.0	29.3
R-3 (%)	0.0	3.2	11.3	0.0%	2.0	13.7	8.6
R-4 (%)	0.0	0.1	1.3	0.0%	0.0	1.9	0.7
R-5 (%)	0.0	0.0	0.0	0.0%	0.0	0.0	0.0
% U rain	0.06	0.31	0.24	0.10	0.25	0.34	0.07
% N rain	8.30	0.62	2.51	33.58	24.45	3.65	43.67
% L rain	73.05	84.27	84.55	54.97	68.20	76.29	41.31
Av. Exploit. (%)	29.98	5.74	7.90	0.73	10.35	45.81	7.10

- **Upper and lower thresholds (*TU, TL*)**: These parameters represent the limits used to determine each type of rainfall in each of the reservoirs. For example, in the Concepción reservoir, the lowest rainfall is less than 48.31 L per day, the normal rainfall is between 48.31 and 187.6 L per day, and the upper rainfall is greater than 187.6 L in a day.
- **Percentage of upper, normal, and lower precipitation (*%U, %N, %L*)**: These parameters represent the average monthly percentage of each of the types of precipitation composing the total monthly precipitation. That is, the parameters represent, on average, the percentage of the total rainfall that each type of rainfall represents over the total of the month. For example, in the Concepción reservoir, the lower rainfall represents, on average, 73.05% of the total rainfall in a month and the normal and upper rainfalls represent 8.3% and 0.06%, respectively. Combining these last three groups of parameters provides a clear indication of how each reservoir takes advantage of each type of precipitation and how frequently each type of precipitation occurs. For example, the Concepción reservoir benefits from high rainfall (0.8173), or rain between 187.60 and 48.31 L, whereas this type of rain only represents, on average, 8.30% of the total rainfall.
- **Importance of the previous rain, R_{-i}**: This parameter represents the dependence on the current exploitation of the rain in the previous months. For example, the Concepción reservoir, in the current month, takes advantage of 68.7% of what was exploited in the previous month and 15.3% of the exploitation of 2 months ago. In brief, rain in the previous months results in greater current use, which is reflected by a larger R_{-i} parameter.
- **Average use**: This parameter represents the monthly average of the percentage of precipitation that finally reaches the reservoir each month according to the simulated model.

First, the unequal average use of the different reservoirs despite their close geographic proximity is remarkable. In this sense and according to the results, whereas the Conde de Guadalhorce and Concepción reservoirs take advantage of 45.81% and 29.98% of precipitation, the Guadalteba reservoir does not reach 1%.

In detail, the rainfall thresholds and their uses also differ dramatically. The exploitation factor of the Concepción reservoir for precipitation less than 48.31 L per day is 0.1688. This means that in a day with a rain below 48.31 L, a 16.88% of the rain is achieving the reservoir. This is, this parameter measures

Table 5. Results for the Concepcion Reservoir, for Past and Present Time Periods.

TIME HORIZON	2000–2020	1970–1999
Parameters	CONCEPCIÓN	CONCEPCIÓN
ROpt	0.7852	0.8977
WeightEvapo	0.3866	2.5138
EU	0.0000	0.2410
EN	1.0000	0.9444
EL	0.2301	0.0997
TU	96.53	180.73
TL	90.45	48.50
R-1 (%)	59.0	68.0
R-2 (%)	34.8	14.5
R-3 (%)	12.1	0.0
R-4 (%)	1.5	0.0
R-5 (%)	0.0	0.0
% U rain	1.03	0.10
% N rain	0.74	9.18
% L rain	79.13	72.49
Av. Exploit. (%)	25.95	27.29

the exploitation rate of each type of rain, lower, normal or upper precipitation. In the case of the Limonero reservoir, the exploitation factor for a similar rainfall, less than 67.46 L per day, is 0.0663. For the Guadalhorce reservoir, the factor for precipitation between 20.73 and 130.81 L per day is 0.0315; by contrast, for the Viñuela reservoir, the factor for precipitation between 12.19 and 148.03 L per day is 0.1188. However, we see how reservoirs such as Concepción or Guadalteba increase their use only with the rain of the previous 2 months, whereas the rest of reservoirs have a higher use if it rained in the previous 3 or even 4 months. That is, reservoirs also have different sensitivities to the state of previous soil moisture. In short, the dynamics under which the different reservoirs take advantage of precipitation differs dramatically and the future situation of two reservoirs can therefore differ substantially even if the climatic conditions remain unchanged.

In the context of climate change, variations in climate parameters will lead to substantial changes. Such changes can result in contrasted dynamics in certain reservoirs that are, a priori, more sensitive to these effects. For example, among the investigated reservoirs, the Guadalteba reservoir has the highest evapotranspiration factor, 2.62, which is approximately ten times greater than that of the Conde de Guadalhorce reservoir; thus, the Guadalteba reservoir's use will be much more sensitive to the temperature increases projected for the Mediterranean area according to the latest IPCC (2021) report. An increase in torrentiality would be beneficial for the Conde de Guadalhorce reservoir if it increases the frequency with which it rains more than 77.37 L per day because the coefficient of use above 77.37 L (1,000) is greater than that below 77.37 L (0.6442 and 0.3785).

Analysis of the time evolution in the level of exploitation of reservoirs

Another aspect considered in the present research is associated with knowing whether the pattern of exploitation of the reservoirs has changed and, if so, to what extent. To explore this approach, we split the time horizon for the reservoirs, when possible, into two parts: the last 20 years (present) and the years before the last 20 years (past). After applying the model to these two series, we found contrasting dynamics between reservoirs and, in addition, different trends between the two periods analyzed for the same reservoir. This information enabled us to identify clear trends and even to anticipate future water deficits motivated by factors related to changes in climatic and/or landscape variables of anthropogenic origin.

Table 5 shows the main results associated with the Concepción reservoir between 1970 and 1999 and between 2000 and 2020. In this case, we observe how the average exploitation has decreased slightly in the 2000 to 2020 period compared with that in the 1970 to 1999 period. This decrease in the average exploitation is attributed to substantial changes in the sensitivity to temperature, rainfall thresholds, and the influence of rain in previous periods.

In the case of the Limonero reservoir, the average exploitation has decreased substantially in the 2000 to 2020 period compared with that in the 1983 to 1999 period; this decrease is much more dramatic than the change observed in the Concepción reservoir, which went from an average use of 14% to one of 4% (Table 6). Again, this change has been mainly motivated by the sensitivity to temperature itself, rainfall thresholds, and the influence of rain in previous periods.

In the case of the Guadalteba, Guadalhorce, and Conde de Guadalhorce reservoirs (Table 7), which are closely related and geographically joined, we observe that, in all three cases, their use in the period 2000 to 2020 increased compared with that in the period 1974 to 1999, in some cases (e.g. the Guadalteba reservoir) dramatically. In two of the three reservoirs, Guadalteba and Guadalhorce, the evapotranspiration factor has decreased, making them less sensitive to increases in temperature. The upper rainfall thresholds in the Guadalteba and Guadalhorce reservoirs have also increased: from values between 100 and 200 L per day to values between 200 and 300 L per day. In both cases, the exploitation factor of the most frequent type of rainfall, lower precipitation, has increased dramatically from 0.0000 to 0.2551 in the Guadalteba reservoir and from 0.0780 to 0.1776 in the Guadalhorce reservoir.

Table 6. Results for the Limonero Reservoir, for Past and Present Time Periods.

TIME HORIZON	2000–2020	1983–1999
Parameters	LIMONERO	LIMONERO
ROpt	0.9177	0.7394
WeightEvapo	1.5903	2.0893
EU	0.8142	1.0000
EN	0.0000	0.3387
EL	0.1667	0.1502
TU	110.76	89.11
TL	53.43	62.02
R-1 (%)	35.6	64.7
R-2 (%)	12.7	41.9
R-3 (%)	1.6	17.5
R-4 (%)	0.0	3.1
R-5 (%)	0.0	0.1
% U rain	0.33	0.75
% N rain	5.44	2.56
% L rain	81.23	84.30
Av. Exploit. (%)	4.33	14.74

Finally, in the case of the Viñuela reservoir, the exploitation, similar to that in the Concepción and Limonero reservoirs, has decreased (Table 8). In the case of the Viñuela reservoir, the exploitation has decreased from 25.71% in the period 1992 to 2005 to 9.56% in the period 2006 to 2020. The fundamental change in this case is found in the rainfall thresholds. Whereas the normal rainfall in the period 1992 to 2005 was between 20 and 91 L per day and was exploited with a factor of 0.4981, in the period 2006 to 2020, normal rainfall encompassed a much wider range—from 14 to 139 L per day—but its exploitation factor decreased from 0.4981 to 0.1746.

As a summary, Table 9 is including the past and present average exploitation of each of the reservoirs, to have a global view on those improving and worsening, and in which amount:

As shown in Table 9, for most of the reservoirs analyzed—except those included in Table 6 (Guadalteba, Guadalhorce, and Conde de Guadalhorce), which are geographically grouped—the exploitation level of rainwater has decreased, leading to a lower availability of water resources.

Discussion

Based on the results obtained for the reservoirs in the years analyzed, we can identify a very unequal degree of use of precipitation. Despite being reservoirs so close to each other, the specific characteristics of each basin will determine its dynamics and hydrological connectivity and, therefore, the water that finally reaches the reservoir (Tetzlaff et al., 2011; Zhang et al., 2021).

The amount of rain in each basin has been determined as a fundamental element when quantifying how much of it will arrive the reservoir itself, as a consequence of the behavior of each area from the point of view of its hydraulic connectivity (Chamizo et al., 2012). In this sense, Zhao et al. (2020) corroborates that it is necessary to consider different rainfall thresholds when analyzing these conductivity processes, establishing that lower or weak precipitation events will not generate a sensitive discharge in reservoirs. In our case study, Table 4 shows these rainfall thresholds and the average exploitation of the reservoirs under study, showing important contrasts between them according to the characteristics of the watershed area and its degree of hydrological conductivity. These thresholds are equally important when it comes to knowing the lag time between the precipitation event and its collection in the reservoir. Guyassa et al. (2017) establish a negative correlation between these aspects, considering a greater lag for weak precipitation events and for areas with important vegetation cover. This fact will be clearly determined by the previous characteristics of soil moisture in the slope area, identifying a clear sensitivity to this variable by reservoirs and their use (Wilson et al., 2016). Therefore, higher soil moisture content implies greater connectivity (Leibowitz & Vining, 2003; Nanda et al., 2019).

Evapotranspiration is another variable that will determine the level of use of the reservoir, as has been properly represented in the current model. Thus, due to the climatic characteristics, agricultural tradition, and other environmental and geographical aspects of the Mediterranean region (Allen et al., 1998; Mereu et al., 2016), this factor is fundamental in this area, where it plays a key role in the hydrological cycle (Montaldo & Oren, 2018). In the context of climate change, the variations predicted by the IPCC (2021) in climate and meteorological parameters will lead to substantial changes in evapotranspiration values (Abtew & Melesse, 2013; Gorguner et al., 2019). Such changes can result in contrasting dynamics in certain reservoirs that are, a priori, more sensitive to these effects. From the results obtained, it is possible to identify the great sensitivity of the Guadalteba reservoir, where the temperature increases projected for the Mediterranean area according to the latest IPCC (2021) report can generate a very low exploitation of rainfall.

The second part of the research deals with the time evolution of the exploitation level of the reservoirs, an aspect that constitutes a dynamic approach according to current needs in water planning and management (Martínez-Austria & Alcocer-Yamanaka, 2019; Simonovic, 2009). Understanding how system conditions can change and, therefore, the use of

Table 7. Results for the Guadalteba, Guadalhorce, and Conde de Guadalhorce Reservoirs, for Past and Present Time Periods.

TIME HORIZON	2000–2020	1974–1999	2000–2020	1974–1999	2000–2020	1974–1999
Parameters	GUADALTEBA	GUADALTEBA	GUADALH.	GUADALH.	CONDE G.	CONDE G.
ROpt	0.8068	0.8297	0.7736	0.8367	0.8016	0.6090
WeightEvapo	0.7110	2.6240	2.4907	1.1592	0.4483	0.1938
EU	0.8253	0.1669	0.8664	0.0000	0.9900	0.7649
EN	0.0000	0.0813	0.0325	1.0000	0.2237	0.8959
EL	0.2551	0.0000	0.1776	0.0780	0.6530	0.2147
TU	279.54	178.27	244.98	148.45	122.68	150.47
TL	69.35	26.33	47.61	125.33	47.73	42.22
R-1 (%)	45.3	68.3	72.0	67.4	53.6	84.2
R-2 (%)	4.2	14.8	51.9	30.7	28.7	42.3
R-3 (%)	0.0	0.0	26.9	2.9	8.2	1.4
R-4 (%)	0.0	0.0	7.2	0.0	0.7	0.0
R-5 (%)	0.0	0.0	0.5	0.0	0.0	0.0
% U rain	0.22	0.09	0.18	0.06	0.30	0.00
% N rain	1.01	16.47	4.02	0.11	0.55	1.05
% L rain	85.67%	73.50	87.47	93.74	77.29	80.96
Av. Exploit. (%)	18.27	0.30	12.04	7.25	68.96	32.50

Table 8. Results for the Viñuela Reservoir, for Past and Present Time Periods.

TIME HORIZON	1992–2005	2006–2020
Parameters	VIÑUELA	VIÑUELA
ROpt	0.8761	0.8377
WeightEvapo	2.4493	2.4651
EU	0.1981	0.7156
EN	0.4981	0.1746
EL	0.0000	0.3313
TU	91.05	139.30
TL	20.06	14.19
R-1 (%)	64.6	47.5
R-2 (%)	26.9	22.5
R-3 (%)	1.9	5.1
R-4 (%)	0.0	0.3
R-5 (%)	0.0	0.0
% U rain	1.33	0.27
% N rain	30.86	36.00
% L rain	52.83	48.63
Av. Exploit. (%)	25.71	9.56

Table 9. Past and Present Average Exploitation of Each of the Reservoirs.

RESERVOIR	PAST (%)	PRESENT (%)	DIFFERENCE (%)
CONCEPCIÓN	27.29	25.95	–1.34
CASASOLA	—	5.74	—
LIMONERO	14.74	4.33	–10.41
GUADALTEBA	0.30	18.27	17.97
GUADALHORCE	7.25	12.04	4.80
CONDE GUAD	32.50	68.96	36.45
VIÑUELA	25.71	9.56	–16.15

reservoirs is essential to improve decision-making regarding water management (Mereu et al., 2016)

The results show a sensible decrease in some of the reservoirs (Table 9) of these levels of rainfall exploitation with respect to the recent past period. This fact is consistent with observations in other studies conducted in the Iberian Peninsula and the Mediterranean area, in which the authors investigated how a reduction in reservoir water levels has occurred and worsened under conditions of climate change (Carvalho-Santos et al., 2017; Lobanova et al., 2017; Nunes et al., 2017; Rocha et al., 2020).

Conclusions

In this work, we developed a model to represent the relationship between the level of precipitation and the water contribution to reservoirs in the province of Malaga—specifically, a model to simulate the dynamics by which each reservoir takes advantage of the rain that falls in its basin. We optimized this model for each watershed using a local search algorithm, offering a good final fit—in some cases, greater than 0.8. Once adjusted, the model enabled us to determine which episodes and intensities of precipitation have a better response at the level of each reservoir in the province of Malaga, as well as the sensitivity of each of them to the average temperature. We believe this information can be particularly useful when predicting the long-term level of these reservoirs because it enables us to predict how future changes in the precipitation pattern and temperature will affect the exploitation of precipitation in each of them. That is, it enables us to predict how the amount of water that reaches the reservoir will be reduced not only by a reduction in precipitation but also by an increase in precipitation, an increase in torrentiality, or an increase in temperatures, all of which are likely scenarios for the Mediterranean region according the IPCC forecasts. Thus, the next stage of this research will be to integrate these scenarios into the model and analyze the effect of the predicted climate changes at the level of these investigated reservoirs.

Author Contributions

Julián Molina: research, methodology, data analysis, software, original draft writing. José Antonio Sillero-Medina: conceptualization, research, original draft writing, writing, editing. José Damián Ruiz-Sinoga: research, original draft writing, review, validation.

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ORCID iD

José Antonio Sillero-Medina https://orcid.org/0000-0002-7856-3239

REFERENCES

Abtew, W., & Melesse, A. M. (2013). *Evaporation and evapotranspiration: Measurements and estimations*. Springer.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration - Guidelines for computing crop water requirements* (FAO Irrigation and Drainage Paper, 56). FAO.

Barcena-Martin, E., Molina, J., & Ruiz-Sinoga, J. D. (2019). Issues and challenges in defining a heat wave: A Mediterranean case study. *International Journal of Climatology*, *39*, 331–342. https://doi.org/10.1002/joc.5809

Bracken, L. J., & Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*, *21*, 1749–1763. https://doi.org/10.1002/hyp.6313

Carvalho-Santos, C., Monteiro, A. T., Azevedo, J. C., Honrado, J. P., & Nunes, J. P. (2017). Climate change impacts on water resources and reservoir management: Uncertainty and adaptation for a mountain catchment in Northeast Portugal. *Water Resources Management*, *31*(11), 3355–3370.

Chamizo, S., Cantón, Y., Rodríguez-Caballero, E., Domingo, F., & Escudero, A. (2012). Runoff at contrasting scales in a semiarid ecosystem: A complex balance between biological soil crust features and rainfall characteristics. *Journal of Hydrology*, 452-453, 130–138. https://doi.org/10.1016/j.jhydrol.2012.05.045

Coscarelli, R., & Caloiero, T. (2012). Analysis of daily and monthly rainfall concentration in Southern Italy, Calabria region. *Journal of Hydrology*, 416–417, 145–156. https://doi.org/10.1016/j.jhydrol.2011.11.047

De Luis, M., Gonzalez Hidalgo, J. C., Brunetti, M., & Longares, L. A. (2011). Precipitation concentration changes in Spain 1946–2005. *Natural Hazards and Earth System Sciences*, *11*, 1259–1265. https://doi.org/10.1016/10.5194/nhess-11-1259-2011

Ehsani, N., Vorosmarty, C. J., Fekete, B. M., & Stakhiv, E. Z. (2017). Reservoir operations under climate change: Storage capacity options to mitigate risk. *Journal of Hydrology*, *555*, 435–446. https://doi.org/10.1016/j.jhydrol.2017.09.008.

Fader, M., Shi, S., von Bloh, W., Bondeau, A., & Cramer, W. (2016). Mediterranean irrigation under climate change: More efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrology and Earth System Sciences*, 20(2), 953–973. https://doi.org/10.5194/hess-20-953-2016

Garcıa-Ruiz, J. M., Lopez-Moreno, J. I., Vicente-Serrano, S. M., Lasanta, T., & Beguería, S. (2011). Mediterranean water resources in a global change scenario. *Earth-Science Reviews*, *105*, 121–139. https://doi.org/10.1016/j.earscirev.2011.01.006

Garrote, L., Rodríguez, I. C., & Estrada, F. (1999). *An evaluation of the regulatory capacity of the basins of mainland Spain* [Conference session]. VI Spanish Conference of Dams, 2, Malaga, (pp.645–656). Spanish National Committee on Large Dams.

Gharari, S., Gupta, H. V., Clark, M. P., Hrachowitz, M., Phoenicia, F., Matgen, P., & Savenije, H. H. G. (2021). Understanding the information content in the hierarchy of model development decisions: Learning from data. *Water Resources Research*, *57*(6), e2020WR027948. https://doi.org/10.1029/2020WR027948

Giorgi, F. (2006). Climate change hot-spots. *Geophysical Research Letters*, 33(8), L08707. https://doi.org/10.1029/2006GL025734

Gorguner, M., Kavvas, M. L., & Ishida, K. (2019). Assessing the impacts of future climate change on the hydroclimatology of the Gediz Basin in Turkey by using dynamically downscaled CMIP5 projections. *Science of the Total Environment*, *648*, 481–499. https://doi.org/10.1016/j.scitotenv.2018.08.167.

Guijarro Pastor, J. A. (2002). Precipitation trends on the Spanish Mediterranean coast. In J. A. Guijarro, M. Grimalt, M. Laita, & S. Alonso (Eds.), *El Agua y el Clima* [Water and climate], AEC, Serie A, 3, (pp. 237–246). Gráficas Loyse.

Guyassa, E., Frankl, A., Zenebe, A., Poesen, J., & Nyssen, J. (2017). Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia. *Journal of Hydrology*, *545*, 299–309. https://doi.org/10.1016/j.jhydrol.2016.12.019

Habets, F., Molénat, J., Carluer, N., Douez, O., & Leenhardt, D. (2018). The cumulative impacts of small reservoirs on hydrology: A review. *The Science of the Total Environment*, *643*, 850–867. https://doi.org/10.1016/j.scitotenv.2018.06.188

Hrachowitz, M., Fovet, O., Ruiz, L., Euser, T., Gharari, S., Nijzink, R., Freer, J., Savenije, H. H. G., & Gascuel-Odoux, C. (2014). Process consistency in models: The importance of system signatures, expert knowledge, and process complexity. *Water Resources Research*, *50*(9), 7445–7469. https://doi.org/10.1002/2014WR015484

Iglesias, A., Estrela, T., & Gallart, F. (2005). *Impacts on water resources. Preliminary assessment of impacts in Spain for the effect of climate change*. (pp. 303–353). Ministry of Environment.

IPCC (Intergovernmental Panel on Climate Change). (2014). *Fifth assessment report*. IPCC.

IPCC (Intergovernmental Panel on Climate Change). (2021). *Climate change 2021: The physical science basis* (Contribution of Working Group I to the Sixth Assessment Report). IPCC.

Jiang, Z., Liu, P., Ji, C., Zhang, H., & Chen, Y. (2019). Ecological flow considered multi-objective storage energy operation chart optimization of large-scale mixed reservoirs. *Journal of Hydrology*, *577*, 123949. https://doi.org/10.1016/j.jhydrol.2019.123949

Katz, R., Brush, G., & Parlange, M. (2005). Statistics of extremes: Modeling ecological disturbances. *Ecology*, *86*, 1124–1134.

Leibowitz, S. G., & Vining, K. C. (2003). Temporal connectivity in a prairie pothole complex. *Wetlands*, *23*(1), 13–25.

Lemus-Canovas, M., & López-Bustins, J. (2016). *Spatio-temporal variability of precipitation in southern Catalonia and its relationship with the Western Mediterranean Oscillation (WEMO)* [Conference session]. Proceedings of the X International Congress AEC: Climate, society, risks and spatial planning, Alicante.

Li, L. H., Xu, H. G., Chen, X., & Simonovic, S. P. (2010). Streamflow forecast and reservoir operation performance assessment under climate change. *Water Resources Management*, *24*(1), 83–104. https://doi.org/10.1007/s11269-009-9438-x

Lionello, P., Abrantes, F., Congedi, L., Dulac, F., Gacic, M., Gomis, D., Goodess, C., Hoff, H., Kutiel, H., Luterbacher, J., Planton, S., Reale, M., Schröder, K., Struglia, M.V., Toretin, A., Tsimplis, M., Ulbrich, U., & Xoplaki, E. (2012). Introduction: Mediterranean climate - background information. In Lionello, P. (Ed.), *The climate of the Mediterranean region - From the past to the future* (pp. 35–90). Elsevier.

Lobanova, A., Liersch, S., Tabara, D., Koch, H., Hattermann, F. F., & Krysanova, V. (2017). Harmonizing human-hydrological system under climate change: A scenario-based approach for the case of the headwaters of the Tagus River. *Journal of Hydrology*, *548*, 436–447. https://doi.org/10.1016/j.jhydrol.2017.03.015

Marcal, J., Antizar-Ladislao, B., & Hofman, J. (2021). Addressing water security: An overview. *Sustainability*, *13*, 13702. https://doi.org/10.3390/su132413702

Martínez-Austria, P. F., & Alcocer-Yamanaka, V. H. (2019). Dynamic modeling in the operation of reservoirs. *UDLAP Environment*, 10. https://www.researchgate.net/publication/338435154_Dynamic_modeling_of_reservoirs_operation_in_Spanish

Mashaly, A. F., & Fernald, A. G. (2020). Identifying capabilities and potentials of system dynamics in hydrology and water resources as a promising modeling approach for water management. *Water*, *12*(5), 1432. https://doi.org/10.3390/w12051432

Mereu, S., Sušnik, J., Trabucco, A., Daccache, A., Vamvakeridou-Lyroudia, L., Renoldi, S., Virdis, A., Savić, D., & Assimacopoulos, D. (2016). Operational resilience of reservoirs to climate change, agricultural demand, and tourism: A case study from Sardinia. *Science of the Total Environment*, *543*, 1028–1038. https://doi.org/10.1016/j.scitotenv.2015.04.066

Michaelides, S., Karacostas, T., Sánchez, J. L., Retalis, A., Pytharoulis, I., Homar, V., Romero, R., Zanis, P., Giannakopoulos, C., Bühl, J., Ansmann, A., Merino, A., Melcón, P., Lagouvardos, K., Kotroni, V., Bruggeman, A., López-Moreno, J. I., Berthet, C., Katragkou, E., . . . Nisantzi, A. (2018). Reviews and perspectives of high impact atmospheric processes in the Mediterranean. *Atmospheric Research*, *208*, 4–44. https://doi.org/10.1016/j.atmosres.2017.11.022

Montaldo, N., & Oren, R. (2018). Changing seasonal rainfall distribution with climate directs contrasting impacts at evapotranspiration and water yield in the Western Mediterranean region. *Earths Future*, *6*(6), 841–856. https://doi.org/10.1029/2018EF000843

Nanda, A., Sen, S., & McNamara, J. P. (2019). How spatiotemporal variation of soil moisture can explain hydrological connectivity of infiltration-excess dominated hillslope: Observations from lesser Himalayan landscape. *Journal of Hydrology*, *579*, 124146. https://doi.org/10.1016/j.jhydrol.2019.124146.

Negri, D. H., Gollehon, N. R., & Aillery, M. P. (2005). The effects of climatic variability on US irrigation adoption. *Climatic Change*, *69*, 299–323. https://doi.org/10.1007/s10584-005-1817-6

Nunes, J. P., Jacinto, R., & Keizer, J. J. (2017). Combined impacts of climate and socio-economic scenarios on irrigation water availability for a dry Mediterranean reservoir. *Science of the Total Environment*, 584–585(C), 219–233. https://doi.org/10.1016/j.scitotenv.2017.01.131

Olcina Cantos, J. (2017). Increase in flood episodes due to rains of hourly intensity in the central sector of the Spanish Mediterranean coast: Analysis of trends in Alicante. *Semata Social Sciences and Humanities*, *29*,143–163. https://doi.org/10.15304/s.29.4213

Pulido-Velázquez, M., Escriva-Bou, A., & Macián Sorribes, H. (2020). *Current and future water balance in basins in Spain, structural deficits and socioeconomic implications*. Studies on the Spanish Economy, eee2020-38. FEDEA.

Qin, P., Xu, H., Liu, M., Du, L., Xiao, C., Liu, L., & Tarroja, B. (2020) Climate change impacts on Three Gorges Reservoir impoundment and hydropower generation, *Journal of Hydrology*, *580*, 123922. https://doi.org/10.1016/j.jhydrol.2019.123922.

Recio, I., Niubis, P., & Martínez, J. (2016). System for simple reservoir operation implemented in the mathematical assistant MATLAB. *Hydraulic and Environmental Engineering*, *37*(1), 28–42.

Rocha, J., Carvalho-Santos, C., Diogo, P., Beça, P., Keizer, J. J., & Nunes, J. P. (2020). Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal). *Science of the Total Environment*, *736*, 139477. https://doi.org/10.1016/j.scitotenv.2020.139477

Ruiz-Sinoga, J. D., Garcia-Marin, R., Martinez-Murillo, J. F., & Gabarron Galeote, M. A. (2011). Precipitation dynamics in southern Spain: Trends and cycles. *International Journal of Climatology*, *31*, 2281–2289. https://doi.org/10.1002/joc.2235

Ruiz-Sinoga, J. D., Garcia-Marin, R., Gabarron-Galeote, M. A., & Martinez-Murillo, J. F. (2012). Analysis of dry periods along a pluviometric gradient in Mediterranean southern Spain. *International Journal of Climatology*, 32, 1558–1571. https://doi.org/10.1002/joc.2376

Sillero-Medina, J. A., Martínez-Murillo, J. F., & Ruiz-Sinoga, J. D. (2021). Efectos del incremento de la erosividad de lluvia en la estimación de pérdida de suelo (RUSLE) en el periodo 1997-2018: Comparación en dos cuencas mediterráneas con diferentes condiciones pluviométricas. *Boletín De La Asociación De Geógrafos Españoles*, 89. https://doi.org/10.21138/bage.3092

Sillero-Medina, J. A., Rodrigo-Comino, J., & Ruiz-Sinoga, J. D. (2021). Factors determining the soil available water during the last two decades (1997–2019) in southern Spain. *Arabian Journal of Geosciences*, *14*, 1971. https://doi.org/10.1007/s12517-021-08265-y

Simonovic, S. P. (2009). *Managing water resources. Methods and tools for a system*. UNESCO.

SPANCOLD (Spanish National Committee on Large Dams). (2013). *Reservoirs and hydrological planning: Big questions* [Conference session]. Technical Conference: Economic sustainability of dams and reservoirs. Madrid, Spain.

Tapiador, F. J., Marcos, C., Sancho, J. M., Santos, C., Núnez, J. A., Navarro, A., Kummerow, C., & Adler, R. F. (2021). The September 2019 floods in Spain: An example of the utility of satellite data for the analysis of extreme hydrometeorological events. *Atmospheric Research*, *257*, 105588. https://doi.org/10.1016/j.atmosres.2021.105588.

Tetzlaff, D., McNamara, J. P., & Carey, S. K. (2011). Measurements and modelling of storage dynamics across scales. *Hydrological Processes*, *25*, 3831–3835.

Vörösmarty, C. J., Rodríguez Osuna, V., Cak, A. D., Bhaduri, A., Bunn, S. E., Corsi, F., Gastelumendi, J., Green, P. J., Harrison, I., Lawford, R., Marcotullio, P. J., McClain, M. E., McDonald, R., McIntyre, P., Palmer, M. A., Robarts, R. D., Szöllösi-Nagy, A., Tessler, Z. D., & Uhlenbrook, S. (2018). Ecosystem-based water security and the Sustainable Development Goals (SDGs). *Ecohydrology and Hydrobiology*, *18*(4), 317–333. https://doi.org/10.1016/j.ecohyd.2018.07.004

Wilson, T. B., Baker, C. B., Meyers, T. P., Kochendorfer, J., Hall, M., Bell, J. E., & Palecki, M. A. (2016). Site-specific soil properties of the US climate reference network soil moisture. *Vadose Zone Journal*, *15*(11), 1–14. https://doi.org/10.2136/vzj2016.05.0047

Zhang, Y., Huang, C., Zhang, W., Chen, J., & Wang, L. (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales. *Environmental Science and Pollution Research*, *28*(38), 52724–52743. https://doi.org/10.1007/s11356-021-16148-8

Zhao, L., Liu, Y., & Luo, Y. (2020). Assessing hydrological connectivity mitigated by reservoirs, vegetation cover, and climate in Yan River Watershed on the Loess Plateau, China: The network approach. *Water*, *12*(6), 1742. https://doi.org/10.3390/w12061742