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Using Landsat Images to Determine Water Storing Capacity in Mediterranean Environments

Gema Marco Dos Santos* Jose Navarro-Pedreño* Ignacio Meléndez-Pastor Ignacio Gómez Lucas

Departament of Agrochemistry and Environment, University Miguel Hernández of Elche, Edif, Alcludia, Elche, 03202, Spain

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ABSTRACT

Reservoirs play an important role in water management and are key elements for water supply. Monitoring is needed in order to guarantee the quantity and quality of stored water. However, this task is sometimes not easy. The objective of this study was to develop a procedure for predicting volume of stored water with remote sensing in water bodies under Mediterranean climate conditions. To achieve this objective, multispectral Landsat 7 and 8 images (NASA) were analyzed for the following five reservoirs: La Serena, La Pedrera, Beniarrés, Cubillas and Negratín (Spain). Reservoirs water surface was computed with the spectral angle mapper (SAM) algorithm. After that, cross-validation regression models were computed in order to assess the capability of water surface estimations to predict stored water in each of the reservoirs. The statistical models were trained with Landsat 7 images and were validated by using Landsat 8 images. Our results suggest a good capability of water volume prediction from free satellite imagery derived from surface water estimations. Combining free remote sensing images and open source GIS algorithms can be a very useful tool for water management and an integrated and efficient way to control water storage, especially in low accessible sites.

1. Introduction

Reservoirs are a very important tool for water management, especially in semi-arid areas^[1]. They facilitate water supply in scarcity periods, flood control, hydroelectric power generation and other uses^[2]. In arid and semi-

arid areas, with water scarcity and irregular precipitation, an efficient use of water resources is one of the greatest challenges for managers^[3], especially considering the climate change projections where a decrease in available water resources is expected^[4,5]. In Spain, there has been a significant increase in water demand mainly to the

*Corresponding Author:

Gema Marco Dos Santos,

Departament of Agrochemistry and Environment, University Miguel Hernández of Elche, Edif, Alcludia, Elche, 03202, Spain;

Email: gema.marcodos.santos@gmail.com

Jose Navarro-Pedreño,

Departament of Agrochemistry and Environment, University Miguel Hernández of Elche, Edif, Alcludia, Elche, 03202, Spain;

Email: jonavar@umh.es

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growth in population, above all in the coastal areas due to tourism. Likewise, the irrigated area, mainly in the South, has increased in the past decades. Increased population, irrigation and energy generation are the main causes of the regulation of river flows. In fact, Spain is the EU country with the largest irrigated area^[6]. Therefore, there is a water stress caused by a situation of lack of water resources and a high extraction rate^[7]. As a result, most of the rivers are regulated by dams, which negatively affect fluvial dynamics such as sediment transport, alteration in the runoff balance, and aquifers recharge. Spain is the European country with the largest number of dams (more than 1,200 dams with total water stored capacity of 56,000 hm³)^[8] and with a large supply network. However, all of these infrastructures entail a very high maintenance cost. Despite this, according to a report carried out by SEOPAN (Spanish Association of Construction Companies and Concessionaires of Infrastructures), Spain is the country of the EU that less economic investment dedicates to the water infrastructures maintenance and improvement (nowadays, it is investing 60% less than in 2007)^[9]. According to data from the Ministry for the Ecological Transition^[10], in March 2019, the Spanish water reserve rose up to 58.1% of the total capacity, and in March of 2021 this was close to 63.1%. The sum of the consequences of climate change and the aging of infrastructures, can lead to an alarming situation with important losses of this valuable resource and the storage capacity.

There are different techniques to estimate the water reserve and the storing capacity. In Spain, the most commonly used equipment to measure the water level in reservoirs are pressure methods (hydrostatic collection, pneumatic capture, etc.), since they have high precision and stability^[11] in addition to the traditional limnometric method. However, the use of this type of sensors could suppose a cost in the maintenance and the time dedicated (i.e. inspections and technical visits), especially for smaller and/or dispersed reservoirs in the territory. Even more, one of the problems in the water reserve temporal series data is the deficiency of homogeneity in the values due to changes in the gauging stations over time^[12]. In developing countries, it could be difficult for the availability and the continue maintenance of these tools to measure the water stored.

Remote sensing is a tool that can be very useful to study the water quantity and quality over time, especially when direct observation or validation in situ is not possible^[1,13]. It offers the possibility of assessing current and monitoring future water demands in order to better allocate limited water resources with integrated

management systems^[14]. Satellite images can provide us with an overview of the resource spatiotemporal dynamics and incorporate it into management measures^[15,16]. Even more, the free availability of Landsat images can help to control and manage water and produce models to estimate the future scenarios of water storage and demand^[17].

Despite the possibility of cloud cover^[18,19] the images obtained from the Landsat ETM and ETM+ sensors present a medium spatial and temporal resolution^[20] that allow to map variations of the surface of the dammed water. There are some researchers who used different remote sensing products to assess, estimate and monitor, and develop methodologies in order to obtain data series^[21-24] that help in the management of water resources, even in developing countries^[25,26].

Considering the facilities of acquiring remote sensing images and the possibilities offered by free Geographic Information Systems (GIS) for modelling and predicting future sceneries, the combination of both could be useful for water management and decision makers^[27-31].

The purpose of this study was to assess the potential use of remote sensing images to estimate storage capacity in different reservoirs by using open source tools and establishing a quick method to estimate the volume of water stored, that can be integrated into an automatic or semiautomatic management system.

2. Materials and Methods

Five reservoirs with different sizes (and water storing capacity) were selected in this study (Figure 1) combining Landsat images and hydrological studies^[32]. These reservoirs are located in the climatic Mediterranean area of Spain: La Pedrera and Beniarrés, both in the province of Alicante, Cubillas and Negratín in the province of Granada and La Serena in the province of Badajoz. The annual average rainfall of all areas is between 300-500 mm and the annual average temperature range from 14°C to 16°C^[33].

Characteristics of each reservoir, such as surface and maximum capacity are summarized in Table 1. La Serena reservoir (38°55'49.4"N 5°13'36.1"W) is located at the confluence of the Zújar river and the Guadalemar river in the Guadiana river basin. It was built in 1990 over a large part of the old Zújar Reservoir. Annual average precipitation values are around 550.40 mm, and frequent droughts periods during summer months. The main uses are mainly irrigation, but also water supply and hydroelectric power generation^[34].

La Pedrera reservoir (38°01'05.9"N 0°51'56.9"W) was built to use it as a regulator in the distribution of water

from the Tajo-Segura transfer to the Campo de Cartagena in 1985. It is located on the Rambla de Alcoriza, in the Segura watershed. This area is characterized by low and irregular rainfall (around 300 mm, mainly in April and October), and high temperature. La Pedrera reservoir is a key element which is part of a natural and man-made environment cataloged as a Protected Landscape of Sierra Escalona and its surroundings. Moreover, this area is classified as a Special Protection Area (SPA) for Birds and Site of Community Importance (SCI) [35,36].

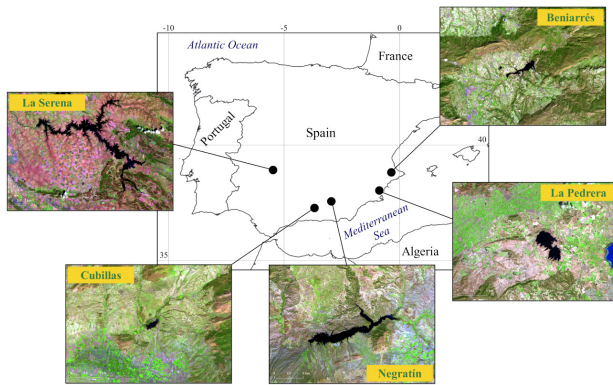


Figure 1. Location of the studied reservoirs. False color composites of each study area are shown.

Source: Landsat 8 OLI RGB:5.6.2

Beniarrés reservoir (38°48'21.2"N 0°21'52.2"W) is located on the Serpis river and it was built in 1958 mainly for agricultural irrigation, but fishing is also allowed. Annual average precipitation is about 650 mm. The reservoir is surrounded by two SCI's: Sierra de la Safor and Valls de la Marina, both with a great endemic vegetation representation [37,38].

Cubillas reservoir (37°16'37.0"N 3°40'13.6"W) was built in 1956 on the Cubillas river and it is not only used for irrigation but also as a bathing area. The Cubillas watershed average rainfall values are around 600 mm, with dry hot summers. It is located close to Sierra de Huétor Natural Park [39].

Negratín reservoir (37°17'19.03"N 3°39'44.66" W) was built in December of 1984 on the Guadiana Menor river and currently is the third biggest reservoir in Andalusia (Spain). The main uses are irrigation and electric generation, but also has a great social component for sailing, fishing or bathing [40]. It is situated 100 kilometers northeast of the Cubillas reservoir.

To describe material and methods employed in this research, a flowchart with the sequence of data sources and analyses is provided (Figure 2).

Table 1. Main characteristics of the study reservoirs. Source: Spanish Yearbook of the Water Gauging Information System [40].

Reservoir	Surface (ha)	Maximum storage capacity (hm ³)
La Serena	13,708.3	3,219
La Pedrera	1,226.9	246
Beniarrés	224.3	27
Cubillas	184.6	21
Negratín	2,016.8	567

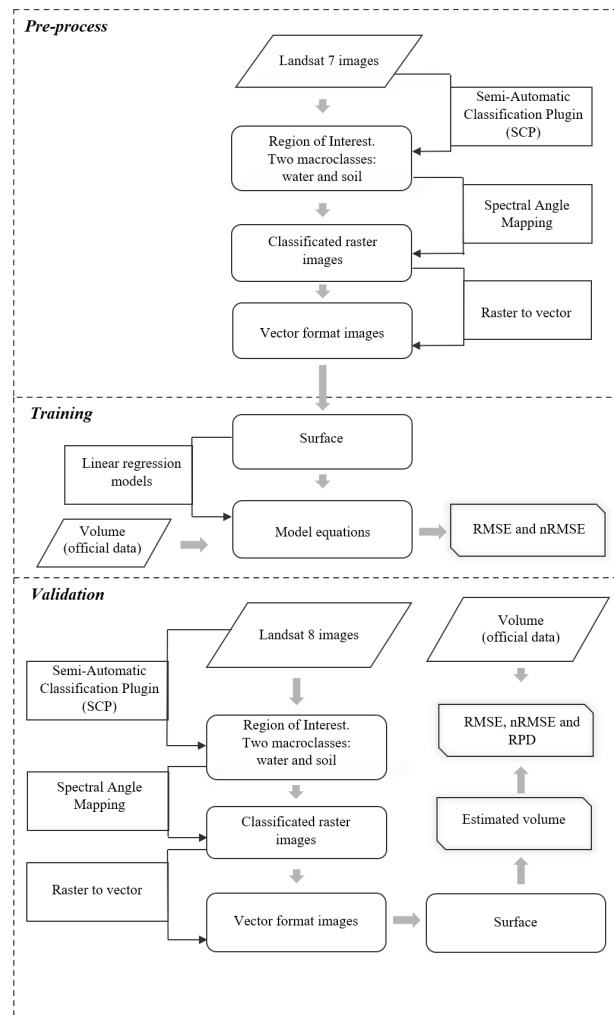


Figure 2. Flow chart of the process: 1) Pre-processing of Landsat 7 images with QGIS and the SCP plugin, 2) Training model, 3) Validation process with Landsat 8.

2.1 Hydrological Data

Water storage data proceeded from the web tool State Monitoring Networks and Hydrological Information [41] owned firstly by the Ministry of Agriculture and Fisheries, Food and Environment (MAPAMA), nowadays by the Ministry of Ecological Transition and Demographic Challenge (MITECO), with information about outlet flow,

reservoir water level, and water storage.

Daily values of water level variation for each reservoir were obtained from the monitoring control stations network. These data do not consider evaporation losses. Reservoir water volume data used for each reservoir were from the same dates when the remote sensing images were obtained. This information is publicly available and facilitated the production of water storage time series.

The Official Gauging Stations Network has been in operation since the hydrological year 1911-1912, so there may be some variations in the data homogeneity, due to changes and improvements in the measurement systems used over the years. Gauging stations are part of the continental water masses monitoring program.

2.2 Remote Sensing Data

Multispectral Landsat images were processed in this study (336 images). Landsat 7 ETM+ (Level-2) images acquired from the U.S. Geological Survey-Earth Explorer Geodatabase^[42], corresponding with dates between October 1999 and May 2003, were employed in the first stage of this study. Although the main limitation was cloud cover, the number of cloud free (under 10%) images used for each dam were the following: 28 images for La Serena, 85 for La Pedrera, 43 for Beniarrés, 35 for Cubillas and 62 for Negratín.

Additionally, a set of images acquired between April 2013 and December 2015 by the Landsat 8 Operational Land Imager (OLI) (Level-2) were used in the second stage of the study. A total of 17 images for La Serena, 14 for La Pedrera, 16 for Beniarrés, 15 for Cubillas and 21 for Negratín were used.

Landsat images have been widely used in numerous studies around the world for the observation and monitoring changes and processes in water masses, mainly due to the image's availability from the 1970s to the present day.

2.3 Image Processing

Firstly, the images were bounded by using a buffer created from the geographical data files (shapefiles) of the reservoirs (maximum surface). This geographical database was obtained from the open source spatial data infrastructure of the different Hydrographic Confederations of the rivers: Guadiana^[34], Segura^[35], Júcar^[37] and Guadalquivir^[39].

A supervised classification approach was employed to calculate the water surface of each Landsat image^[43]. For each one, the algorithm was trained with sets of pixels belonging to the following categories "water" or "upland". In this study, we focused on delimiting the area corresponding to the water surface, associated with

the thematic class "water". The Spectral Angle Mapper algorithm (SAM)^[44,45] was employed for mapping surface water extent. The algorithm calculates the similarities between the spectral signatures of the training image and the spectral signatures of the pixels of the image as vectors in an equal dimension to the number of bands (bands 1, 2, 3, 4, 5, 7 for Landsat 7 and bands 2, 3, 4, 5, 6, 7 for Landsat 8). The SAM equation is the following (Equation 1):

$$(x, y) = \cos^{-1} \left(\frac{\sum_{i=1}^n x_i y_i}{\left(\sqrt{\sum_{i=1}^n x_i^2} \right)^{\frac{1}{2}} \left(\sqrt{\sum_{i=1}^n y_i^2} \right)^{\frac{1}{2}}} \right) \quad (1)$$

where n is the number of bands in the image, x is the spectral signature vector of a pixel image, y is the spectral signature vector of the training area. Therefore, a pixel belongs to the class having the lower angle (Equation 2):

$$x \in C_k \Leftrightarrow \theta(x, y_k) < \theta(x, y_j) \forall k \neq j \quad (2)$$

where C_k is the k coverage class, y_k is the k class spectral signature, and y_j is the j class spectral signature.

Digital image processing analyses were performed with the QGIS vs. 3.4 "Madeira" open source Geographical Information System^[46] and the Semi-Automatic Classification Plugin (SCP)^[47].

2.4 Statistical Analyses

Descriptive statistics of estimated surface water and officially registered water volume were compared for each reservoir. After that, a statistical modeling approach for predicting water volume from remote sensing surface water estimation was done.

Least square regression models were computed to predict water volume from the obtained surface water maps. In order to develop a cross-validation modeling approach, Landsat 7 images were used for training and Landsat 8 images were for independent validation. In this sense, 75% of the images were employed for training and 25% for independent validation.

The training stage implied the development of regression models between surface water estimations and official water volume. Then, regression coefficients were used to compute the estimated water volume in the validation stage and compared with measured water volume. A set of statistical measurements were used to assess the accuracy of both modeling stages. Firstly, Pearson correlation coefficient (R^2) was calculated to explain how much variation in the dependent variable y (volume) is explained by x (surface) variable. Then, the adjustment of the estimation model was evaluated by using the Root Mean Square Error (RMSE) and

Normalized Root Mean Square (nRMSE) [48,49]. RMSE compares a predicted value and an observed value (Equation 3).

$$RMSE = \sqrt{\frac{\sum (M - E)^2}{n}} \quad (3)$$

where M = measure value, E = estimated value, and n = number of samples used for prediction. The smaller a RMSE value is, the closer the predicted and observed values are. Due to reservoirs have different dimensions, the nRMSE was calculated in order to provide a practical comparison among regression models for reservoirs with different spatial scales. This measurement was computed as a normalization of the RMSE respect to the range of the response variable (Equation 4).

$$nRMSE (\%) = \frac{RMSE}{range} \cdot 100 \quad (4)$$

Finally, the robustness of the predictions in the validation stage were evaluated with the Residual Predictive Deviation (RPD) that is computed as the standard deviation (σ) of observed values divided by the Root Mean Square Error or Prediction (RMSEP) as shown in Equation 5.

$$RPD = \frac{\sigma}{RMSEP} \quad (5)$$

To interpret the results of the RPD statistics, Cheng et al. [50] proposed that successful models should have RPD values higher than 2, moderately successful models have RPD values in the range 1.4 to 2, and unsuccessful models have lower values. All statistical analyses were developed with the R programming language [51] in the RStudio (<https://www.rstudio.com/>) integrated development environment.

3. Results

During all the studied period, reservoirs exhibited large stored water fluctuations. Average water volume of La Serena was 2369.9 hm³ (74% of its maximum capacity), 83.9 hm³ for la Pedrera (34% of its maximum capacity), 11.1 hm³ for Beniarrés (41% of its maximum capacity), 15.8 hm³ for Cubillas (75% of its maximum capacity) and 388.1 hm³ for Negratín (68% of its maximum capacity). Those water bodies with a lower value than the maximum capacity correspond to reservoirs with greater seasonal variability, measured by their coefficient of variation. In fact, significant negative correlation between both variables (R=-0.94; p-value<0.05) was obtained. It denotes the high variability of the water surface, especially in drier Southeast of Spain.

Training stage implied the development of regression

models among the estimated water surface of each reservoir from Landsat 7 images and the officially measured stored water data (Figure 3). In these five cases, we reported R² values over 0.9.

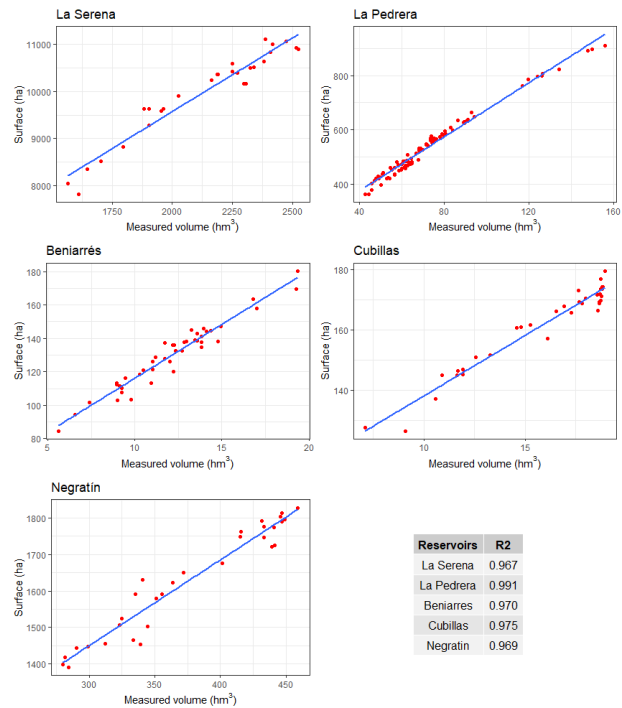


Figure 3. Linear regression between water surface and water storage in the five reservoirs (note: R² means R²).

In order to increase the knowledge about the performance of the regression models, RMSE and nRMSE were computed along with the Pearson correlation coefficient (Table 2). Lower RMSE values indicate a better fit of the models, and the lower values were obtained for Beniarrés (RMSE = 0.713) and Cubillas (RMSE = 0.742) reservoirs. These results should be analysed carefully because this statistic is scale-dependent. To avoid this problem, RMSE was normalized with the range of the predicted variable, thus obtaining the nRMSE. A more coherent comparison of the model was possible with the nRMSE and its values were about 20-25% except for La Pedrera, that was notably lower (nRMSE = 13.4%). All of them show adequate results of the model adjustment [50].

Table 2. Cross-validation results. Estimation of water volume from remote sensing surface water.

Reservoir	Training			Validation			
	R ²	RMSE	nRMSE	R ²	RMSE	nRMSE	RPD
La Serena	0.967	72.352	25.0%	0.939	37.408	33.2%	3.01
La Pedrera	0.991	3.288	13.4%	0.991	3.926	12.7%	7.90
Beniarrés	0.970	0.713	24.0%	0.973	1.018	22.3%	4.49
Cubillas	0.975	0.742	21.7%	0.990	0.378	13.7%	7.32
Negratín	0.969	14.721	24.2%	0.930	11.644	35.8%	2.79

Validation of the previous regression models was

developed with an independent Landsat 8 repository of images. Coefficients of the training stage were employed to predict water volume from estimated water surface. Then, water storage predictions were compared with officially measured water volume [52].

4. Discussion

Our results suggest that this methodology used for estimating surface water was robust enough (Table 2 and Figure 4), even at highly variable water bodies (human consumption, irrigation...) such as our studied reservoirs. Pearson correlation coefficients were always high ($R^2 > 0.9$) and RMSE and nRMSE were similar to those obtained in the training stage. La Pedrera (nRMSE = 12.7%) and Cubillas (nRMSE = 13.7%) reservoirs reported the better results for those statistics.

The predictive capability of regression models was evaluated with the residual predictive deviation (RPD) statistics. All the models reported RPD values higher than 2. That is a threshold commonly employed to identify model that could bring successful predictions of selected variables.

The use of temporal series of images to study and monitoring hydrologic dynamics in arid and semi-arid areas is becoming of great interest due to the increasing pressure on the water resources [53,54]. In addition, predictions of climate change cause growing concern about the efficiently management of resources.

In this study, according to the results obtained, the relationship between the water surface of the reservoirs and the stored water presents a good adjustment although some values of nRMSE were relatively low. Values of RPD over 2 indicate a successful prediction with maximum values for La Pedrera and Cubillas.

The complex sinuosity of the shore of the reservoirs and the existence of vegetation that covers the borders could affect the delimitation of the water surface by using automatic classification tools.

Despite the usually clouds coverage presented in these areas, there are a large number of images available to obtain good prediction models for water storage. However, there may be changes in the storage capacity due to structural, operational level modifications or sedimentation processes [55,56]. Knowing these, managers could quickly re-estimate the available water and use this methodology efficiently.

The information provided from this study could be useful when trying to estimate the available volume mainly in those areas where reservoirs monitoring has a complex accessibility, cost and time-consuming [17,52]. This information could be integrated into semiautomatic or

automatic decision-making tools and big data management and can help to study the effects of the climate change and predict future sceneries to determine water availability.

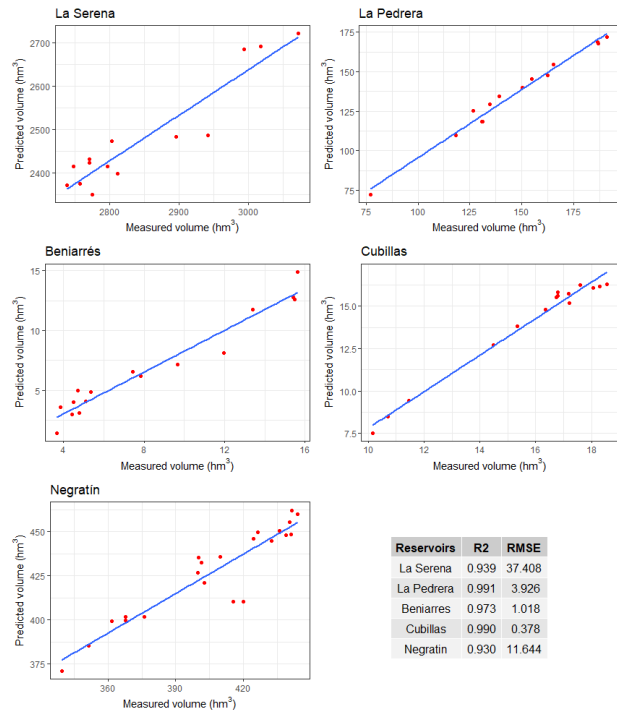


Figure 4. Comparison between measured and predicted volume obtained from validation in Landsat 8 images (note: R2 means R^2).

5. Conclusions

The relationship between area and water stored obtained in this study presents a good adjustment with high R^2 values and great RCP values, mainly in two reservoirs: La Pedrera and Cubillas. The study indicates the possibility of incorporating this methodology into management systems as an auxiliary tool to control water reservoirs. One of the main advantages of using remote sensing is the availability of images to create temporal series with water storage data in a quick and less costly way by using an open source Geographic Information System and free download images such as Landsat. This can help to take decisions and create strategies to predict different future scenarios.

This methodology has the aim of facilitating the implementation of an essay tool and method to manage water resources with a minimum cost, based on the use of free sources and open software.

Another advantage may be that this type of methodology can be easily automated. It is possible to create plugins and run personalize applications. For instance, using a programming language, a script can be created to

automate the process of obtaining update images, processing and calculating the water surface. To manage and analyse large volumes of information, as well as adjust and customize the methodology, this type of tools is very efficient and suitable. In this sense, this would be the first step for an automated management of big data and control data of a wide variety of reservoirs in order to establish regional or national strategies for water supply, hydroelectrical energy production and irrigation water availability.

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Data Availability Statement

Data obtained for the reservoirs are from open source and public availability.

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Conflicts of Interest

The authors declare no conflict of interest.

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