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Conditioning factors in flooding of karstic poljes—the case of the Zafarraya polje (South Spain)

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Abstract

The Zafarraya polje undergoes periodical flooding, of which the last episode (1996–1997) was analysed in detail on this paper. On the basis of the retention curves of the two lakes that formed in the northwestern and southwestern sectors, we calculated the total infiltration capacity of the polje to have a maximum value of 3–3.5 m^3/s and so we infer that when the flow of the Arroyo de la Madre exceeds this figure, there will be a risk of flooding in the polje. We also propose a model for the 1996 flood that can be extended to other similar occurrences in this and other poljes where we can establish the role played by groundwater and surface water during this flood. In response to the heavy precipitation, the flow of the Arroyo de la Madre rose abruptly, exceeding the infiltration capacity of the main swallow holes on the polje, causing first the northern lake and then the southern lake to form with only surface water supply. The water table of the karst aquifer rose sharply, reaching a situation of equilibrium between the level in the lakes and the water table in this sector of the karst aquifer that prevented infiltration through the swallow holes. In the case of the southern lake, there were even cases of swallow holes that began to operate as estavelles. During this phase of maximum flooding, one single lake was present, which was divided into two once more when the water table of the karst aquifer in the polje sector began to fall and surface supply also began to decrease.

Keywords: Karst; Polje; Flooding; Swallow hole; Estavelle

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1. Introduction

Geologically speaking, a polje is a large, karstic, closed depression with a flat bottom often slightly tilted towards the drainage point and surrounded by steep walls and prone to intermittent flooding (Gams, 1978; Prohic et al., 1998). Poljes tend to be areas used for settlement and economic development; they are often the only arable areas in karstic regions where bare rock outcrops predominate with no soil formation. In this sense, polje flooding is poorly understood and requires greater study in order to mitigate its socio-economic impact.

The first step towards taking preventive measures against this phenomenon should be to establish the dynamics and determine the cause of the flooding, which may be an unusual high supply of surface water and/or groundwater.

This study concerns the Zafarraya polje in the province of Granada in southern Spain (Fig. 1). Three main towns are located on this polje (Zafarraya, Ventas de Zafarraya and El

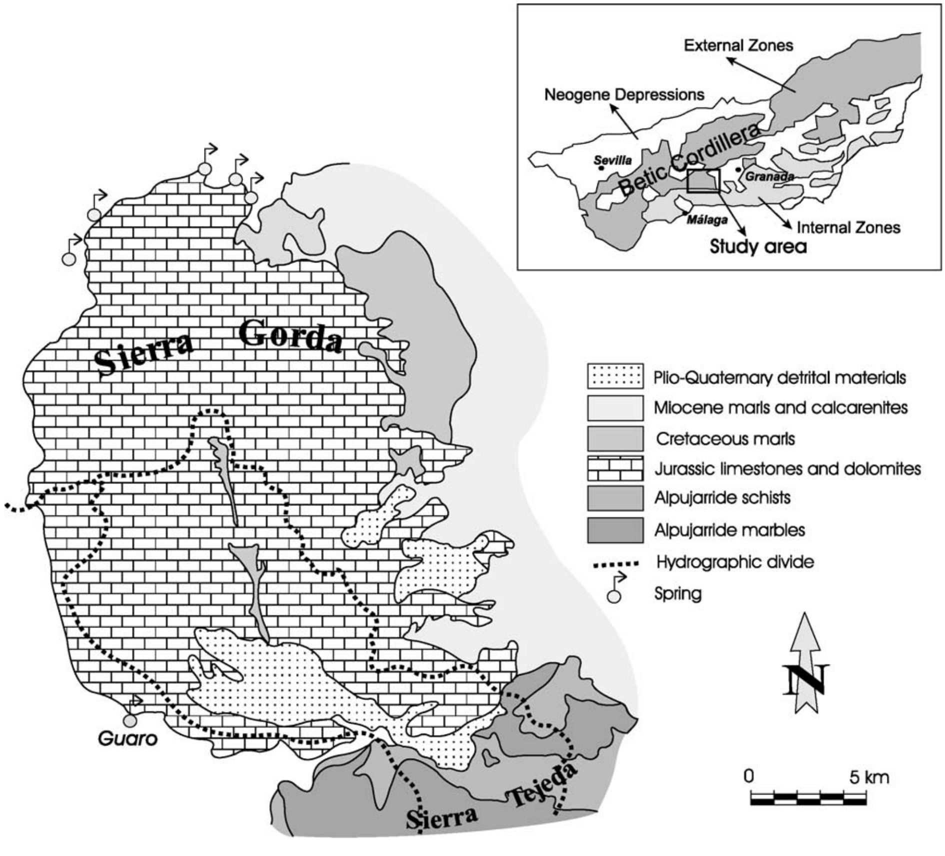

Fig. 1. Geological setting of the study area.

Almendral, Fig. 2) with over 2000 ha of arable land that provides a high income per capita for the inhabitants of the region.

Flooding of the Zafarraya polje normally coincides with periods of heavy rain. We have only been able to find written records of five important floods in the last 100 years, the most recent of which is the subject of this study.

- December 1891–January 1892 (Moreno, 1987), causing the isolation of two towns in the polje (Zafarraya and El Almendral). This may have been the largest single flood in living memory when the water level must have reached a maximum depth of 11 m (898 m a.s.l.) and must have lasted some time since the inhabitants of the region had to build a raft to move from one town to the other.
- 1957 (Moreno, 1987), when the water flooded 400 ha of farmland.
- December 1962–January 1963 (Hidalgo, 1974), when the water reached approximately a maximum depth of 7 m (894 m a.s.l.).
- January 1970 (Moreno-Garzón, 1972), a maximum depth of 4 m (891 m a.s.l.).
- December 1996–January 1997, maximum depth reached of 5 m (892 m a.s.l.) and one lake was formed, flooding 500 ha of farmland.

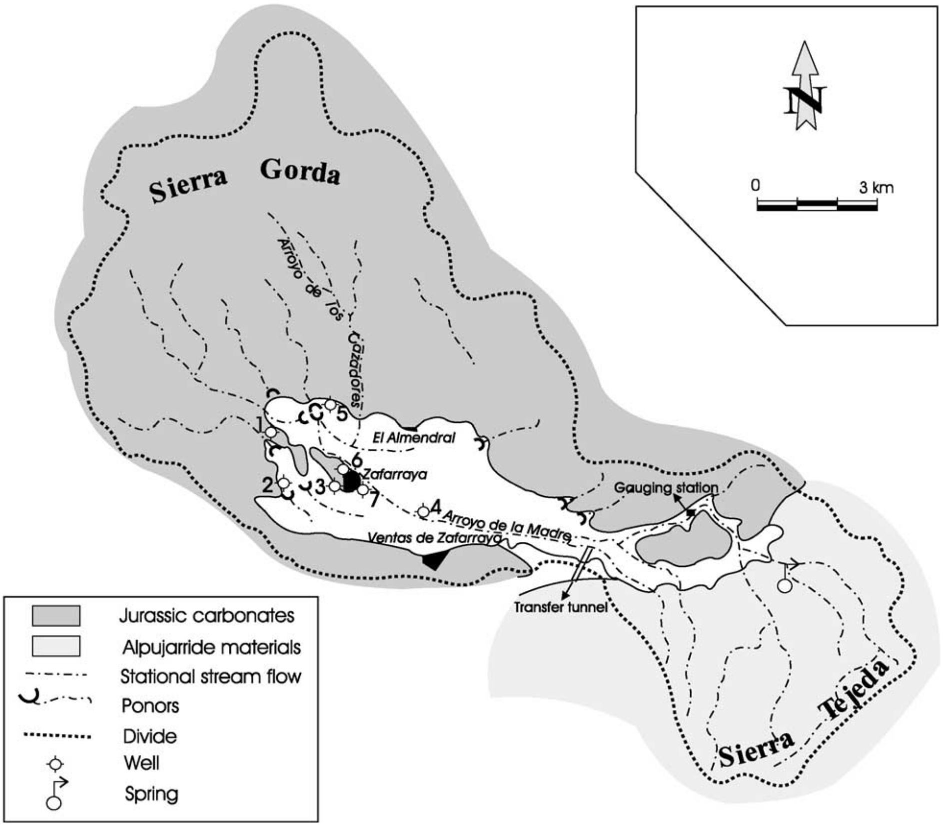

Fig. 2. Catchment and drainage pattern of Zafarraya polje. Location of control points in the polje.

Between the 1970 and 1996 floods, small, short-lasting swamping of the polje sinks occurred, which we did not consider to have reached the category of flooding.

The main aim of this study is to describe the flooding in a karstic polje. We therefore undertook a quantitative characterisation of the hydrological process in the Zafarraya polje on the basis of the data available from the last flood in 1996 and determined volumes of flood water as well as drainage rates of the polje. The latter parameter is vital in taking preventive action. Finally, we examined the influence of both surface water and groundwater on the dynamics of the flooding process.

2. Geological context

The Zafarraya polje is a tectonic, karstic depression situated in the limestone massif of Sierra Gorda, in the central sector of the Betic Cordillera, and more precisely, in the Subbetic Zone of the External Zones or South Iberian Palaeomargin (Fig. 1). This massif consists of intensely fractured Early Jurassic limestones and dolostones over 1000 m thick (Pistre et al., 1999). Coinciding with the Zafarraya polje, a sedimentary filling lies on these Mesozoic carbonates. The base of this filling consists of Upper Miocene calcarenites and marls. Detrital Quaternary sediments overlie the latter and are the results of, on one hand, sediment supply from the surrounding river courses and, on the other, decalcification clay deposits from carbonate dissolution. The maximum thickness of the sedimentary filling of the Zafarraya polje is found in the southern sector, near Ventas de Zafarraya (over 200 m), and decreasing towards the margins, with less than 10 m in the northwestern sector.

From the geomorphological point of view, the Zafarraya polje is a large karstic landform situated in a mountainous region presenting a broadly developed, typically Mediterranean exokarstic landscape. Despite the presence of numerous lapiés, corrosional plains, canyons and dry valleys, the most characteristic features of this karst are the extensive small doline fields (over 1600 have been mapped, Pezzi, 1977) and the large poljes. Zafarraya is the largest active polje, i.e., with endorrheic or internal drainage through swallow holes (ponors) and subjected to periodic flooding in times of heavy rain.

Throughout its evolution, the Zafarraya polje has changed from being a tectonic depression with marine sedimentation in the Upper Miocene to an exorrheic fluvial basin with little sedimentation during the Uppermost Miocene, Pliocene and Lower Pleistocene. Its present endorrheic operation is, therefore, relatively recent, approximately since the Middle to Upper Pleistocene due to the neotectonic subsidence that is active in the polje (Lhenaff, 1977, 1986; López-Chicano, 1995).

3. Description of the Zafarraya polje

The Zafarraya polje is one of the main poljes in the Iberian Peninsula and the largest (22 km^2) in the Betic Cordillera. It consists of a closed, elongated depression lying WNW–ESE, 10 km in length and 3.5 km at its widest point, with the flat bottom slightly inclined westwards at a mean slope of 0.4% (Fig. 2). It is traversed by the Arroyo de la

Madre, a seasonal river channel rising on the Sierra Tejeda (southeastern sector) and flowing into the ponors located at the northwestern edge of the depression, at a height of 887 m a.s.l. Other ponors located to the southwest of Zafarraya collect the surface runoff sporadically occurring on the southwestern edge of the polje. The main ponors are alluvial swallow holes (Milanovic, 1981), in which the carbonated rocks scarcely outcrop and are located beneath unconsolidated Quaternary alluvial deposits. Small collapses occur in the detrital sediments around these filtration points causing pipes ranging in depth from several centimetres to several metres. Only one of the ponors in the southwestern sector of the polje consists of large blocks of rock and open cracks (López-Chicano et al., 1996).

Within the 151 km^2 of the basin supplying the polje, there are several subsidiary endorrheic subbasins, the largest and most important of which is the Arroyo de la Madre basin. Some subbasins share the same swallow hole, usually at the end of Arroyo de la Madre. This is the case of the streams in the northwestern sector, which, together with Arroyo de la Madre, have sporadic flow toward the ponors located northwest of Zafarraya, while the ponors to the southwest of the town collect the flows from the northern margin of the Sierra de Alhama, on the southwestern edge of the polje (Fig. 2).

About 98 km^2 (65%) of the total area of the basin lie on the Jurassic limestone belonging to the Sierra Gorda aquifer, 22 km^2 (15%) are alluvial deposits in hydraulic connection with the karst aquifer of Sierra Gorda, and the remaining 31 km^2 (20%) correspond to carbonated and metapelitic materials of Sierra Tejeda, which forms an independent hydrogeological unit (Fig. 1).

The high permeability of the intensely karstified, carbonate rocks allows high infiltration of surface water. Thus, only Madre and Cazadores can be considered legitimate seasonal streams, the other tributaries being dry valleys. These two streams not only have larger drainage areas but also flow locally over impermeable rocks allowing high surface runoff. Arroyo de la Madre is even supplied by springs draining the Sierra Tejeda aquifer that guarantee some permanent flow (Fig. 2). Simultaneous measurements at different points show that this stream loses large amounts of flow (60%) through infiltration in the alluvial deposits of the eastern sector of the polje (López-Chicano et al., 1996).

4. Hydrological and hydrogeological operation

Two independent hydrogeological units can be distinguished. The first is the detrital Quaternary filling of the Zafarraya polje, constituting an unconfined intergranular aquifer, and the second is an unconfined karst aquifer made up of the Jurassic limestones and dolostones of Sierra Gorda (Fig. 1).

The Sierra Gorda aquifer is one of the most important carbonate aquifers in southern Spain both in area (almost 300 km^2) and in resources (over 130×10^6 m^3 year^{-1}, López-Chicano, 1992). The limestone and dolostones are almost completely lacking in vegetation and soil cover, meaning that the infiltration rate in this bare karst is almost 50% (López-Chicano, 1992). The main recharge of the aquifer comes, therefore, from direct infiltration of rain (96.4%), with a mean annual rainfall of 840 mm, whereas indirect recharge from stream flow (Arroyo de la Madre) is only 3.6%. Almost 95% of the drainage of this aquifer occurs through 20 or so springs on the northern margin (Fig. 1) at an altitude of approximately 500 m a.s.l. The rest of the natural discharge of the hydrological system takes place through a number of overflow type springs at Guaro on the southern margin at an altitude of approximately 700 m a.s.l., which are only operative when the water table reaches high level in the rainy season.

Adjacent to a polje, karst aquifers show high annual piezometric variation (Bonacci and Zivaljevic, 1993). Fig. 3C shows the rise of more than 150 m at points 1, 2 and 3 at the end of 1995. This was, in fact, an extreme situation as it occurred during a shift from a very dry period to a very wet one and the change in level was therefore very high. Seventy-five to one hundred metres can be taken as normal variations between dry and wet seasons. This graph also shows that, while the rise in level is rapid (100 m in 5 days is possible), fall is slower, taking more than 6 months.

Detailed observation of the evolution of the water table at point 3, where daily data are available, shows that the water level recessions of several years present three segments of differing slope but the slope remains the same during the different episodes (Fig. 4A). The

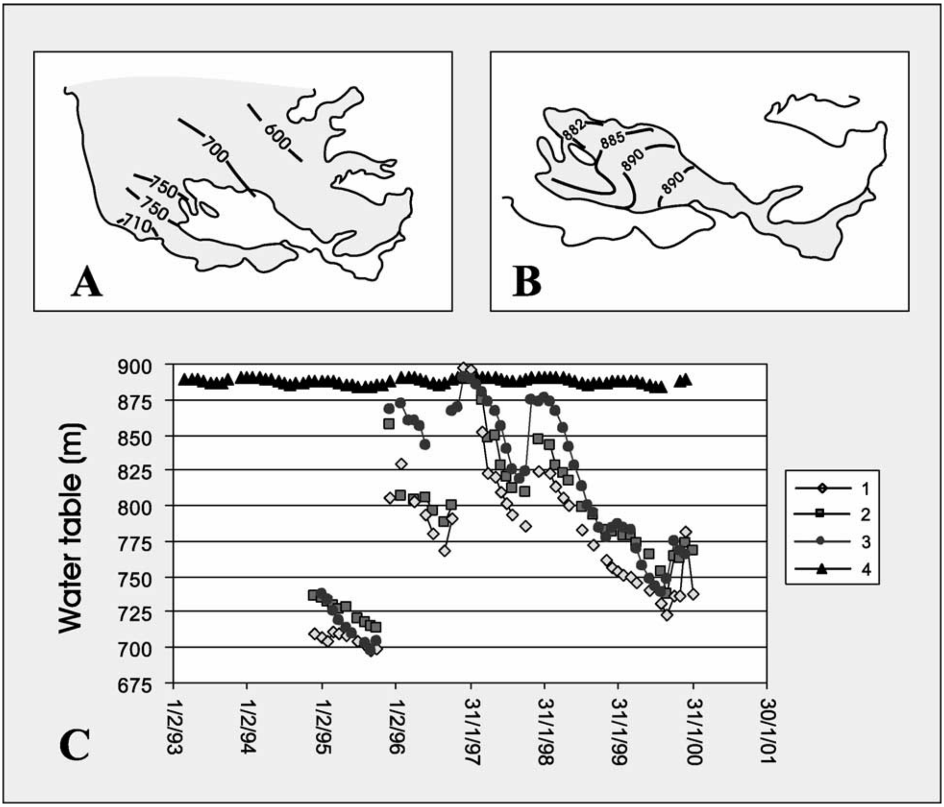

Fig. 3. (A) Water table map of the Sierra Gorda karst aquifer adjacent to the polje in November 1989 (López-Chicano and Pulido-Bosch, 1989). (B) Water table map of alluvial aquifer in July 1982 (Ollero and García, 1983). (C) Water table evolution at three wells in the karst aquifer (1, 2 and 3) and one well in the alluvial aquifer (4).

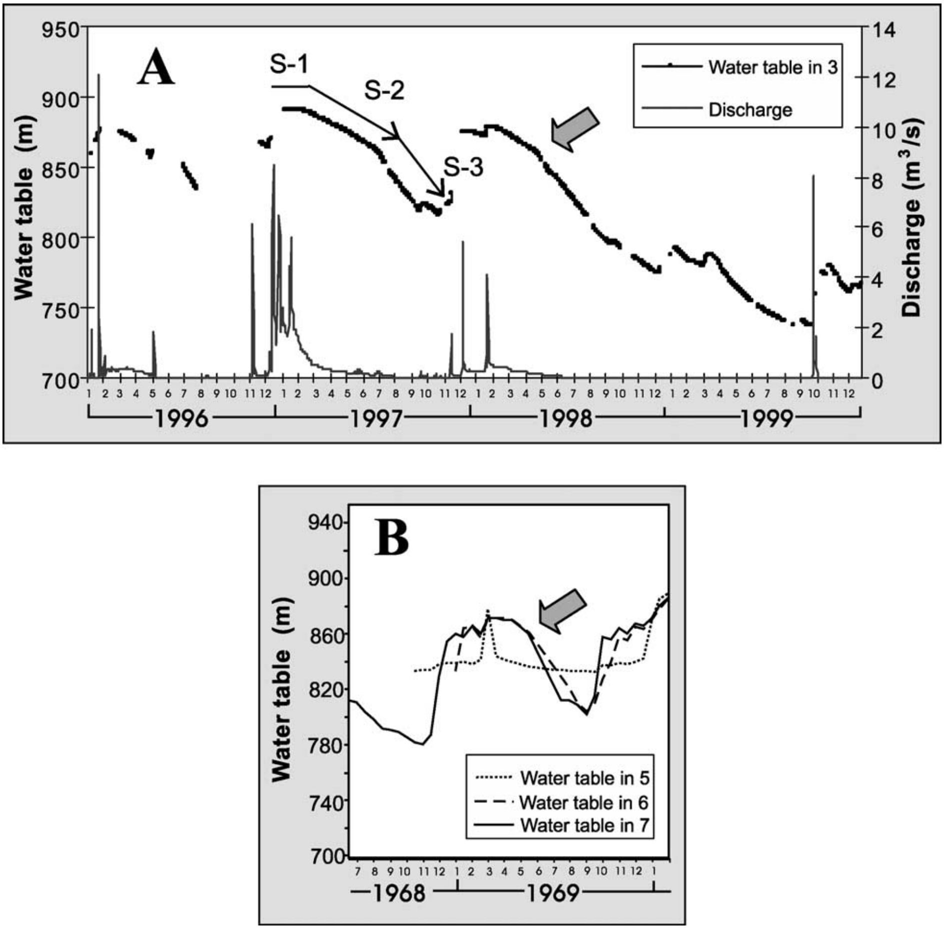

Fig. 4. (A) Evolution of water table at point 3 of karst aquifer and discharge in the Arroyo de la Madre. The arrow marks the change of slope between segments of different slope on the descent curve of the water table, invariably at the same altitude of approximately 860 m a.s.l. (B) Evolution of water table at points 5, 6 and 7 of karst aquifer from Hidalgo (1974).

slope of the fall curve is determined by the recharge/discharge ratio of the aquifer or changes in storage capacity.

Discharge is a parameter that varies little, as the flow from the springs remains fairly constant, apart from exceptions such as the Guaro spring, which can have flows of up to 3 m^3/s and at other times be dry. We therefore mainly relate the different segments of the descent curve with recharge variations or changes in the aquifer's storage coefficient.

The first, short lasting segment has practically zero slope, indicating that the level remains constant over a short period. In these circumstances, recharge of the aquifer should be equal to discharge, as the aquifer is supplied by surface water through the swallow holes. Fig. 4A, representing the water table trend at well 3 in the karst aquifer and the flow of Arroyo de la Madre, shows that the level does indeed begin to fall when the flow of the Arroyo drops below 1 m^3/s.

The passage from second to third segment, occurring during the dry season, involves a significant increase in slope, meaning that the water table drops more quickly. It is important to indicate that this change occurs at the same altitude, around 860 m a.s.l., and when compared with former data by Hidalgo (1974), it also presents the same change in slope at exactly the same height and at other points in the same sector of the karst aquifer (Fig. 4B). This can probably be explained by a change in storage coefficient of the karst aquifer in this zone close to Zafarraya. The storage coefficient is higher up to this altitude and so a similar discharge produces a slower drop in level than at greater depth. This drastic change in storage coefficient suggests a different degree of karstification of the aquifer on the vertical plane, probably related to a karstification palaeolevel near the surface that would be reflected in a less pronounced drop in the water table (second segment).

The spatial distribution of the water table can only be determined in a small area of the karst aquifer, as no more data are available through lack of wells or observation points. The karstic water table map (Fig. 3A) was made using measurements from November 1989, which was the end of the dry season that year. Although the date itself is not very representative, it is interesting to note the permanent presence of a water table high near Zafarraya, which divides groundwater flow in the aquifer northward and southward. This high shifts slightly northward during the wet season and indicates a preferential recharge zone in the karst aquifer explained by the infiltration of the Arroyo de la Madre flow through the swallow holes, whose location coincides with the water table high, and supply from the detrital aquifer (the water table of this aquifer is at its lowest in this area).

The mean annual recharge (around 10×10^6 m^3 $year^{-1}$, Ollero and García-García, 1983; López-Chicano, 1992) of the alluvial aquifer in the polje is considerably less than that of the karstic one. Transmissivity varies from 20 to 200 m^2/day and storage coefficient is around 13%. The main recharge occurs through direct infiltration of rainwater on the polje surface and surface runoff. Discharge takes place underground towards the karst aquifer of Sierra Gorda.

The water table of the alluvial aquifer (line 4 of Fig. 3C) is near the surface (the altitude of the surface of the polje ranges from 887 to 1000 m) and seasonal variations are much less pronounced (less than 10 m) than those of the karst aquifer. The water table map shown in Fig. 3B was made using measurements carried out in July 1982 at over a hundred points on the detrital aquifer. Once again, the date is not representative but it does allow us to see that groundwater flow is westward, with discharge across the northwestern margin of the polje (Fig. 3B).

The two aquifers have different water tables and so we can speak of two independent systems. In fact, much of the bottom of the detrital aquifer is isolated from the karst aquifer by impermeable Miocene materials. However, there is normal supply from the detrital to the karst aquifer across the contact zones between permeable detrital rocks and the limestones of the Sierra Gorda aquifer, depending on a higher hydraulic head in the detrital aquifer. This flow can invert, with discharge from the karst aquifer to the detrital if the hydraulic head is higher in the former, which is what tends to occur during large floods (Fig. 3C).

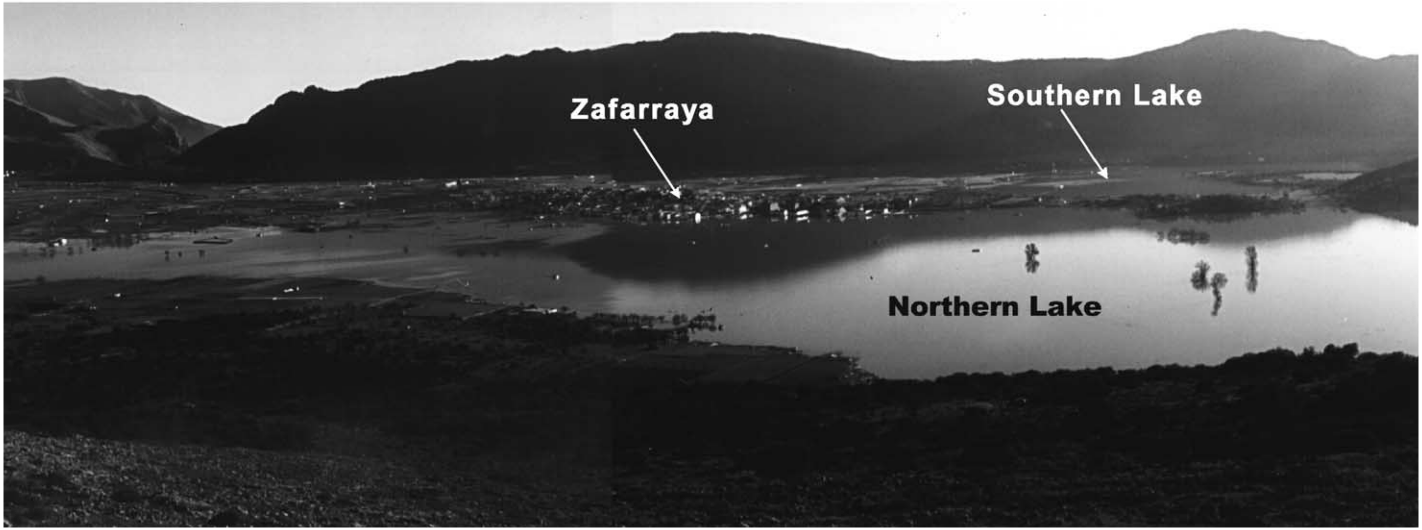

Fig. 5. Lake formed during the 1996–1997 flood of the Zafarraya polje. The photograph was taken on January 5, 1997, when flooding was highest.

5. Flooding of the polje (1996)

Although the 1996 flood was not the worst in recent times, as pointed out above, it did, however, have a catastrophic effect on the area, calculated at around 600 million pesetas (about 3.5 million euros): a considerable loss for a rural economy with few inhabitants.

After a prolonged drought of some 5 years, 1995–1996 was the first hydrological year with heavy precipitation (1620 mm, when the annual mean is 950 mm), which caused a rise of up to 175 m in the water table of the Sierra Gorda karst aquifer (Fig. 3C), only 11 m below the lowest swallow holes (887 m a.s.l.). In 1996–1997, precipitation was not so intense as the previous year but as the water table was already quite high and since there was no water deficit in the unsaturated zone, the reaction was flooding of the polje in the form of two independent lakes at first in the western sector, which later joined to become one single lake. We now give a detailed description of the order of events in the 1996–1997 flood:

- November 12, 1996: 362 mm of precipitation fell in only 7 days. The ponors in the northwestern sector collapsed and resulting ephemeral flooding (ponding) lasted approximately 8 days.
- December 18, 1996: Precipitation on this occasion was also high but not so much as in the previous episode—247 mm in 7 days. The main flood began in the northwestern sector. A second lake then appeared in the southwestern sector, south of Zafarraya. Flooding lasted approximately 75 days.
- January 5, 1997: The two lakes joined to form a single lake for a few days and the highest level was recorded reaching 892 m (Fig. 5). The levels of the lakes varied

Fig. 6. Panoramic view of the Zafarraya polje during the last phase of flooding, when the northern lake was much smaller than the southern.

depending on rainfall until they began to fall at different rates at the beginning of February.

• March 6, 1997: The level of the northern lake had fallen to the altitude of the ponors. The southern lake remained present (Fig. 6).

• March 15, 1997: The southern lake had practically disappeared, the level being measured at 888.67 m a.s.l.

We now examine the discharge of the Arroyo de la Madre, the levels of the two lakes and the water table of karst aquifer throughout the flood.

6. Methodology

The initial data on which the flood process was studied were as follows:

- Discharge in the Arroyo de la Madre measured at a gauging station in the eastern sector of the polje (Fig. 2), where mean daily flow values were recorded.
- Levels of the two lakes, measured using a theodolite giving centimetre precision.
- Water table at well 3, also levelled, using the continuous record provided by a limnigraph of the Confederación Hidrográfica del Sur, also levelled with centimetre precision.

7. Arroyo de la Madre discharge

Fig. 7 shows the flows of the Arroyo de la Madre and precipitation measured at a meteorological station inside the polje. An initial observation is that the lag time of the

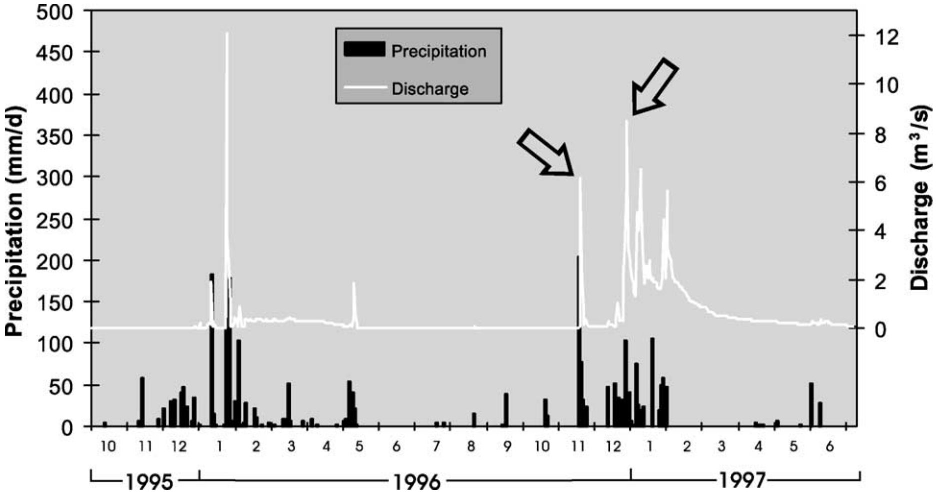

Fig. 7. Arroyo de la Madre discharge in relation to daily precipitation. Arrows show that maximum flow values occurred practically 1 day after maximum precipitation values.

flow to precipitation is very short, showing a peak practically the day after heavy precipitation. A clear depletion curve can also be seen during February and March, when there was no precipitation, resulting from groundwater supply from Sierra Tejeda (Fig. 2).

It is noticeable that in a 3-month period, flows higher than 4 m^3/s were measured over 10 days at least, particularly if we consider that the mean flow of the stream in the last 15 years has been 160 l/s.

Regarding distribution in time, an isolated maximum flow was recorded on and around November 12 (first arrow in Fig. 7), which was responsible for ponding at this time. Flows later dropped until abundant precipitation made them grow once more, reaching an absolute maximum of 8.5 m^3/s on December 21 (second arrow in Fig. 7), causing a considerable increase of the area flooded. The high flow remained until approximately January 28 when recession began.

8. Retention volume

The data used for this part of the study correspond to the emptying of the lakes since continuous data on filling are not available.

A retention curve was made for each lake in order to determine the volume of water stored according to the height of the water levels. For this purpose, we used a 1:10 000 scale topographic map and measured the basin surface with a planimeter for different levels of filling. The water volume for each interval of topographic contour lines was represented as the volume of a truncated cone. The result obtained is shown in Fig. 8, where it can be seen that the northern lake retained almost three times more water than the southern one.

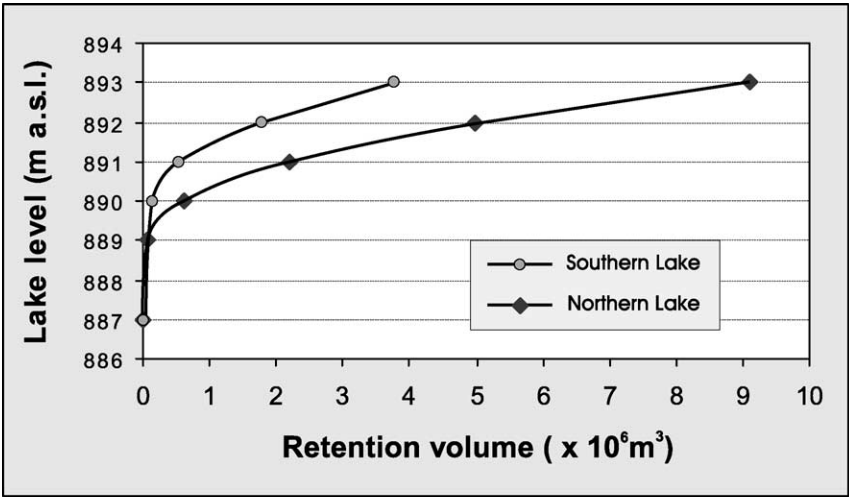

Fig. 8. Retention volume curves in northern and southern lakes.

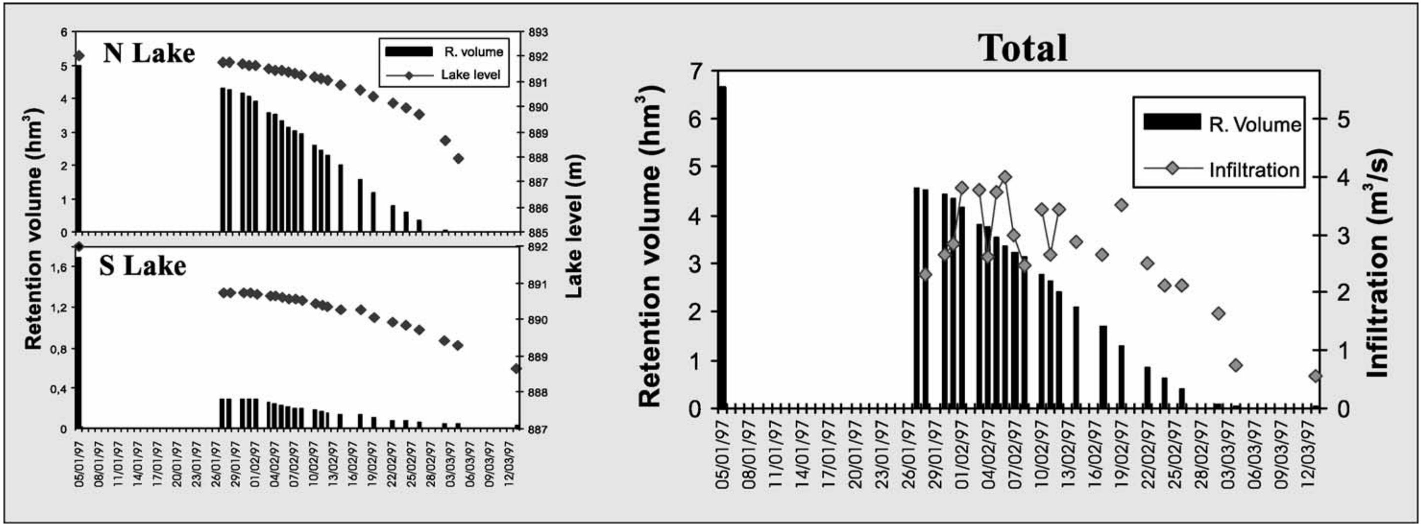

Fig. 9. Retention volume during emptying of each lake and total retention volume (considering both lakes) and the total infiltration rate of the polje.

Having drawn up the retention curves, we were then able to calculate the evolution of the water really retained in each lake over a period of time (Fig. 9). At its highest level (892 m a.s.l.), the northern lake had a maximum of 5 million m^3. This volume remained relatively stable until the beginning of February, when a rapid fall was recorded (136 000 m^3/day), coinciding with the decrease in flow of the Arroyo de la Madre. The southern lake reached a maximum volume of just 1.7 million m^3, corresponding to an altitude of 892 m a.s.l. The different operation of the two lakes can be seen in the fact that the decrease in water volume was slower in the southern lake (8300 m^3/day).

9. Calculation of swallow capacity in the polje

Calculation of the swallow capacity of the ponors in the Zafarraya polje is a rather complicated matter as it involves numerous factors (Bonacci, 1987), which, moreover, are not constant but vary with time. For example, the fact that the ponors are alluvial means that their morphology changes considerably from one flood to the next and, in addition, they can be blocked by the common practice of throwing rubbish into them or by debris transported during higher water levels. However, we think that this factor would probably have an influence at the beginning of flooding, since after a time, the ponors should be well established and cleared.

Another important factor is that, as the flooded surface grows, infiltration capacity also increases, as new ponors and permeable sectors at higher altitude come into action. In view of the foregoing, we propose an infiltration capacity for the polje as a whole and not for the ponors in particular. Values are given according to the height of the lake.

Infiltration capacity was calculated on the basis of the variation of retained water volume in the two lakes during emptying (based on the fall in water level in both lakes) plus the water entering the lakes every day (Ristic, 1976; Zibret and Simunic, 1976; Bonacci, 1987). A minimum value was taken for the latter as we only took into account the measured flow of the Arroyo de la Madre and not the other smaller flows, such as Arroyo de los Cazadores or possible groundwater supplies. Calculation was carried out for the two lakes together, as it was not known how the flow from Arroyo de la Madre was distributed between them.

Specifically, we applied the following equation:

$$I = Q - \Delta V$$

where I = infiltration rate in the two lakes, Q = Arroyo de la Madre discharge; and ΔV = variation in retention volume of the two lakes based on two consecutive measurements.

Infiltration was estimated from January 27 on, when the level in the two lakes were measured. Results are rather approximate, since, apart from the simplifications mentioned above, only one daily value was available for the flow and water level.

Fig. 9 shows that total infiltration varies in the first stage, although the mean value remains quite constant at 3–3.5 m^3/s. After March 3, the value dropped.

The most important fact to emerge from this is that when the Arroyo de la Madre's flow approaches 3.5 m^3/s, flooding is likely.

10. Relation between water table of karst aquifer and water level in the lakes

In this section, we examined in detail the relation between water table of karst aquifer in well 3 and the water level reached in the two lakes formed on the polje. We chose the data from point 3 as it is located on the water table high of the karst aquifer and its position is strategic as it lies just between the two lakes (Fig. 2) and, finally, its data record is continuous using a limnigraph.

Fig. 10 shows the water level in the northern and southern lakes and also the water table at wells 3 and 5, as this relation is of particular interest when establishing the degree of influence of groundwater on the flooding of the polje. The first significant fact is that the two lakes are quite independent since the water levels drop at different rates (Fig. 11). As of the highest altitude (892 m a.s.l.), the level drops more quickly in the southern lake than in the northern one.

The water table recorded at point 3, i.e., in the area of the karst aquifer where maximum water table values were recorded, stayed between the levels of the two lakes at the beginning of the measurement period (beginning of level fall), i.e., lower than the level of the northern lake and higher than the level of the southern lake, although it was some 4 m above the height of the sink holes in the northwestern sector. From mid February, the water table fell below the level in both lakes.

11. Flood dynamics

In order to determine the role played by surface water and groundwater in the floods on the Zafarraya polje, we must examine the relation between the water table of the karst aquifer and the water level in the lakes. When the water table level is higher than that of the lakes, groundwater discharge would mainly occur through the ponors and when the level of the lakes is higher than that of the water table the opposite would occur, i.e., the ponors would act as swallow holes would recharge the aquifer.

On the basis of the data recorded mainly at well 3 (we have also taken into account other punctual data recorded at wells located on the karst aquifer and indicated in Fig. 12), the water levels in the lakes, the flows supplied by the Arroyo de la Madre and field observations, we propose a model for formation of the two lakes and their controlling factors that would be as follows:

11.1. Phase 1

The Arroyo de la Madre discharge rose abruptly (>3.5 m^3/s) as a result of abundant precipitation in a short period, exceeding the infiltration capacity of the main ponors located in the northwestern sector of the polje (Fig. 12.1). The northern lake was first to form and the water table of the karst aquifer began to rise quickly, although it did not reach

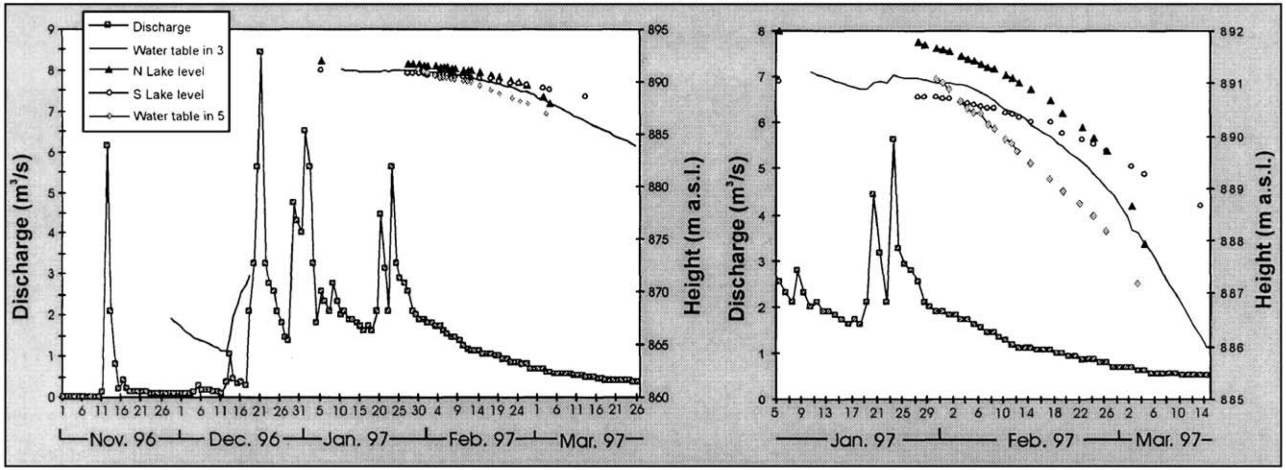

Fig. 10. Arroyo de la Madre discharge, lake levels and water table in karst aquifer throughout flooding of the Zafarraya polje.

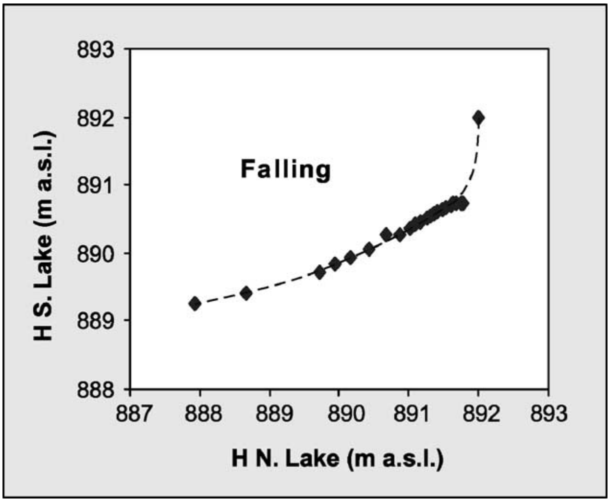

Fig. 11. Relation between southern and northern lake levels during falling.

the level of the ponors. This phase would correspond to what happened on the Zafarraya polje between the 18th and 19th of December 1996, when high peaks were recorded in the Arroyo de la Madre discharge and there was a rapid rise in the water table at point 3 (Fig. 10).

11.2. Phase 2

The northern lake grew rapidly and its level continued to rise until, at a point near the town of Zafarraya, it overflowed the dividing line between the northern and southern sectors, with transfer from the northern lake towards the southwestern sector of the polje. This caused rapid growth of the southern lake, which was smaller than the northern one, since the surface water supply here was much smaller than in the northwestern sector (Fig. 12.2). The Arroyo de la Madre flow continued to be high. Given the lack of data for the karst aquifer (the limnigraph installed in piezometer 3 became blocked due to the rapid rise in level), in order to determine the possible influence of groundwater on the flooding of the polje during this phase, we have only been able to estimate the total water supplied by the Arroyo de la Madre from December 18, 1996 (when flow began to be significant) until January 5, 1997 (when the first measurement of water level in the lakes was made). The total supply of surface water for this interval was 5.6×10^6 m^3, which is slightly less than the maximum amount of water stored in the two lakes (6.7×10^6 m^3). By this calculation, we can infer that although we have no concrete evidence of groundwater supply, in this second phase, we can say that infiltration into the ponors and the polje in general must have been negligible, as an equilibrium had been reached between the level in the northern lake and the water table of the karst aquifer in this sector (Fig. 12.2). This is a situation similar to that of the flood in late January 1970, when the water table at points 6 and 7 of

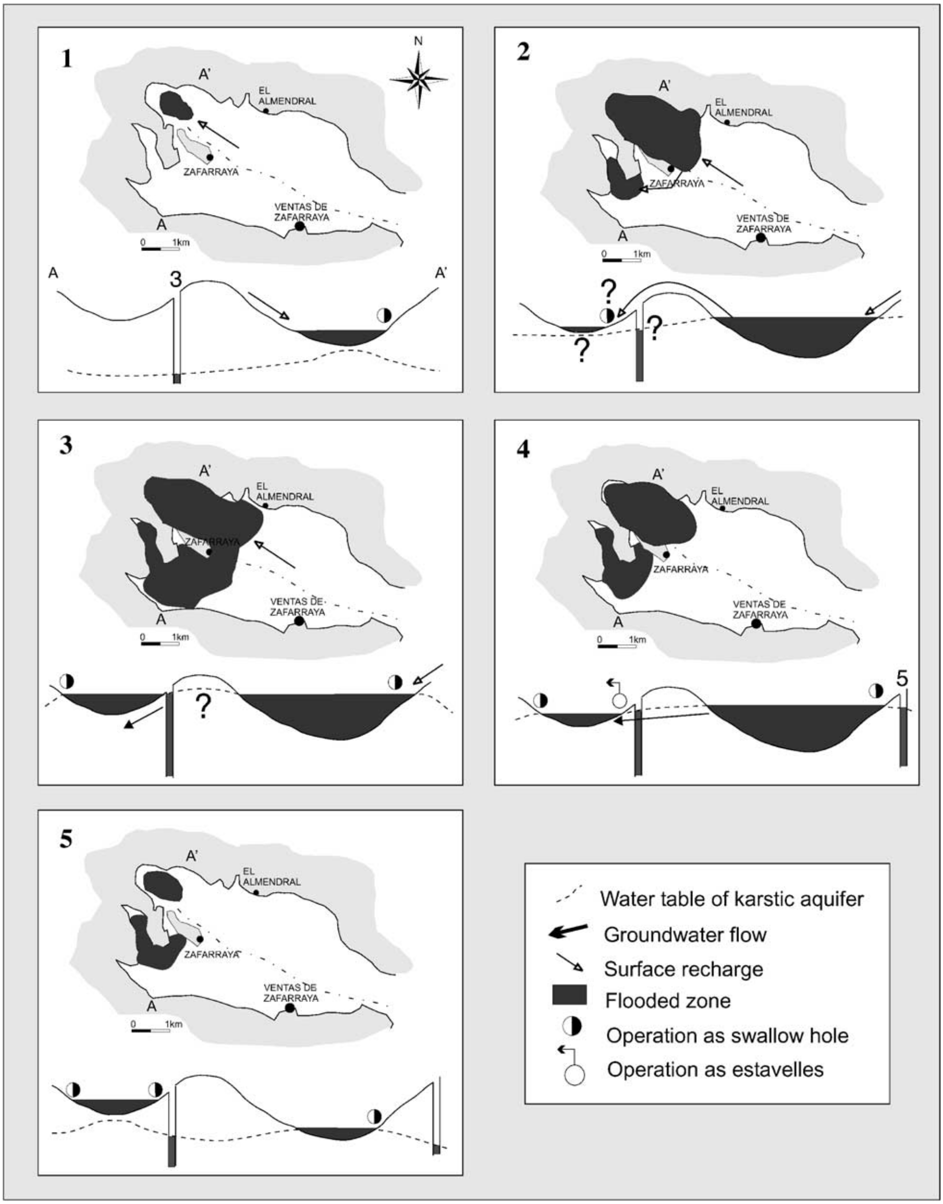

Fig. 12. Model of the 1996 flood.

the karst aquifer rose to very near the surface and in the case of well 5, the level rose to 2.4 m above the level of the ponors just before it was reached by the flood that occurred then (Fig. 4B).

11.3. Phase 3

The maximum level (892 m a.s.l.) was reached on the 5th of January, when a single lake formed that remained as such with very high, almost invariable, levels until the 10th of January (confirmed by direct field observations), which indicated equilibrium between recharge (the flow of the Arroyo de la Madre continued to be high, over 4 m^3/s on 5 consecutive days) and discharge (Fig. 12.3).

11.4. Phase 4

Precipitation decreased and, in response, depletion began in the Arroyo de la Madre flow (Fig. 10) and the single lake split once more into two separate parts. During this phase, there was groundwater flow to the southern lake (confirmed visually, see Fig. 13), since the level of the northern lake was higher than that of the southern one and there was hydraulic connection between the two across this sector of the karst aquifer, which meant that some ponors of the southwestern sector of the polje would have inverted, acting as outlets for the water (Ford and Williams, 1989). The level of the southern lake fell very slowly, indicating that there must have been some slight infiltration in some part of the lake (probably on the southern side), while groundwater continued to enter on the northern edge (Figs. 12.4 and 13), which is a situation that normally arises in the wet season, as noted by Milanovic (1981). In this phase, supply to the southern lake would have been almost only groundwater, whereas to the northern lake, it would probably only have been

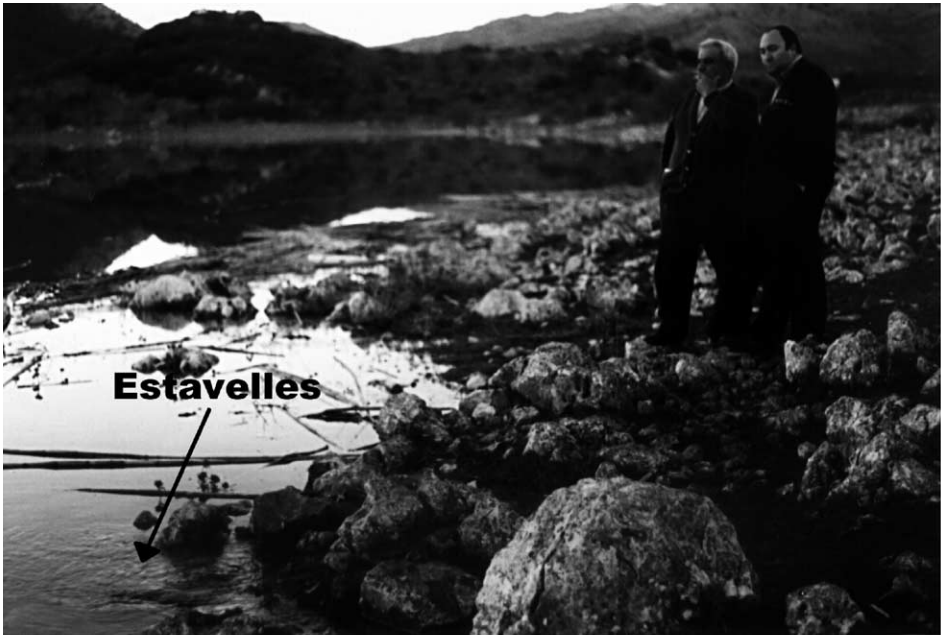

Fig. 13. Estavelle on the northern edge of the southern lake.

surface water. This situation would have lasted from the 11th of January to the 13th of February 1997 (Fig. 10).

11.5. Phase 5

The water table of karst aquifer fell below that of both lakes, cutting off groundwater supply to the southern lake, as shown by an increase in the rate of water level fall (Fig. 10). The levels continued to drop more quickly in the northern lake, which indicates that the infiltration capacity was higher in the northern lake, as was to be expected in view of the more developed swallow holes in this zone, so that on 26th of February, the level in the northern lake began to be lower than that in the southern one. This meant that the northern lake disappeared first, despite its receiving the entirety of the supply from the Arroyo de la Madre, while the southern lake remained about 25 days longer (Figs. 6 and 12.5). This phase would correspond to the events between the 13th of February and the disappearance of the last lake towards the end of March 1997.

12. Conclusions

On the basis of the detailed study of the flooding of the Zafarraya polje in 1996–1997, we can obtain specific conclusions that are valid for this polje alone, as well as other more general conclusions that could be applied to any polje. We conclude, therefore, that the maximum infiltration capacity of the Zafarraya polje is approximately 3–3.5 m^3/s, and so we infer that when the flow of the Arroyo de la Madre exceeds this figure, there will be risk of flooding in the polje. The infiltration capacity of the Zafarraya polje is not constant, but decreases parallel to the decrease in flooded surface area, as the number of ponors involved in water evacuation drops, at the same time as the permeable filter surface of the limestones and dolostones in the karst aquifer decreases.

Another more general conclusion that can be drawn from this study is that during the 1996 flood of the Zafarraya polje, the factor that brought about the main flooding was the high flow of the Arroyo de la Madre, but what made the flooding more extensive and prolonged was the intersection of the water table of the karst aquifer with the height of the main sinkholes in the polje. This is so because otherwise, the lakes formed during flooding would have disappeared quickly, as what has happened on other occasions when the water table of the karst aquifer in this sector was located at considerably more depth (such as the case of ponding on November 12, 1996), and would not have lasted several months. Groundwater was therefore mainly responsible for the flood, although we also conclude that surface water provided an important supply that increased the volume of water retained in the lakes.

From the foregoing, we can infer that the main flood risk on a polje takes place when at least 2 years of heavy precipitation occur as this implies high, persistent recharge of the karst aquifer. During this wet period, the water table rises sharply, reaching such heights that it even intersects the ponors, giving rise to flooding of the polje, as what happened during the 1969–1970 flooding of the Zafarraya polje. Actions taken in an attempt to reduce the risk of flooding on a polje should therefore aim to locally lower the water table of the karst aquifer, as it is the groundwater that causes the most catastrophic events. Surface water supplies are normally not very high, as the topographic catchments are usually made up of karstic rocks with high permeability, allowing high infiltration, but not very significant surface runoff. Surface water therefore causes small instances of flooding, as long as the evacuation capacity of the sinkholes is insufficient, but it never causes flooding of the dimensions caused by groundwater.

12.1. Measures to be taken to avoid flooding

The Borough authorities of Zafarraya undertakes periodic cleaning of the main infiltration points of the polje by excavating and removing the sediments that accumulate there every year. While this activity should be continued, certain walls and gabions built during the 1930s around the main sinkholes and along the last stretch of the course of the Arroyo de la Madre, which gave some stability to the alluvial edges, while also allowing maximum infiltration.

There is also a tunnel from the Arroyo de la Madre to another basin South of the polje and East of Ventas de Zafarraya (Fig. 2), which was built in 1990 to transfer water resources to the South and diminish the likelihood of flooding on the polje. This transfer was not operative during the 1996 flood, as the farmers of the area refuse to lose their water resources. However, this hydraulic infrastructure should be made operative at time of maximum flood risk, i.e., with high water table levels (less than 20 m deep) and surface runoff flows of around 3 m^3/s.

12.2. Other measures that could be taken

- The construction of small dams along the Arroyo de la Madre, to retain the water and recharge the underlying aquifers in the eastern sector of the polje, where the total thickness of the aeration zone is usually at least 50 m, although this would cause flooding of some arable land of high economic value. An alternative would be an artificial recharge with runoff water through wells in the karst aquifer.
- Some roughing filters should be constructed in the main streams to retain agricultural debris sediments, thus preventing the risk of debris blocking the sinks. Likewise, there should be specific regulation for the disposal of agricultural waste at areas far removed from the banks of the river flows.
- Since the position of the water table in the eastern sector of the Zafarraya polje is a fundamental factor in the occurrence of large-scale flooding over an extended period of time, another significant preventive action would be to exploit to a certain extent the groundwater in this sector, thus keeping the water table depleted. The water extracted could be used for agricultural purposes during the dry season.

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