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A multicriteria system for the monitoring and alert of the cracks found in Santos Morcillo Lake, Central Spain.

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Abstract

This article describes the multicriteria Monitoring and Alert System designed to allow safe access to Santos Morcillo Lake (located in Ruidera Lakes Natural Park, Central Spain). In the spring of 2007, two families of cracks were observed on both banks of the lake, located near the barrage separating it from the downstream Batana Lake. A sinkhole was also detected. This raised great community alarm, since it was feared that the barrage would collapse. A geoelectric and geotechnical survey was carried out to monitor the crack aperture, the barrage movements and the evolution of the lake water level. On the basis of the information obtained, a model was designed that was able to offer a simple and consistent explanation of the system's behaviour. Therefore, the model was used as a basis to define the safety assessment system proposed here. The system is based on the data from previously installed monitoring devices that would be processed daily by the Technical Staff of the Park. In the event that a warning should be triggered, an integrated analysis of all the information must be conducted, and an alert would be activated. The alert level will depend on how reliable the mobilisation hypothesis is, and different degrees of restricted access to Santos Morcillo, Batana and Colgada Lakes will take effect.

Keywords

Monitoring; alert system; cracking process; sediment consolidation.

1. Introduction

Santos Morcillo Lake (SML) is located in the central stretch of the lake system formed by Ruidera Lakes Natural Park (RLNP), in the centre of Spain (figure 1). The system is part of the wetland area known as La Mancha Húmeda, a UNESCO (United Nations Educational, Scientific and Cultural Organization) Biosphere Reserve since 1980. The 15 lakes of the Park were formed as a result of the development of tufa barrages that intercept the flow of the Guadiana Alto River (figures 1 and 2). The system is quite unique and only comparable to the one in Plitvice, Croatia [1], although Ruidera is set in a much more arid environment. In Plitvice, the mean annual rainfall is about 1620 mm, while in Ruidera it is 490 mm.

In the spring of 2007, extensive cracking was observed in the bed of SML, on both banks near the barrage separating it from Batana Lake (figures 3 and 4). At the same time the cracks were detected, a large sinkhole was found on the right bank (figure 4). The sinkhole and the cracks aroused great community alarm, since, after a preliminary analysis, some experts estimated that these elements pointed to the development of a large-scale collapse that could affect the SML-Batana barrage. For this reason, the regional Government of Castilla-La Mancha closed Santos Morcillo, Batana and Colgada Lakes to the public. They also commissioned the authors of this paper to carry out a detailed study.

That study started reviewing other analyses on piping and sinkhole processes, which are well known phenomena reported in literature. In this sense, the contributions in [2-7] are of interest. Case studies focused on the application of monitoring techniques on subsidence or sinkhole events (among others, [8-12]) were also examined. Even though these studies usually deal with larger sinkholes (with the implications in the monitoring

precision) and under atmospheric conditions, the ideas they present conformed a basis for the definition of the monitoring under the sub-aquatic conditions in SML.

Hence, eight crackmeters [13] were placed on the lake bed (see figures 3 and 4). These instruments showed the variation in the crack aperture with a precision of 0.001 mm. The installation of these devices was not conventional, as the crackmeters had to be installed underwater by divers at a depth of some 3 m (figure 5). Owing to the lack of available experience on the installation in such conditions, a new installation procedure was developed [14]. Figure 6 a plots the crack aperture evolution dcw obtained for each crackmeter. A diver type electronic limnigraph and a reference barometer were installed (figure 2) [15]. The error in their readings is lower than 2.5 mm. Figure 6 a also shows the field measurements of the lake water level, H . This figure shows the rise of the water level in January and, especially, in February-March 2010. Finally, a levelling network (65 points, see figure 3) was installed for precise levelling [16] (the levelling error is below 0.1 mm). This network was used to follow the development of trends that might lead to the collapse of the barrage. Figure 6 b shows an example of the increment of the vertical displacements dz in seven of the levelling points.

During the study, a simple alert protocol was applied. Depending on the risk inferred through the levelling and crack aperture measurements, the use of the lakes was restricted in accordance with a flood analysis developed by Seco and Sarasúa [17] for CHG, the Public Administration responsible for the management of the water in the Guadiana River basin.

On the basis of the data gathered during the study, a model was developed that offers a consistent explanation of the origin of the cracks and the sinkhole, in addition to providing a simple reproduction of the crack opening observed during monitoring [18].

For this reason, the hypothesis of a collapse being in development was ruled out, and in July 2010 it was recommended to open Batana and Colgada Lakes for public use.

Nevertheless, since there is still a considerable degree of uncertainty in the model, it was deemed necessary to establish an enhanced Monitoring and Alert Protocol (MAP) to be able to open SML for use under safe conditions. This article presents a description of this protocol, including an explanation of its fundamentals and scope, as well as the details of its implementation. However, before describing the MAP, the geological and hydrogeological environment of SML will be reviewed, and the cracks formation will be analysed.

2. Description of the geological and hydrogeological environment of the SML

RLNP, part of the Guadiana Alto River, is located on the Ruidera Fault. This is one of the most important structural elements of the Campo de Montiel aquifer (see figure 7 a). The aquifer, covering an area of around 2500 km², is mainly made up of Liassic carbonate rocks, lying on a base of Triassic material that may be considered impermeable. From a geomorphological standpoint, Campo de Montiel forms a plateau (900-1100 m.a.s.l.). For this reason, it was long considered an “undeformed” unit. However, recent studies [19, 20] have shed light on its structure, essentially created by the Betic deformation during the Alpine orogeny. Perhaps the most representative structural elements are the two families of faults: the NW-SE, like the Ruidera Fault, and the ENE-WSW family. These structures have conditioned the hydrogeological functioning of the aquifer, causing the Guadiana Alto River to be the primary drainage element of the Campo de Montiel aquifer.

The water from the aquifer that drains through the Guadiana Alto River is supersaturated in calcite (see [21]). Hence, the drop of the partial pressure of dissolved

CO₂ in the sharp river bends favours the precipitation of calcite and the formation of barrages [22]. Moreover, on the banks of the lakes formed by the barrages, stromatolite terraces have formed and fine sediments have been deposited on the lake floors. Barrages, terraces and sediments are the three most important elements comprising RLNP's tufa lakes. [22-25] provide a detailed description of these elements.

Stromatolite development is an indicator of stability of the system. This bio-chemical structure only develops in water without suspended matter [22]. Therefore, they are not compatible with a continuous contribution of terrigenous materials into the lakes. This fact, together with the existence of rock blocks resting in metastable equilibrium on the steep valley slopes, makes it unlikely that the cracks are due to seismic events or gravitational movements.

Over the course of their history, tufa systems have experienced different stages of development and accumulation (mainly during wet periods [26]), followed by stages of remarkable erosion, which have partially or totally destroyed the systems [22]. This is why the Guadiana Valley presents tufa terraces at different levels, with the upper ones dating as far back as 250 ka B.P. [22], while the present tufa deposits located in the bottom of the valley are younger than 10 ka B.P. [26].

Although the present deposits have not undergone these major erosion episodes, they have been affected by variations in climate, which have caused a significant amount of heterogeneity. This has been evidenced by the boreholes drilled in the barrages [20, 22, 27], as well as in the lake sediments [24, 25]. The heterogeneous nature of the terraces, due to both environmental changes and their growth dynamics [24, 28], has been observed with geophysical survey techniques. According to the results obtained by Grande et al. [29] using a Ground Penetrating Radar recognition approach [30], the terraces were found to be composed of four basic elements: (i) almost homogeneous

tufa levels, (ii) conical growth forms, both isolated and grouped, (iii) loose material (probably detrital tufa sand), and (iv) layers of more compacted lime material. This degree of detail was not able to be detected in either the geoelectrical survey carried out by Pedley in Lengua Lake [23] or the two electrical tomography campaigns conducted in SML by the authors of this paper (figure 8 a, showing one of the 11 tomographic sections). Nevertheless, the two electrical investigations make it possible to identify the existence of “vertical conductive chimneys” (see figure 8 a) that connect the conductive materials identified on the bottom of the tomographies with the lake floor. In addition, it is interesting to note that there is a marked correlation between the position of the cracks and the position of some of the chimneys in SML [18].

The connecting role played by the chimneys makes their internal structure even more complex. Since the flow between the lake water and groundwater becomes concentrated in the chimneys, owing to their heterogeneity, they developed highly porous internal structures or even internal conduits, which act as preferential flow paths. These elements were clearly visible in the sinkhole that developed next to the cracks (see figure 9).

To complete the hydrogeologic description of the SML environment, it should be noted that the groundwater flow beneath the Ruidera Lakes has a karstic structure. There is a complex network of preferential flow channels (see [27] and references therein) showing a priority for development at the contact point between the Liassic rocks and the Triassic material (figure 7 b). Although no karst caves were identified under the bed of SML in the two geoelectric campaigns carried out, the channels were confirmed to be generally aligned in the direction of Ruidera Fault, coinciding with the orientation of the conductive chimneys. Therefore, there may be different flow channels below the

chimneys, with a differentiated hydraulic behaviour and potentiometric head distributions.

3. Cracks formation

The arrangement of the topography, cracks and conductive chimneys led to the cracking configuration outlined in figure 8 b, which responds to the functional model idealised in figures 10 a and b. Given the complex and heterogeneous internal structure of the conductive chimneys (or “columns”), the model adopts the whole column as the support of the analysis (on the basis of Pachepsky et al. [31]).

The sediments are assumed to be saturated, or near saturation [32]. Thus, their behaviour is controlled by the effective stress [33], that is, the difference between the weight load and the pore water pressure. With the rising of the interstitial water pressure, the effective stress decreases. Therefore, the void ratio increases [34], and the column tends to swell. The heave caused by swelling is restricted by the crust, which is idealised as a slab. A swelling pressure p is introduced (figures 10 a and b) as a function of the vertical displacement, which depends, in turn, upon p . This is an implicit problem which is greatly simplified by assuming that the slab has a linear elastic behaviour, and that the consolidation of the sediments is also linear. The parameters in Table 1 were adopted [18].

Moreover, given the rapid response of the columns to the variation of H (figure 6 a), probably due to the drainage of the sediment overpressure through the preferential flow paths previously referred, a drained behaviour was assumed. This further simplifies the formulation [18]. The variation of the groundwater potentiometric head h at the contact with the Mesozoic rocks (not necessarily the same value in all the conductive columns,

see Section 2) and the variation of H were discretised into daily steps, superimposing their effect with that of p .

Before cracking was complete, the system followed the conceptual model outlined in figure 10 a. In this model, when the sediments swell, the maximum tensile stress is found at point “Q”. When the crust had acquired sufficient thickness to provide a certain degree of rigidity, the tensile stress exceeded its tensile strength and cracking would take place. As cracking progresses, the system gradually changes its behaviour to the one outlined in figure 10 b, corresponding to a fully cracked crust. This constituted a process of “adaptive-dynamic cracking” that incorporates cracking as a natural process of crust development.

However, over the first three decades of the 20th century, the anthropogenic distortion caused by the construction of several small Hydroelectric Power Stations broke with this dynamic. Particularly, the operation until the 1970s of Santa Elena Station near the barrage of Batana Lake (figure 2) caused the potentiometric head to decrease drastically, thus boosting the development of the crust [29]. Meanwhile, the chimneys sediments were “contracted” (low interstitial water pressure), thus ceasing their application of swelling pressure to the slab. At the end of the operation of Santa Elena Station, the potentiometric head increased 4 m in Batana Lake. However, the thick crust deposited while the Station was in operation restricted the flow from the aquifer to SML, so H did not increase as much as h . Then, in SML, the interstitial water pressure increased while the weight load remained approximately constant. The sediments swell pushing up the crust, initiating its cracking [18]. The complete cracking was a process that probably did not take place instantly. Instead, it was favoured by the cyclic loading exerted by the swelling/shrinkage of the sediments as a response to the variation of the potentiometric head. This cracking process was not as smooth as the “adaptive-

dynamic” type described before. The fact that the damage was completed in a situation of shrinkage, with a low potentiometric head but with a non-negligible lake water depth, as in the spring of 2007 [18], may have induced a piping process causing the sinkhole. A videoprobe inspection of the sinkhole evidences the existence of conduits (figure 9). This piping process is similar to the piping into a buried channel described by [35]. Hence, the “column and slab” model (C&SM) of Navarro et al. [18] offers a sound explanation of the origin of the cracks and the sinkhole of SML.

Moreover, adopting the conceptual model synthesised in figure 10 b, the model also allowed for the simple reproduction of the crack opening observed. This is shown in figures 11 a and b, which illustrate the correlation between the variation of the crack width dcw measured with the crackmeters and the settlement ds calculated with the C&SM. Therefore, it has been proposed for use as a basic tool to design the system’s monitoring process.

4. MAP components

Taking the C&SM as a basic monitoring tool means accepting the crack aperture data dcw measured with the crackmeters as the essential component of the MAP. The study of the evolution of dcw and its comparison with the output of the column and slab model, dcw_M (see figure 12 b), will comprise the first analysis or “Mode 1” of the MAP. To compute ds and dcw_M with the C&SM, the time evolution of the lake water level H needs to be known. Thus, the time evolution of H is the second information input to be used in the MAP.

It is interesting to stress that the time evolution of H in SML is mainly controlled by (i) the rainfall over the lake, (ii) the evapotranspiration, (iii) the lateral run-on, (iv) the overtopping water both entering from Salvadora Lake and flowing out towards Batana

Lake and (v) the seepage through the barrages between SML and both Salvadora and Batana Lakes, and the bed infiltration to and from groundwater. If H experiences a significant change while the four first factors remain constant, it could be due to the activation of a preferential flow path linked to a collapse mechanism. For this reason, the study of the evolution of H is a supplementary tool for the identification of anomalous behaviour. This has been called “Mode 2” of the MAP, independent from Mode 1.

Although Mode 2 will be able to point out anomalous seepage values at the barrage between SML and Batana Lake, significant mobilisation could occur in the downstream side of the barrage without major changes in the seepage. This way, it would be useful to include an additional component in the MAP, independent from the other two and focused on the monitoring of the barrage. In agreement with the monitoring performed in the study that enabled the development of the C&SM, it was decided to use the levelling network conforming the 65 points in figure 3. The barrage movements will be characterised with them, making it possible to identify movement trends inconsistent with the general evolution of the settlement. This analysis has been called “Mode 3” of monitoring and alert.

5. MAP Mode 1: crack opening

It is recommended to use the eight crackmeters installed from the beginning of the study plus four additional crackmeters to improve the crack opening monitoring on the right bank. All dataloggers should be adapted so that the measurements can be automatically radio transmitted [36] to the facilities of the RLNP Technical Staff (RLNP-TS). There, these data should be processed daily in keeping with the procedure outlined in figure 13.

In order to apply this procedure, the current limnigraph should also be modified, so that its records can be read remotely as well.

Each crackmeter takes a reading every fifteen minutes. The daily standard deviation with regard to the maximum average daily value of dcw should be calculated for each crackmeter to check its performance. The analysis carried out along the period of study shows a limited deviation in the readings, with a coefficient of variation seldom above 0.5 % (see figure 12 a). Then, if substantially higher values are recorded, the cause should be investigated. As a first attempt, it is proposed to activate warning 1 (figure 13) if the coefficient of variation is greater than 2 % (see figure 12 a). The data analysis would continue otherwise.

The soundness of the evolution of the daily mean value of dcw should be also checked. This requires taking into account the results shown in figure 12 b. It illustrates the deviation of the daily mean crack aperture measured in the field, dcw , against the one calculated with the model for each crackmeter, dcw_M . As can be seen, the deviation is not structured and may be interpreted as “white noise”. This is the result to be expected when the model, dcw_M , satisfactorily explains the real behaviour of the system, dcw . However, if the deviation adopts a defined trend, the model drifts away from reality. This could happen if a collapse mechanism not taken into account in the C&SM is activated. The results in figure 12 b show that, even in episodes of rapid variation of the lake water level, periods with the same deviation trend longer than 5 days did not occur. For this reason, our proposal is to identify an “anomalous” trend of dcw with regard to dcw_M when the deviation increases or decreases monotonously for 5 days or more. In the event that this should happen, warning 2 should be activated (figure 13).

6. MAP Mode 2: lake water-groundwater flow rate variation

If a collapse mechanism were mobilised, the cracking process would be expected to be boosted. Additionally, an increase in the porosity of the already highly porous internal structures (or internal conduits) existing in the conductive chimneys would occur. Therefore, the flow between the lake water and groundwater would rise in a coupled manner. Although it is unlikely, this mechanism could affect cracks different to those where crackmeters were installed. Mode 1 of the MAP would not detect this process. Nevertheless, whatever cracks were in fact mobilised, the movement would be reflected in the variation of the average flow rate between lake water and groundwater f [L/T]. This explains the interest in Mode 2 of the MAP.

In accordance with that indicated in Section 4, the analysis of the evolution of H is a good way to identify the flow rate between lake and groundwater. Knowing the geometry of SML, from data provided by CHG, the hypsometric curves plotted in figure 14 a were obtained. They relate H to V (volume of water contained in the lake) and A (inundated area). Consequently, the values of V and A can be derived from the H values recorded with the limnigraph. This way, the study of H is equivalent to the study of the conservation of water mass in the lake. This dynamic water budget [37] is defined by the ordinary differential equation:

$$\frac{dV}{dt} = (p(t) - e(t) - f(t)) \cdot A(t) + R(t) + S(t) - B(t) \quad (1)$$

which, adopting an Euler's scheme [38] with time steps of one day, may be discretised as follows:

$$V_{i+1} = V_i + (p_i - e_i - f_i) \cdot A_i + R_i + S_i - B_i \quad (2)$$

where V_i is the water volume contained in SML on day i [L^3], A_i is the average value of the inundated area of that day [L^2], p_i is the direct precipitation over the lake on the day analyzed [L], e_i is the evapotranspiration [L], R_i is the value of the run-on that reaches

the lake [L^3], S_i is the overtopping water volume entering from Salvadora Lake [L^3], and B_i is the water flowing out in the same way towards Batana Lake [L^3]. Finally, f_i [L/T] takes into account the flow through the bed of SML and the seepage through the barrages.

The value of p is known thanks to the information provided by the weather station (see figure 1 c). R may be estimated from p by means of the curve number method [39]. Moreover, the temperature data in the weather station also makes it possible to estimate the potential evapotranspiration by using the Hargreaves method [40, 41]. The value obtained was modified to take into account that the evapotranspiration recorded is mainly associated with open water evaporation. In keeping with Kohler et al. [42], e was considered to be equal to 70 % of the potential evapotranspiration. According to the RLNP-TS, there is a high correlation between S and B . When an overtopping flow occurred in Salvadora Lake ($S>0$), an overtopping was also recorded in SML ($B>0$). Therefore, provided the lack of experimental data about S and B , the difference $S-B$ was modelled instead of the two variables separately. A typical formulation based on the flow-rate over weirs may be used [43]:

$$S - B = C \cdot (H - H_0)^{3/2} \quad (3)$$

where C is a parameter to be identified. H_0 , the minimum height value at which the flow starts, was assumed to be equal to 797.5 m, the mean height at which overtopping occurs on the barrage of SML. If $H < H_0$, it will be assumed that $S=B=0$.

In addition to C , another parameter, F , was introduced in the water budget model to estimate f :

$$f = F \cdot (H - h) \quad (4)$$

This linear approach should be interpreted as a working hypothesis used to express in the simplest possible way the dependence of f on the lake water level H and the

groundwater potentiometric head h . For operational purposes, the values of h obtained with the cracking model in crackmeter 2 on the right bank may be used.

To identify the two parameters, the water depth data from 24 September 2009 to 29 September 2010 was analysed. A systematic global search by means of a grid-search algorithm [44] was applied. Table 2 shows the search space used and the optimum parameters identified. The negative value of C indicates that B was greater than S for the time analyzed, so Guadiana Alto River was a gaining stream in SML. That is consistent with the data measured by Plata et al. [27] in the period from April to November 1996. Figure 14 b shows the satisfactory fit obtained. Hence, it seems reasonable not only to accept the proposed procedure to estimate the effect of S and B , but also to work with the f model identified.

Figure 14 b also shows that the absolute deviation between the measured values, H , and the estimated values, H_M , of the lake water level was rarely greater than 0.2 m. Hence, a deviation exceeding the 85th percentile of the measurements recorded (equal to 0.059 m, see figure 14 b) may be understood as an outlier. In that case, f may not reproduce the flow rate between lake water and groundwater accurately. This could be caused by a mobilisation of the lake bed, so warning 3 should be activated (figure 13).

7. MAP Mode 3: barrage movements

From August 2009 to October 2010 (see figure 6 b), the movements of the barrage SML-Batana were monitored by means of high precision levelling. The levelling network consists of 2 bench marks or reference points, 65 levelling points, and 10 loops [16]. Perhaps the best way to distribute the error is to use a holistic approach, for example, based on the least squares method so that the closure error of the loops vanishes and the two control points are fixed [16]. It was found that, given the precision

of the levelling carried out, this approach yielded practically the same results as when the application of a conventional method of weighted distribution (according to the distance between levelling points) per loop was used. Therefore, this last procedure was adopted. As indicated in the Introduction, the error was lower than 0.1 mm.

Although such a high data density is always both desirable and advisable, it was not feasible in the long term. Moreover, this was not justified given the stability of the recordings obtained (figure 6 b). Nevertheless, monitoring the movements provides key information needed to identify a potential barrage collapse. It is thus proposed to carry out levelling measurements initially every two weeks.

As illustrated in figure 6 b, despite the relevant changes in the lake water level (figure 6 a), the variation in the settlement in two weeks was lower than 1 mm in all the points. For this reason, it is proposed to activate warning 4 if a variation in settlement over 1 mm is recorded [16]. Furthermore, when the levelling data obtained along 14 months of levelling are grouped in series of several days, few groups show a monotonous trend. It is enough to make three-days groups to obtain only a 7 % of groups of this kind. Even in those cases, the monotonous trend was not linked to a collapse mechanism, as checked in the field survey. However, it is proposed to activate warning 4 if a monotonous trend is shown for three consecutive readings at any of the levelling points (figure 13).

8. Warning, alert and model revision

As indicated in figure 13, if any of the 4 warnings were issued, the RLNP-TS should inform a group of experts, and the levelling should be accomplished on a daily basis. All the data should be sent to the group of experts, who would take charge of the monitoring, conducting an integrated analysis (IA) of all the available information.

If, on the basis of the IA, it is deduced that the warning is due to a reading error or an inaccurate interpretation of the information, alert level 0 should be maintained (figure 13). The lakes should be open for use in keeping with the current recommendations in RLNP.

On the other hand, if no errors are found, but it is not possible to identify any trend that would indicate a collapse development in either Mode 2 or Mode 3, alert level 1 should be applied (figure 13). In this case, it is advised to forbid access to SML and Batana Lake and the third of the area of Colgada Lake located next to Batana Lake (figure 2). This is a conservative option. However, a possible collapse cannot be excluded, even with no evidence of it. Therefore, actions should be taken for the sake of safety, in keeping with the study of the flood analysis carried out by Seco and Sarasúa [17].

Finally, if after conducting the IA, a trend is identified that might be associated with collapse movements, alert level 2 should be activated (figure 13). In this case SM, Batana and Colgada Lakes will be closed to the public.

While warnings 1 or 2 are in effect, the group of experts should conduct an IA on a daily basis to review the alert level that should be applied. When the level returns to 0, the RLNP-TS should recover the responsibility for monitoring and alert.

It is worthy of note that the progressive mobilisation trend of a free collapse is not compatible with the alternate closing-opening pattern experienced by the cracks owing to the variation of h and H (figure 6 a). For this reason, warning 1 could in some cases be attributed to an error in data reading or equipment malfunction. Similarly, the outliers that give rise to warning 2 can indicate that the used parameters need to be revised. Therefore, warning 2 will always require the revision of the cracking model. Moreover, the group of experts should check the model every 6 months, even if no warning occurred. The new information may be used to improve the model.

The review of warning 3 must be carried out with special care. The identification problem described in Section 6 should be solved again, using all the available data on H . It must be taken into account whether or not the warning is associated with a change in the hydraulic behaviour of the lake.

It is important to note that, after one year of study and monitoring, during which C&SM has become consolidated, no mobilisation trends were detected. For the sake of caution, and bearing in mind that the water level reached historical maximums, alert level 2 was applied during the months of January and February 2010. However, barring the occurrence of small local collapse incidents associated with the erosion caused by overtopping flows, safety was not jeopardised.

9. Conclusions

A plausible “column and slab” model (C&SM) for the cracking process observed on both banks of the Santos Morcillo Lake (SML) near the barrage separating it from Batana Lake [18] provides the basis for the definition of a monitoring and alert system. Although the model proved to be robust in the validation exercises carried out (see figure 11), it is not exempt from uncertainty. Therefore, it is advisable to develop a Monitoring and Alert Procedure (MAP) to manage SML in safe conditions.

The MAP can be largely interpreted as a test of dynamic contrast or validation of the C&SM. Thus, the crackmeter data is the MAP’s cornerstone. The crack aperture evolution d_{cw} should be processed daily by the Ruidera Lakes Natural Park Technical Staff (RLNP-TS). When a noticeable discrepancy appears between the model predictions and the aperture readings, a warning should be activated.

To calculate the model predictions of the crack aperture, the C&SM uses the readings of the lake water level H [18]. Thus, the monitoring of H in SML should be continued.

Given the effort made to retrieve this information, more output could be obtained if it were used to analyse the water mass balance in the lake (Section 6). This way, independent and complementary information to the crack aperture becomes available to identify the potential development of mobilisation mechanisms. If the daily dynamic water budget predicted values of H inconsistent with the experimental ones, the system should be carefully revised, and a warning should be activated.

The information in dcw and H is linked mainly to the behaviour of the bed of SML. Thus, it would be useful to have additional information on the performance of the barrage between SML and Batana Lake. A relatively simple and precise way (reading precision of 0.1 mm) is to continue the levelling survey set up in the study phase. A warning should be activated if a rapid movement of a levelling point is observed or there is a monotonous trend that could indicate some kind of mobilisation.

If a warning were activated (figure 13), the RLNP-TS should contact the group of experts, who would carry out an integrated analysis of all the available information. The alert level would then be changed to 1 or 2. Level 1 should be issued when mobilisation cannot be identified so it is not certain whether mobilisation exists or not. In this case, Santos Morcillo, Batana and the third of Colgada Lake located next to Batana Lake should be closed to public access. Alert level 2 should be issued when mobilisation is detected. Then, the access of the rest of Colgada Lake would also be prohibited. The restriction levels are based on a flood analysis carried out by Seco and Sarasúa [17] for the administrations responsible for the management of RLNP.

The group of experts, the RLNP-TS and Castilla-La Mancha Regional Government should, at all times, coordinate with the agencies responsible for taking action in the event damage should occur (Civil Protection Services and the Civil Guard) so that good safety conditions are maintained without causing community alarm.

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Figures

Figure 1. (a) Situation of the Campo de Montiel aquifer (dark grey) in the Upper Guadiana Basin (light grey). (b) Location of Ruidera Lakes Natural Park in the Campo

de Montiel aquifer. (c) Group of lakes, situation of SML (circle), and location of the weather station (WS) at Ruidera Lakes Natural Park. Adapted from Navarro et al. [18]

Figure 2. General view of Salvadora Lake (SL), Santos Morcillo Lake (SML), Batana Lake (BL), Colgada Lake (CL) and flow direction (FD); location of the electronic limnigraph (D), barometer (B) and Santa Elena Hydroelectric Power Station (HPS).

Figure 3. Map showing the location of the 65 levelling points (triangles), cracks (white lines), and tomographic section A-A' in SML. The levelling points referred in figure 6 b are highlighted (black triangles).

Figure 4. (a) Cracks, crackmeters and sinkhole (S) in the right bank. (b) Cracks and crackmeters in the left bank.

Figure 5. Underwater image of an installed crackmeter.

Figure 6. (a) Evolution of the aperture d_{cw} of the cracks on both banks and the water level H in SML (b) Evolution of the increment of the vertical movements dz detected in 7 levelling points of the right abutment of the barrage SML–Batana (see figure 3).

Figure 7. (a) Hydrogeological transmissivity and geological structure of Campo de Montiel aquifer (adapted from [18]). (b) Longitudinal cross section along the Guadiana Alto Valley in RLNP (adapted from [22]) and plan view of the lakes out of scale.

Figure 8. (a) Example (section A-A', figure 3) of the results of the electrical tomography survey carried out in Santos Morcillo Lake. The box highlights one of the conductive chimneys identified. (b) Diagram of the configuration of the materials around the cracks: (1) Mesozoic material, (2) buried (old) stromatolite constructions, (3) marginal stromatolite, (4) carbonate sands, (5) lime muds, (6) current functional crusting surface, (7) cracks, (8) current highest lake water level, (9) old highest lake water level (prior to the beginning of this century). The dashed line represents the zone considered in figures 10 a. Adapted from Navarro et al. [18].

Figure 9. Conduit located at the bottom of the sinkhole (see figure 4 a)

Figure 10.(a) Model of the column and slab (see figure 7 b) interaction before cracking. (b) Model of the column and slab interaction after cracking. Adapted from Navarro et al. [18].

Figure 11. Variation of the crack width, dcw , measured with crackmeters 2, 3 and 4 (see figures 4 a and b) and computed settlements, ds . (a) Right bank. (b) Left bank. Adapted from Navarro et al. [18].

Figure 12. (a) Evolution of the coefficient of variation (daily standard deviation with regard to the maximum average daily value on the right bank). (b) Variation of the deviation of the crack aperture measured in the field, dcw , from the one calculated with the model, dcw_M , for each crackmeter.

Figure 13. Flow chart of the monitoring and alert protocol (MAP). dcw is the crack aperture evolution, H is the lake water level, p is the precipitation, T is the temperature and dz is the vertical movement. CV indicates the coefficient of variation (see figure 12). dcw_M and H_M are, respectively, the values of the crack aperture and the lake water level computed by using the C&SM.

Figure 14. (a) Hypsometric curves of SML. (b) Field (H) and model (H_M) values, and absolute deviation between them ($|H - H_M|$).

Tables

Table 1. Mechanical parameters used in the column and slab model to characterise the column sediments and the crust. Adapted from [18].

Table 2: Parameters of the hydraulic model defined by equations 3 and 4.

Column oedometric modulus (MPa)	10
Crust Young's modulus (MPa)	550
Crust Poisson's modulus	0.3
Crust compressive strength (MPa)	4.5
Crust tensile strength (MPa)	0.92

Table 1

	Optimum	Maximum	Minimum
$C \text{ (m}^{3/2}/\text{d)}$	-25425	-15000	-30000
$F \text{ (1/d)}$	1460	2000	500

Table 2

c)

b)

a)

Figure 2

Figure 5

Figure 8

a)

b)

Figure 11

a)

b)