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Time-lapse photography for monitoring reservoir leakages (Montejaque dam, Andalusia, southern Spain)

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ABSTRACT

A methodology based on the use of time-lapse photographs is presented to evaluate the leakages over time of a reservoir (Montejaque dam, Málaga Province, Spain) that feeds a karstic aquifer. In particular, photographic control allows the evolution of water levels in the dam and the river that feeds it to be monitored. Through changes in water volume, which are calculated from the level differences, daily leakages are evaluated, and the relationship between leakages and the water level of the reservoir is established. The proposed method includes adjusting the hydric balance and the use of digital terrain model and climate data. The inputs (river flow and direct precipitation) and other outputs (direct evaporation) are also evaluated. Values between 4 m^3/s and 0.35 m^3/s are obtained for the reservoir infiltration, clearly superior to the values obtained at the time of the construction of the dam in the 1920s. Mobilisation of the filling of fractures and conduits in karstic massif and calcite dissolution are processes that can influence this behaviour. When the water level is very low, the obtained values are below the historical leakages due to deposition of clay sediments at the reservoir bottom.

Key words | karst, Montejaque dam, non-metric cameras, reservoir leakages, Sierra de Líbar aquifer, time-lapse photographs

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INTRODUCTION

The use of photogrammetry in hydrology has been traditionally restricted to the development of surveying applications aimed at the geometric definition of the ground surface by using relief maps and/or digital terrain models (DTM) with varying degrees of detail. Such applications often involve the use of sophisticated instruments and aerial platforms, as well as the performance of complex processing operations. Recently, Molina *et al.* (2014) reviewed the typology, evolution, limitations and usefulness of geomatic methods, including close-range photogrammetry, as applied to the knowledge of water resources. Close-range photogrammetry is useful for various hydrological applications that require dimensional measurements with very low uncertainty (about ±1 mm). In this case, camera calibration is required to determine the internal parameters. However, in recent years, the proliferation of video cameras and low-cost digital cameras has enabled the development of new applications that are less demanding from the metric perspective.

A useful type of photography for the study of dynamic phenomena is obtained using time-lapse cameras. These digital cameras are simple, generally not metric, economical and capable of autonomous operation. They can be permanently located in one location and can perform successive shots based on an electronic timer scheduled at regular intervals (from a few seconds to one or more days). The photographs are stored in a memory card or other device and can be periodically downloaded by the user or transmitted remotely.

The hydrological and geomorphological applications of such instruments for various purposes have been described

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by several authors: for the study of snow cover and its evolution (Mernild & Hasholt 2006; Farinotti et al. 2010; Parajka et al. 2012; Garvelmann et al. 2013), glacial advance speed (Harrison et al. 1992; Shroder 2013) or recoil of periglacial coastal cliffs (Wobus et al. 2011). Bowman et al. (2007) used time-lapse photography and other techniques to study the process of drainage and beach sediment compaction. Some authors used time-lapse cameras and image analysis techniques to estimate hydrological variables such as effective width, a hydraulic parameter highly correlated with discharge in braided rivers (Gleason et al. 2015) or directly to estimate river discharge and its evolution (Young et al. 2015), even from videographic image sequences (Creutin et al. 2003). These techniques are also used in the control of laboratory experiments, such as studies of the change of state of water in different thermodynamic conditions (Ganguly & Alexeenko 2012) or in measuring the effects of hydric erosion on scale models (Brasington & Smart 2003), although the latter case used photographs obtained with metric cameras.

This paper describes a novel application based on the use of non-metric time-lapse photographs to determine the temporal evolution of the leakages in a reservoir. These leakages feed an adjacent karstic aquifer. Photographic information is combined with other data sources (direct measurement, meteorological data, topographic information). Although there are electronic devices for the continuous monitoring of some of the variables considered here, at times, it may not be feasible to install such devices for various reasons (e.g., technical, economic, administrative). The methodology presented is an alternative that provides satisfactory results at very low cost.

STUDY AREA: MONTEJAQUE RESERVOIR AND HUNDIDERO-GATO UNDERGROUND COMPLEX

Montejaque dam is located 6 km to the west of the town of Ronda, within the Natural Park of the Sierra de Grazalema (Cádiz and Málaga provinces, Spain, Figure 1). It was built for hydroelectric development in the Guadares river, a tributary of the Guadiaro river.

The dam was completed in 1924 and was a pioneer in its time in terms of size (84 m from the foundation) and construction techniques (double curvature arch concrete dam) (Figure 2).

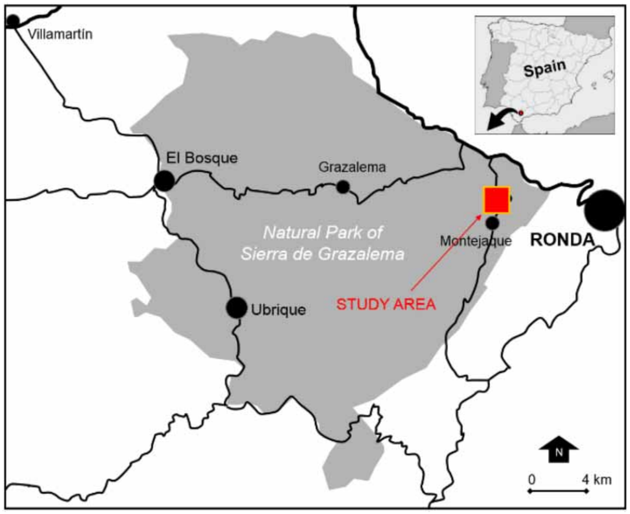

Figure 1 | Location of the study area.

However, it never became operational due to the high leakages that affect the reservoir. The reservoir floods Jurassic carbonate rocks in the area of Tavizna hill, and this zone is affected by severe karstification processes. Figure 3 shows a view of the reservoir and lithologic and tectonic map of the area.

Permeability problems in the rocks were detected while preparing the area prior to constructing the dam. Various ground treatment works were conducted both from the surface and inside the rock massif. Injections of various

Figure 2 | Current view of the Montejaque dam.

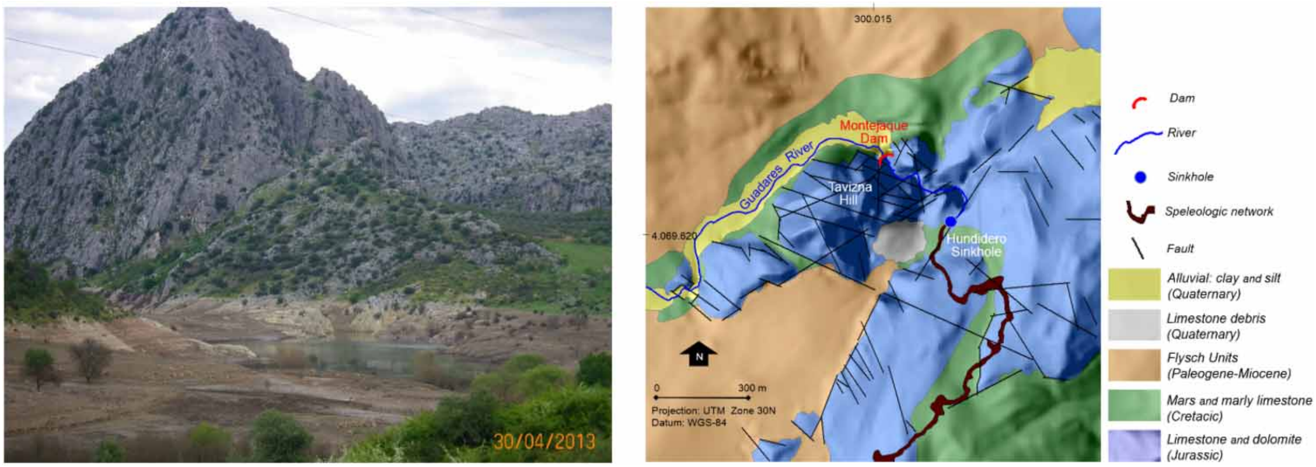

Figure 3 | Left: View of the Montejaque reservoir and Tavizna hill from the southwest. Right: Lithologic and tectonic map of the area.

materials (clay, concrete, asphalt) were performed in a series of drillings that were constructed for this purpose. Karstic cavities and surface karstic sinkholes were sealed. Conduits and fissures were closed from inside the massif using the existing speleologic system. Concurrently, to evaluate leakages, preferential flow pathways were identified by fluorescence and chemical tracers. Leakages were gauged, and water pressures were systematically measured. As those measures produced no satisfactory results, more complex and expensive alternatives were proposed but were never implemented (Naranjo 2009). Even after all the ground treatment works performed for over 15 years, it was not possible to reduce the leakages to acceptable levels. Thus, the construction was abandoned.

The reservoir leakages feed a karstic hydrogeological system integrated with the 'Sierra de Líbar' aquifer, which is characterised by the extensive development of exokarstic and endokarstic forms. In fact, before the construction of the dam, the River Guadares was completely infiltrated in the karstic massif, even in episodes of severe flooding, through a huge cavity that is nearly 50 m high (Hundidero cave, Figure 4(a)). This cavity acted as a sinkhole. The hydrogeological system is discharged by the 'Cueva del Gato' spring (Figure 4(b)), which is connected to the sinkhole through a speleological network of almost 8 km in length and that acts as a drain. This spring has a typical karstic functioning, with fast response to precipitation, sharp fluctuations in flow (between less than 0.05 m^3/s and more than 15 m^3/s) and very quick depletion. Benavente & Mangin (1984) studied the response of the spring by time series analysis. They identified dual influences: the surface water infiltrated at the dam and meteoric water or other sources infiltrated in the karstic massif through abundant exokarstic forms. A detailed description and interpretation of the Hundidero-Gato complex is available in Delannoy (1998). Moreover, Andreo *et al.* (2006) identified recharge areas of the spring 'Cueva del Gato' that are independent of the dam by tracer test. Therefore, the usefulness of the method proposed in this paper is related to the determination of the time evolution of one of the most important inputs in this hydrogeological system.

MATERIALS AND METHODS

The proposed application is based on the use of photographs taken with a Brinno TLC-100 camera (Figure 5). This instrument is a low-cost, time-lapse camera that is capable of outdoor operation, with an opening angle of 49.5°, a video resolution of 1,280 × 1,024 and a storage capacity of 8 GB. It allows exposure programming at intervals between 5 seconds and 24 hours. The functioning is autonomous: the camera is powered by disposable batteries and has a variable duration of operation, with a shooting interval of up to 200 days in the case of daily photographs.

In this study, two cameras were installed. They were hidden in the ground to prevent acts of vandalism. The first (location 1) was installed near the dam to record the

Figure 4 | Hundidero-Gato underground complex: (a) Hundidero Cave, (b) Cueva del Gato spring.

variation in the reservoir water level. It was placed in the left margin, at a distance of around 100 m from the dam, with the optical axis approximately horizontal and oblique to the construction. The second camera (location 2) was placed in the Guadares riverside, at the entrance of the reservoir, to record the water level of the river in a section regularised under a bridge, which had previously been used as a gauging station. The camera-channel section distance is less than 10 m. In this case, the objective is to reconstruct the hydrograph in the study period.

The camera at location 1 (reservoir) was placed on the ground for 5 weeks (between 03/04/13 and 07/05/13), during which time it automatically acquired photographs at regular intervals of time. This time period extended from the maximum storage of the reservoir, which resulted from a very wet spring, until emptying. The range of variation of the water level recorded at the dam was greater than 20 m (between 667.75 and 647.65 m asl). However, the registration period for the camera at the river (location 2) was lower, beginning on 22/04/13 and also ending on 07/05/13. In both cases, the interval between shots was scheduled every 30 minutes, thus obtaining between 22 and 26 frames per day with sufficient lighting. However, for this work, only one photograph was processed per day, except in specific cases that required higher temporal resolution or were used to check measures.

In parallel to the automatic registration of photographs, some direct measurements were made both of the water level reservoir from the crown of the dam using an electric water level meter and of the river streamflow using a micro current meter. These measurements were necessary to calibrate the measurements made using the images and to transform the positions of the water surface in the photographs to storage (reservoir) or streamflow (river).

The working scheme is shown in Figure 6. To determine the leakages, a balance method was considered. The changes in water level in the reservoir are due to the differences between the inputs and the outputs, for a given time interval (in the present study it has been considered a day). The entries refer mainly to the contribution of the main water course that feeds the reservoir, which has been monitored with time-lapse photographs. Inputs derived from direct precipitation on the water sheet have been taken into account. The contributions of the surface slope to the reservoir

Figure 5 | Brinno-TLC100 camera hidden in the ground at a location near the dam (above) and near the river, where it flows into the reservoir (bottom).

outside the main channel have been considered to be insignificant and have not been regarded. As for the outlets, only two types have been identified: the infiltration into the permeable materials that make up the reservoir vessel and the losses by direct evaporation from the water sheet of the reservoir. The infiltration into the permeable materials depends basically on two factors: the flooded surface of permeable rocks and the hydraulic load, both of which are determined by the reservoir level. The infiltration is the unknown variable that is deduced after the estimation of the rest of the variables of the water balance. Finally, direct evaporation depends on the temperature, humidity, solar radiation, wind factors and the surface exposed to evaporation; the latter also depends on the reservoir level. Thus, inputs, outputs and storage variations were estimated.

Instead of performing camera calibration to determine the internal orientation parameters, following simplified methods designed for low-cost cameras (Remondino & Fraser 2006), we chose to perform relative measurements between photographs, supported by direct measurements of the position of the water level. The structural characteristics of the camera (plastic structure, precarious fixation of the lens and of the CCD in the focal plane), together with the variable environmental conditions (wind, humidity, temperature) contribute to a poor dimensional stability of the camera. Dilatations and dimensional changes can affect focal length, position of the principal point, radial and tangential distortion coefficients, which makes it difficult to carry out interior orientation and thus the rigorous metric exploitation of the photographs. To overcome this inconvenience it would have been necessary to carry out a recalibration of the camera for each photograph, making the process not feasible.

The digital treatment performed has been basically oriented to achieve a very good geometric coincidence among all of the photographs of each set. For this purpose, we used the method of control points with transformation functions (Wolf 1983). For both the set of photographs obtained in the reservoir and the set obtained in the river, a photo was selected as reference, and the rest were adjusted to it. The adjustment was performed by applying first- and second-degree polynomial transformation functions, which were defined by a number of control points between 15 and 50. Control points were preferentially selected in the area of the frame where distance measurements were to be performed thereafter (Figure 7). The imposed condition was that the root-mean square error between the positions in the reference image and the positions in the transformed image should be less than 0.5 pixels and that the single residue for each point was a maximum of 1 pixel.

Without the geometric transformation it would not have been possible to make precise dimensional measurements between photographs. It should be noted that although all of the photographs were taken from the same point, the camera orientation suffered slight alterations as a result of the camera's own dimensional instability and because of variables and environmental conditions. After adjusting the images, we proceeded to determine the displacement of the water surface between successive photographs, expressed in image units (pixels). This displacement was measured in every image using the following routine: the mean of five measurements was considered after removing values that differed by more than 1 pixel from the mean.

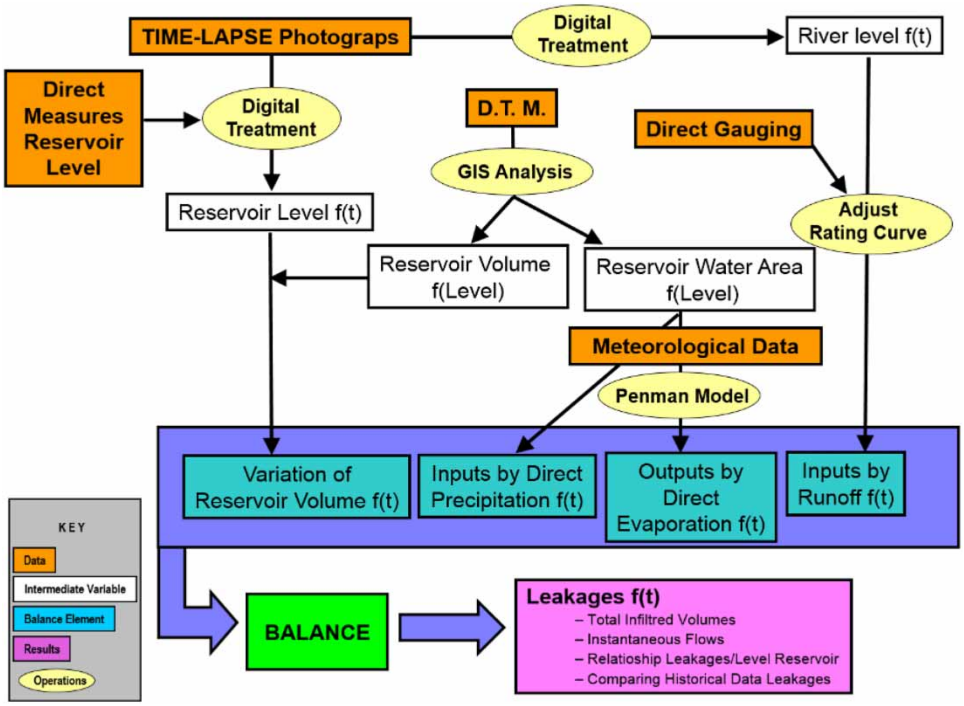

Figure 6 | General outline of the method.

Figure 7 | Example of processed time-lapse photography: photo taken on 24/04/2013 in location 1 (near the dam): (a) original image, indicating the area geometrically adjusted by control points, (b) detail of control points considered, (c) geometrically transformed image.

For photographs of the dam (location 1), the image units were transformed into terrain units from the consideration of water sheet measurements made with an electric water level meter with respect to the crown of the dam. In this way, the sizes of the pixels on the ground in the measurement area image were determined (between 4.2 cm and 4.4 cm). The accuracy obtained by repetition of measures was estimated to be on the order of half a pixel (2.2 cm).

Processing the images obtained in the river (location 2) was similar, but it was necessary to establish a rating curve from the position of the sheet water in the photographs and the flow determinations that were obtained using the micro current meter. The control points used to adjust the set of photographs were taken on one of the walls of the artificial river channel. In this case, the sensitivity in the determination of distances on the photograph was better because of the lower camera-object distance.

In this way, water level data (reservoir) and instantaneous flow data (river) were obtained from the photographs. Moreover, a DTM with a resolution of 5 m, produced by the IGN (National Geographic Institute, Ministry of Public Works), was used to define the geometry of the reservoir basin and determine the volume of storage and the water surface for each water level of reservoir. These variables are necessary for the procedure outlined in Figure 6.

Finally, daily meteorological information was used to evaluate the precipitation falling on the reservoir and the direct evaporation from its surface. Daily precipitation data were obtained from Ronda station, which is situated 6 km from the dam. Evaporation was evaluated daily by the Penman–Monteith equation (Allen *et al.* 1998), using meteorological data from the Villamartin agroclimatic station, which is situated 40 km northwest of the study area (Figure 1). This station is the closest and has a record of the necessary variables (solar radiation, maximum, mean and minimum temperature, maximum and minimum relative humidity, pressure and wind at 2 m above the ground).

RESULTS AND DISCUSSION

First, the analysis of the DTM led to defining the characteristic curves of the reservoir (Figure 8). In the graph 'flooded area versus reservoir level', we can observe a clear change in the slope starting at the value 660 m asl. This change is a consequence of the transition from the alluvial plain of the bottom of the reservoir towards the steepest slopes. The graph 'storage volume versus reservoir level' shows remarkable similarities with respect to the curve obtained using the data from the original project (year 1924). However, at present, there is a lower storage capacity (between 0.3 and 0.6 hm^3 less). This difference is explained by the sedimentation of fine materials (silt, clay and fine sand) at the bottom of the reservoir since the construction of the dam, indicating a relatively small degree of sedimentary fill (between 1 and 2 cm/year at the bottom of the reservoir).

The photographic monitoring of the dam, along with direct measures, has helped define the evolution of the reservoir level and its daily variations. Daily water level change is obtained by calculating the difference between reservoir levels of 2 consecutive days (Figure 9).

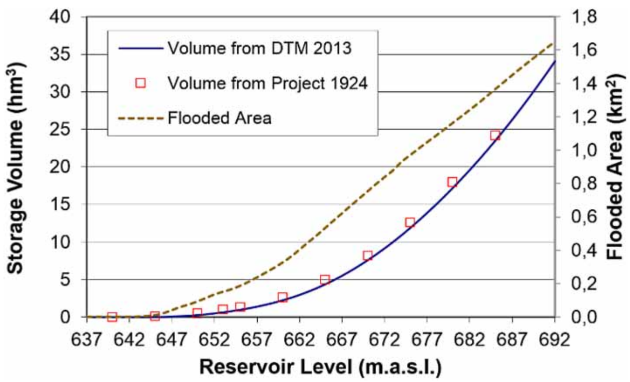

Figure 8 | Results obtained from the DTM analysis of the reservoir basin: graphs of flooded area and stored volume versus reservoir water level and comparison with historical data.

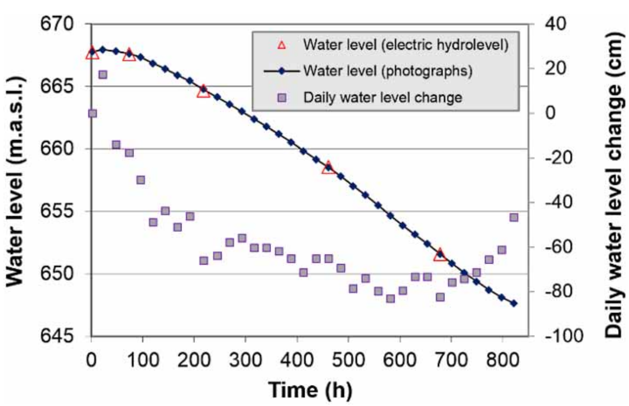

Figure 9 | Evolution of reservoir water level obtained from measurements in photos and daily descents, obtained by difference of each day with respect to the previous day.

The photographic monitoring of the river and direct gauging have helped define the rating curve in relative terms. From this information, a hydrograph of flow rates during the monitoring period was generated (Figure 10).

The results obtained for the time evolution of balance sheet items are shown in Figure 11. These results are restricted to the period with gauging of the river. In this case, both evaporation and direct precipitation from or on the water surface may be omitted because they represent less than 1% of the leakages. However, in a general case, the possibility of large-value rainfall events should be considered. The inputs by the river represent 6% of the leakages during control, but obviously, the entries surpassed these when the reservoir level grew. The daily leakages were evaluated based on differences. These values decrease approximately linearly with time, from 350,000 m^3/day (high water) to 25,000 m^3/day (when the reservoir is almost empty). The reduction of leakages must be motivated both by reducing the hydraulic head and by decreasing the submerged permeable surface on the slopes of the Tavizna hill.

Finally, an approximately linear relationship in the range of levels considered is obtained by comparing the instantaneous flow infiltration with the reservoir level (Figure 11). The leakages vary from less than 0.35 m^3/s with an almost empty reservoir (<0.25% capacity) to nearly 4 m^3/s when the level is 665 m asl, which represents 15% of its capacity. If we compare these results with historical data (CSE 1928), a significant and progressive increase in the leakages is shown, except for very low levels, in which we observe the opposite effect.

This result is justified by the clay deposit at the bottom of the basin, which is somewhat waterproof, although there are preferential infiltration funnels, as described in the course of

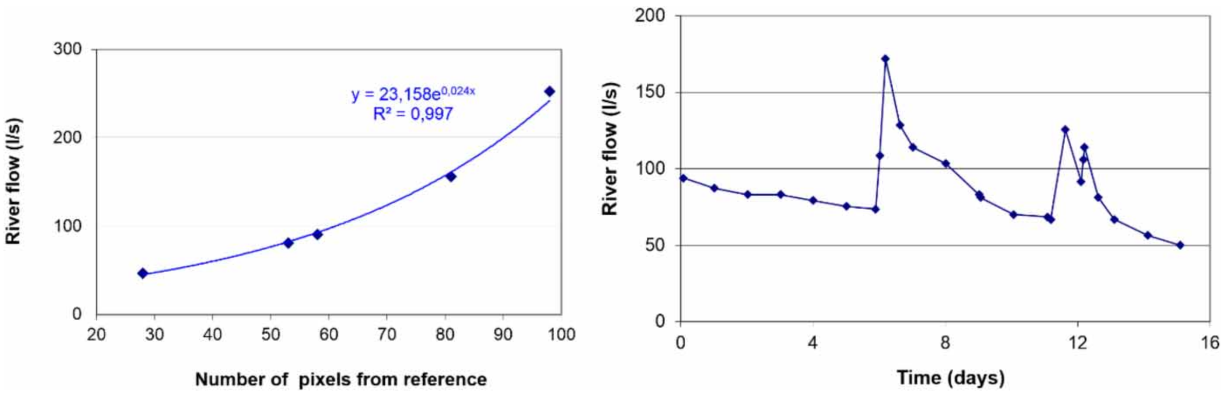

Figure 10 | Left: Rating curve obtained by direct gauging (level is expressed in units-photography). Right: Hydrograph of the Guadares river, obtained from the treatment of photographs taken at location 2.

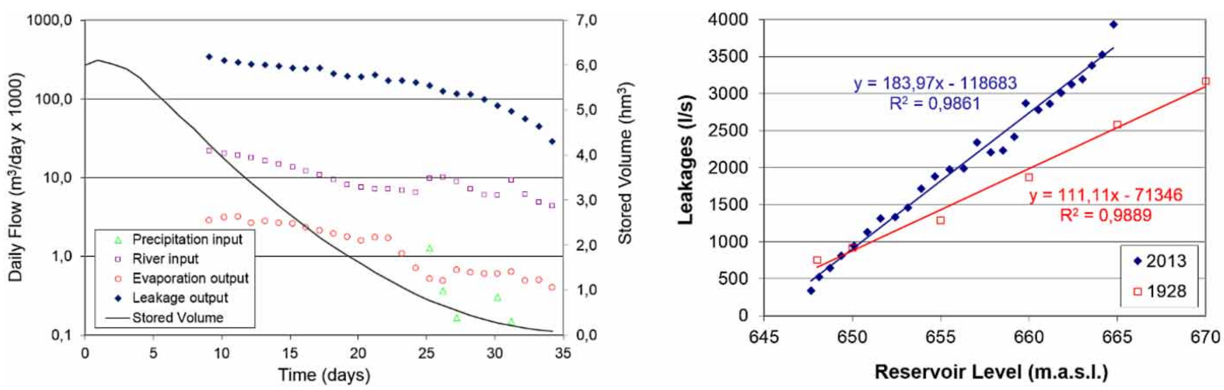

Figure 11 | Left: Evolution of the elements of the balance between 12/04/13 and 07/05/13. Right: Relationship between leakages and reservoir water level and comparison with historical data.

the construction works. The overall increase in leakages, which reaches 60% at high levels, must result from two phenomena: (1) gradual displacement of the materials used in soil treatment for filling cracks and ducts (clay, cement, asphalt) and (2) dissolution and mechanical erosion within the carbonate formation due to forced circulation through fissures and conduits as a result of increased hydraulic load.

Finally, some advantages of the method are as follows:

- At a very low cost, it has been possible to monitor a complex phenomenon such as the leakages of a reservoir with an acceptable level of accuracy. Given the low price of the equipment, the risk of theft of the cameras can be reduced by installing redundant equipment.
- Once the necessary measures are taken *in situ* (calibration), it is possible to obtain information from the photographs without stepping on the ground, so no access or equipment installation permissions are required. This point is particularly valuable for cases that do not have the cooperation of the owners of the land or the works.
- Although we chose to exploit a daily photographic image in this paper, the availability of images allows for greater density of measurements in time, without the need for further action in the field.
- Using this method allows the reconstruction of historical hydrographs from photographic records.

CONCLUSIONS

The proposed method is based on the exploitation of time-lapse photographs and has made it possible to obtain information on reservoir leakages and their evolution during the control period. It was not necessary to develop any complex installation *in situ*, only to place two low-cost cameras, which were hidden in the ground. The results indicate that it is feasible to monitor the variation of reservoir level in a range of more than 20 m to obtain measurement accuracies on the order of 2 cm. The continuous monitoring of the inflow to the reservoir was also possible by time-lapse photographs. The treatment of the photographs has made it possible to reconstruct the hydrograph of the stream that feeds the reservoir. The leakages have gone from 4 m^3/s to 0.35 m^3/s in 25 days, keeping a double linear relationship with respect to time and the water level of the reservoir. Regarding the historical data, there is a significant deterioration in the sealing conditions of the reservoir, except when it has very little stored volume. The latter is interpreted as a result of fine fluvial deposits covering the bottom of the reservoir basin.

Some difficulties in performing measurements on photographs have been differences in lighting conditions, the presence of waves or plant debris on the water surface, the specular reflection of the water and the existence of moisture fogging the camera lens. In particular, the darkness of night is a constraint but can be overcome by using synchronised lighting devices. To test the method, the treatment of photographs has been performed manually, but software could be implemented for the automatic recognition of forms to expedite the process of treatment.

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