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Recent Pockmark activity in Lake Banyoles (NE Spain) severely affected by changes in climate and land use

Teresa Serra [a,*], Mario Morellón [b], Marianna Soler [a], Blas L. Valero-Garcés [c], Flavio S. Anselmetti [d], Jordi Colomer [a]

[a] *Department of Physics, Campus de Montilivi, University of Girona, 17003, Girona, Spain*
[b] *Department of Geodynamics, Stratigraphy and Paleontology, Faculty of Geological Sciences, Complutense University of Madrid, 28040, Madrid, Spain*
[c] *Instituto Pirenaico de Ecología-CSIC, 50059, Zaragoza, Spain*
[d] *Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, 3012, Bern, Switzerland*

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ABSTRACT

Study region: Two giant pockmarks in Lake Banyoles (NE Spain) have been surveyed over the last 35 years. The giant pockmark 'B1' has maintained an 'eruptive' mode with permanent groundwater discharge, whereas, the giant pockmark 'B2' has displayed alternating quiescent and eruptive phases.

Study focus: Interannual variability of lake-subsurface groundwater discharge in both pockmarks and the main lake aquifer level correlates with changes in the accumulated rainfall during the previous 10 months in the north-east of Spain. In the eruptive phase, the lutocline, marking the top of suspended sediments, is warmer than the ambient lake water and generates a turbid hydrothermal plume.

New hydrological insights for the Region: Results show that the permanent hydrothermal plume at pockmark B1 is no longer penetrating the lake's background stratification due to the loss of plume buoyancy. The available data demonstrate that current climate change coupled with a depletion of groundwater resources has strongly impacted the hydrogeology and limnology of the main pockmark of the lake and also the distribution of suspended sediment in the water column.

1. Introduction

Most of the available climate-data series indicates a drier Mediterranean region since the 1980s, with drought events becoming one of the most impactful environmental disasters. This is likely to worsen by the end of the 21st century as global warming continues (Spinoni et al., 2017). An unequivocal increase in air temperatures, particularly large during the spring and summer seasons, has been also recorded in the region during the same period (Lionello et al., 2012). On the Iberian Peninsula, the period 1950–2015 showed an increase in the frequency and severity of droughts (Spinoni et al., 2017). Changes in temperature patterns from 1960 to 2006 show a significant increase in the frequency and intensity of hot daily temperature extremes over north-eastern Spain, in the number of warm nights, warm days and tropical nights, and in the annual maximum temperatures (El Kenawy et al., 2011). The warming has been greater in the coastal areas along the Mediterranean Sea compared to the mainland areas. Although there is a large spatial rainfall

* Corresponding author.
E-mail address: teresa.serra@udg.edu (T. Serra).

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variability, the regional meteorological data series for north-eastern Spain shows the impact of a drying Mediterranean region with a ~30 % reduction in rainfall during the last 30 years (Moreno et al., 2005) and a reduction in the historical flow records of the main rivers in the region (Gallart et al., 2011). In addition, increased human activity in the Mediterranean coastal regions of Spain over the past decades (intensive agriculture, tourism) have caused a higher consumption of surface and groundwater resources (Llamas et al., 2015; Saurí et al., 2013). The drastic reduction in water resources projected for the end of the 21st century in the region (Pascual et al., 2015) might have a considerable impact on river flows and groundwater, threatening the ecological and limnological dynamics of the wetlands and lake systems. All the above-mentioned global changes are expected to greatly impact the water bodies in the Mediterranean region. The knowledge of the fate of such water bodies under different scenarios is crucial for their future management. Therefore, research into the long-term evolution of these water bodies is required to understand the compounding effects of climate variability and anthropic pressures. In the current study, the long-term variability of the hydrology of Lake Banyoles, the largest karstic lake in the Iberian Peninsula is investigated and the role of rainfall variability and water usage during the last decades are assessed.

1.1. Pockmarks activity in Lake Banyoles

Lake Banyoles, located in north-eastern Spain, is the largest and deepest non-glacial lake on the Iberian Peninsula. It originated from karstic activity during the Pleistocene (Julià, 1980) and is still an active karstic system fed by groundwaters that form a dynamic lutocline (sharp sediment interface) (Casamitjana et al., 1988; Moreno-Amich and García-Berthou, 1989). A high-resolution geophysical survey of the Lake Banyoles pockmarks combined with the multidisciplinary analysis of sediment cores, revealed depositional changes in relation to the lake's hydrology and pockmark activity during the last ~7600 cal yr BP (Morellon et al., 2014). Six lacustrine pockmarks have been reported in Lake Banyoles (Casamitjana et al., 1988), two of which, B1 and B2, have the largest diameters (of ~300 m). Subterranean springs discharge groundwater into pockmarks B1 (eruptive) and B2 (quiescent/eruptive), resuspending sediments upwards to a sharp interface (i.e., lutocline, Fig. 1). These processes of sediment resuspension within the

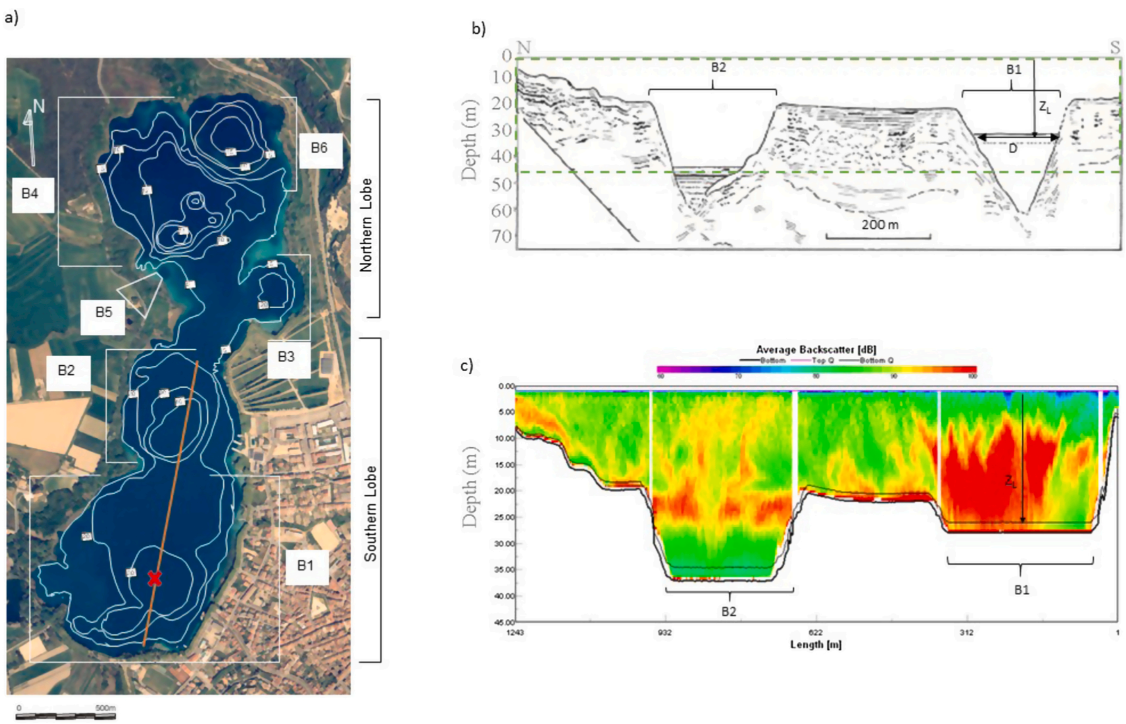

Fig. 1. a) Bathymetric map of Lake Banyoles constructed from echo-sounding profiles (Moreno-Amich and García-Berthou, 1989) and from an aerial photograph of Lake Banyoles (with permission of the Cartographic Institute of Catalonia, Spain). The lake has six giant karstic pockmarks. B1 is active and B2 is episodically active, and both are situated in the southern lobe of the lake. The red cross indicates the position where the vertical temperature profiles and sediment samples were measured. b) Graphic interpretation (from a north–south seismic transect marked in Fig. 1a, replotted from Canals et al., 1990) with a schematic view of the giant pockmarks B1 and B2. The lutocline is located at a depth Z_L from the surface and the plumes with diameter D at their base. Below the lutocline the sediment mud may either be in suspension or settled. The dashed green rectangle indicates the part corresponding to the part c of the Figure. c) North to south ADCP (RDinstruments, US) backscattering image transect with the depth of the lutocline marked as Z_L and the active plume developed at B1 (Soler et al., 2008). ADCP data was collected by our research group and has been published in the work of Soler et al. (2008). The black thick line indicates the position of the bottom of the lake except within the pockmarks, where it represents the position of the lutocline. Color bar indicates the backscattering level measured by the ADCP. The orange line in Fig. 1a corresponds to the transect made with the ADCP sensor shown in Fig. 1c and should be close to the seismic transect shown in Fig. 1b found by Canals et al. (1990).

pockmark are known as fluidization of the sediment (Casamitjana and Roget, 1993; Colomer et al., 2002). The giant pockmarks have been surveyed for several decades and provide a unique opportunity to test the dynamic relationships between groundwater flows, climate change and anthropogenic impacts in karstic lakes.

1.2. Known pockmark activity and groundwater flow in Lake Banyoles and other lakes

The pockmark activity level can be quantified by different parameters such as the groundwater flow rates or water discharge (Loher et al., 2016; Reusch et al., 2015; Wirth et al., 2020), by the depth of the sediment interface resuspended by the inflow of water (Casamitjana and Roget, 1993), by measurements of chloride and methane, or pockmark size and eruptions (Andresen et al., 2021). Groundwater discharge is the driving process that has maintained active pockmarks over thousands of years in some well-studied lakes as Lake Neuchâtel (Western Switzerland; Loher et al., 2016; Reusch et al., 2015; Wirth et al., 2020), Yellowstone Lake, (Sohn et al., 2019), the Hurlington Bay Lake Champlain, Vermont (Manley et al., 2004), several lakes in the coastal area of Limfjord in northern Denmark (Andresen et al., 2021) and Lake Banyoles (Serra et al., 2020). Lake Neuchâtel has four giant pockmarks (Reusch et al., 2015), two of which have diameters between ~100 and 160 m and current sediment mobilization. The currently active Chez-le-Bart pockmark (diameter ~160 m, and lutocline depth of 132 m) and the Treytel pockmark (diameter ~100 m and lutocline depth of 128 m) have presented ‘quiescent’ fluid phases as well as ‘eruptive’ events with subsurface mud mobilization (Loher et al., 2016; Reusch et al., 2015; Wirth et al., 2020). In Limfjord (Denmark), more than 20 separate seafloor depressions have been identified (Andresen et al., 2021). The largest three depressions in this area have diameters in the range 420−600 m. Three more medium depressions have diameters in the range of 220−350 m and the remaining depressions in the range 10−130 m. All were situated in a shallow area below 4.5 m deep.

The Chez-le-Bart and the Treytel pockmarks are comparable in size to pockmarks B1 (~300 m and lutocline depth ~25 m) and B2 (~250 m and depth ~20 m) in Lake Banyoles (Fig. 1) during its maximum eruptive phase (Colomer et al., 1998a; Colomer et al., 1998b; Serra et al., 2005; Soler et al., 2007). In both Lakes Neuchâtel and Banyoles, the eruptive phases of the most active pockmarks are due to higher groundwater discharges, leading to the remobilization and spilling of sediment over the pockmark rims (Morellon et al., 2014; Wirth et al., 2020). During the eruptive phases in Lake Neuchâtel, the sediment suspension was reported to be only 2.6 °C warmer than the hypolimnetic waters (Wirth et al., 2020), while in Lake Banyoles the maximum water temperature differences have been reported to be 8.6 °C and 8.1 °C in B1 and B2, respectively (Colomer et al., 2002, 2003; Serra et al., 2002). Densely clustered pockmarks have been also described in Eckernförde Bay, wester Baltic (Jensen et al., 2002). They have been originated by artisan groundwater seapage and by the presence of a Tertiary and Pleistocene artesian aquifer system below the area (Khandriche and Werner, 1996).

To the best of our knowledge, lacustrine hydrothermal plumes have only been described in the tectonic-karstic Lake Banyoles (Serra et al., 2005) and in the Yellowstone Lake, USA (Sohn et al., 2019). In Lake Banyoles, hydrothermal plumes rise to ~25 m above the lutocline (Canals et al., 1990; Casamitjana et al., 1988; Roget et al., 1993) (Fig. 1). Acoustic Doppler current profiler and conductivity-temperature-depth data acquired in Yellowstone Lake reveal the presence of a buoyant plume above the “Deep Hole” hydrothermal system located southeast of Stevenson Island (Sohn et al., 2019). Distributed venting in the ~200 × 200-m hydrothermal field creates a plume with vertical velocities of ~10 cm/s in the mid-water column, corresponding to a ~70-m rise height and a mass flux of 1400 kg/s. The same techniques applied to Lake Banyoles over the distributed circular pockmark B1 (~300 m diameter) determined a hydrothermal plume rising to a height of 25 m, vertical velocities of 5–20 cm/s in the mid-water column, a mass flux of 600 L s^{-1} and a sediment mass flux of 1300 kg d^{-1} which can double when pockmark B2 is also active (Soler et al., 2007). The surface-water temperature of Lake Banyoles during the months of July, August and September has increased over the past 44 years at a rate of 0.52 °C $decade^{-1}$ and the water temperature at a depth of 20 m has decreased at a rate of −0.66 °C $decade^{-1}$, resulting in a

Table 1
Abbreviation list of the main parameters and acronyms used in the current study.

B1	Name of pockmark, see Fig. 1
B2	Name of pockmark, see Fig. 2
Ri	Richardson number
Ri_c	Critical Richardson number
g’	Reduced gravity
B_o	Buoyancy flux at the lutocline
R	Radius of the lutocline
D	Diameter of the lutocline
h_o	Depth of the convective layer
g	Gravity constant
ρ	Background density
$\Delta\rho_o$	Difference between the density of the environment and the discharged fluid
w_s	Particle settling velocity at the lutocline
F_o	Groundwater discharge
A	Area occupied by the lutocline
$Rainfall_{10months}$	10 months accumulated rainfall
h	Piezometric level
z_L	Lutocline depth
ADCP	Acoustic Current Doppler Profiler

strengthening of the lake's summer stratification, with the seasonal thermocline being situated between 5 and 10 m deep (Serra et al., 2020). Lake stratification has also been found to have expanded from approximately three months (June to August) in the 1970s to approximately six months (May to October) in the late 2010s (Serra et al., 2020).

Although the hydrodynamics of pockmarks B1 and B2 is well understood, the long-term evolution of the main pockmark B1 and its variability due to climate changes have not been previously documented. In this contribution, to complete our understanding of the hydrological cycle in the lacustrine pockmarks of Lake Banyoles, we integrate all the hydrological and sedimentological knowledge at intra- and inter-annual scales and investigate how they correlate with climate variability. Specifically, we present data on the long-term evolution of pockmark B1, the vertical position of the interface of the sediment in pockmark B1 and the piezometric level and their relationship with the long-term evolution of rainfall in the study zone. Therefore, this study provides new information on the longevity of the main pockmark in Lake Banyoles, a topic not been addressed previously.

2. Methods

Hydrological, climate, limnological and groundwater data have been compiled in this manuscript from several sources. All the parameters considered in the present study and the acronyms for the name of the pockmarks are listed in Table 1.

Vertical water-temperature profiles from pockmarks in Lake Banyoles were collected by our group from 1986 to 2000 using a thermistor sensor (sensor 3145, Aanderaa Instruments, Bergen, Norway) with a 0.1 °C resolution. The thermistor sensor was deployed using a depth resolution of 10 cm. From 2000 onwards, the water-temperature profiles have been taken with a CTD SBE19plus (Sea-Bird Electronics, Inc., Washington, USA) with an accuracy of 0.005 °C and a resolution of 0.0001 °C. Raw data (4 Hz) were low-pass filtered (1.0-s corner period for depth and pressure and 0.5-s corner period for temperature) and, following the manufacturer's recommendations, temperature was lag-corrected relative to depth measurements prior to averaging all data into 0.5-m bins. The depth of the lutocline can be detected by a sharp increase in the temperature in pockmark B1. The temperature of the sediments in suspension at its top, i.e., the lutocline, was 19.0 ± 0.1 °C warmer than the temperature of the surrounding epilimnetic water, which ranged from 11 °C in winter to a maximum of 18 °C in summer (Serra et al., 2020). The lutocline could also be detected by a sharp flat bottom signal when profiling the water column with either an Acoustic Current Doppler Profiler (ADCP) Backscattering (Soler et al., 2008) or a sharp signal from a seismic profiling (Canals et al., 1990; Morellon et al., 2014) caused by abrupt density changes (Fig. 1).

Regional rainfall data for the period 1950–2019 have been downloaded from the Castellfollit de la Roca meteorological station (managed by the Catalan Meteorological Agency and available at the website www.meteo.cat). This is the larger dataset available closer to the recharge area of the lake aquifer (Sanz, 1981, Fig. 2). This dataset has been previously tested for quality and homogeneity controls following the HOMER method (Mestre et al., 2013). The temporal variations in the piezometric level recorded in the lake aquifer were obtained from the Catalan Water Agency for the period 2008–2019 that recorded the level once per month.

The effect of the lake's stratification on the development of the hydrothermal plumes evolving from the lutoclines in the pockmarks of the lake can be studied by means of the Richardson number ($Ri = g'h_o/(B_oR)^{2/3}$, where h_o is the depth of the convective layer, g' is the density difference caused by the temperature variation in the thermocline, B_o is the distributed buoyancy flux at the lutocline, and R is the radius of the lutocline). The Richardson number here is the balance between the stratification force versus the buoyancy force at the lutocline (Narimousa, 1996). Ri at the lake's active pockmark B1 will be used to identify under what conditions the hydrothermal turbid plume developing upwards from the lutocline will likely penetrate the lake's background stratification. The height up to where the hydrothermal plume can rise to is associated to the distributed buoyancy flux over the lutocline area (Soler et al., 2008). The buoyancy flux, B_o, is a function of both, the apparent gravitational acceleration, g'_o, and the mean outflow velocity, w, with g'_o = g

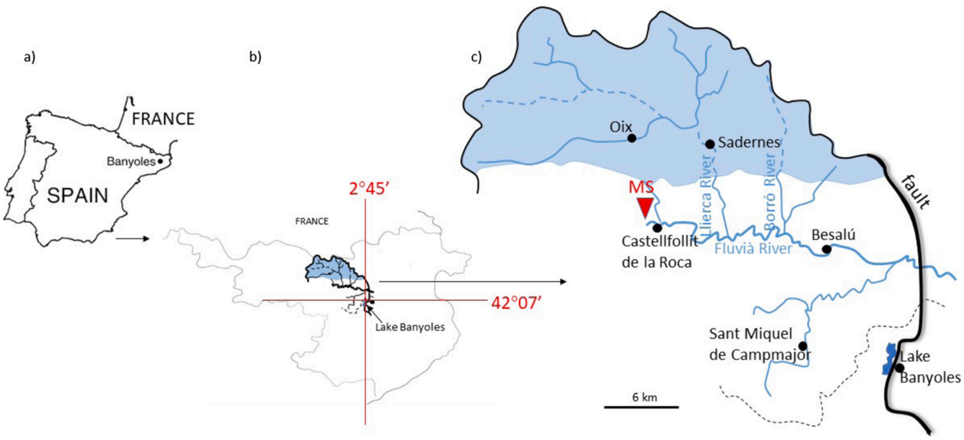

Fig. 2. a) Location of Lake Banyoles (Catalonia, north-eastern Spain). b) Zoom of the region under study with a small view of the watershed. Horizontal and vertical red lines indicate the latitude and longitude where the Lake is situated, respectively. c) Watershed of Lake Banyoles with the location of the recharge area shaded in blue (Sanz, 1981) and the Castellfollit de la Roca meteorological station (red triangle). The black bold line on the right represents the position of a geological tectonic fault. The dashed line indicates the Fluvià River basin boundary.

$\Delta\rho_o/\rho$, with $\Delta\rho_o$ as the difference between the density of the environment and the discharged fluid. In the eruptive phase of the pockmark, the upward velocity at the lutocline equals the particle settling-velocity, w_s, as was first described by Casamitjana et al. (1988). Therefore, the buoyancy flux, B_o, can be calculated as $B_o = g'_o w_s$. The critical Richardson number is: $Ri_c \sim 11$, above which plumes do not penetrate through thermal stratification but propagate radially along the base of the mixed layer (Narimousa, 1996).

In order to determine the buoyancy flux, the settling velocity at the lutocline of pockmark B1 was measured by taking sediment samples 1 m below the lutocline with Ruttner bottles, at different stages of the eruptive phases over the past 35 years by our research group. Measurements were carried out in the laboratory by allowing the sediments to freely settle in sediment settling columns and recording the downwards settling of the top interface at different times, from which the settling velocity was determined. The groundwater discharge, F_o, entering through pockmark B1 can be calculated as $F_o = w_s A$, where A is the area occupied by the lutocline. In the calculations an approximately circular shape area $A = \pi R^2$ was assumed (see Fig. 1).

3. Results

The annual rainfall in the study region has decreased slightly during the last 69 years (1950–2019, with a rate of −22.81 mm decade^{-1} (Fig. 3a), although the slope of the trend is not statistically significant ($p = 0.099$). No significant trend was found for any season (winter, summer, spring or autumn) but a mean decrease of 7 % was obtained for the annual rainfall comparing the 1990–2019 period with the 1950–1970 period. The piezometric level (h) of the main Banyoles Lake aquifer also decreased from 208 m in 2009 to

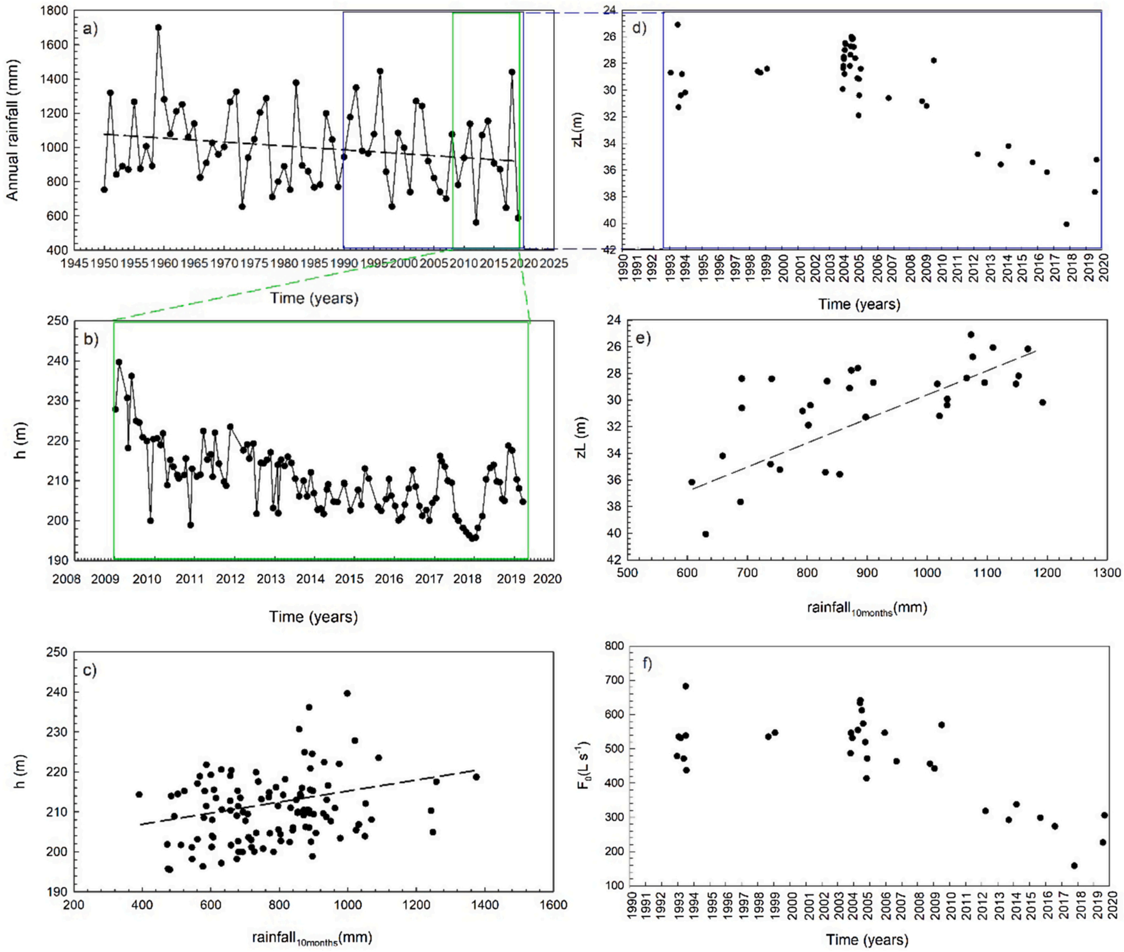

Fig. 3. a) Annual rainfall (in mm) for the period (1950–2019) from the Castellfollit de la Roca meteorological station. The dashed line represents the best fit linear trend to data found (annual rainfall=−2.28 year + 5525.10, $r^2 = 0.040$, $p = 0.099$). b) Piezometric level (h, in m) for the Lake Banyoles aquifer for the period 2009–2019. c) piezometric level versus the 10 month accumulated rainfall ($rainfall_{10months}$, in mm). The dashed line represents the linear trend fit to the data ($h = 0.011 rainfall_{10months} + 201.58$, $r^2 = 0.057$, $p < 0.010$). d) Temporal evolution of the lutocline depth z_L for the period 1993-2020. e) z_L versus $rainfall_{10months}$. The dashed line represents the linear trend fit to data ($z_L = -0.014\ rainfall_{10months} + 43.01$, $r^2 = 0.425$, $p < 0.010$). f) Temporal evolution of the flux of water (F_o, in L s^{-1}) entering through the pockmark B1 for the period 1993–2020. The green box in panel a) corresponds to the period 2009–2019 when the piezometric level was measured, shown in panel b). The blue box in panel a) corresponds to the period 1993–2020 when the lutocline depth was measured, shown in panel d).

200 m in 2019 (Fig. 3b). Data on the piezometric level was correlated to the previous 10 month accumulated rainfall (Fig. 3c). Despite the high scattering of the data and the low correlation coefficient, the linear trend was significant and with a positive slope ($h = 0.011 rainfall_{10months} + 201.58$, $r^2 = 0.057$, $p < 0.01$), i.e. the greater the accumulated rainfall the greater the piezometric level (Fig. 3c). In addition, the level of the lutocline (z_L) oscillated between 25.1 m–31.9 m during the period 1993–2004 (Fig. 3d). However, from 2004, z_L increased gradually presenting a maximum value of 40.09 m in 2017 (Fig. 3d). Data on the depth of the lutocline (z_L) was correlated with the 10 month accumulated rainfall (Fig. 3e). The linear trend was significant and had a negative slope ($z_L = -0.014 rainfall_{10months} + 43.01$, $r^2 = 0.425$, $p < 0.01$), i.e. the greater the accumulated rainfall the lower the depth of the lutocline z_L. The groundwater discharge into pockmark B1 in the 1990s varied from 437 L s^{-1} to a maximum of 682 L s^{-1}, that corresponds to the shallowest depth (situated at 25.1 m) of the lutocline (Fig. 3f). Discharge fluxes in the period 2000–2010 remained constant with a mean value of 528.32 L s^{-1}. After 2010, discharge fluxes decreased linearly down to ~200 L s^{-1} (Fig. 3f).

The monthly Richardson number from May to October in 1989, 1999, 2009 and 2019 was calculated considering a constant groundwater discharge to maintain sediments in suspension within the pockmark up to the lutocline depth of $z_L = 30$ m, with a diameter of the lutocline of $D = 2R = 232$ m and with a buoyancy flux, B_o, of 1.1×10^{-7} m^2 s^{-3} (Fig. 4a). During all these years, the

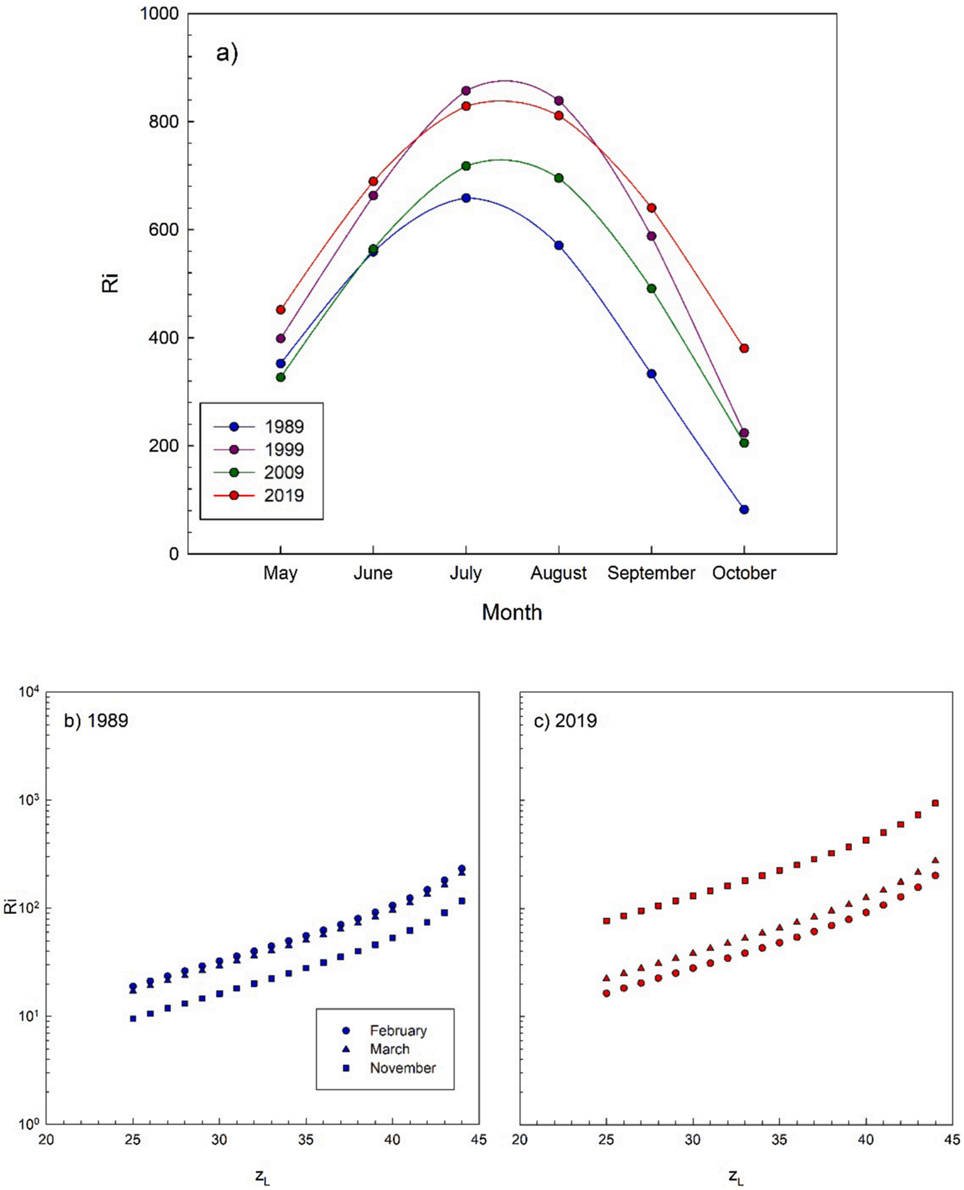

Fig. 4. a) Richardson number versus month for a fixed inflow of water to the lake with a velocity of 1.2×10^{-5} m s^{-1} corresponding to a $z_L = 25$ m, and for the different water-column stratifications for years 1989, 1999, 2009 and 2019. b) Richardson number versus the depth of the lutocline z_L for the water-column stratification of 1989. c) Richardson number versus the depth of the lutocline z_L for the water-column stratification of 2019.

Richardson number had the same pattern: it increased gradually during the stratified period, reaching a maximum in July, decreasing afterwards until the end of the year. Although the different years had the same Ri patterns, Ri presented an overall increase from 1989 to 2019. Considering the water column stratification for 1989 and 2019, we examined the scenarios of a reduction in the groundwater discharge (Fig. 4b and c). The groundwater discharge ranged from 682 L s^{-1}, (for which the depth of the lutocline was measured at $z_L = 25.1$ m, with 1.2×10^{-5} m s^{-1} water velocity at the lutocline), to a hypothetical depth of the lutocline of $z_L = 44$ m, with a groundwater discharge velocity of 1.6×10^{-6} m s^{-1} at the lutocline, corresponding to a discharge flux of 61 L s^{-1}. Considering the stratification of the water column in 1989, the range of calculated Richardson numbers increased as the depth of the lutocline increased for the months at the beginning (February and March) and the end (November) of the stratification period (Fig. 4b). For a stratification of the water column like in March of 1989, an increase in z_L from 25 m to 44 m would cause an increase in Ri of 13.6 times. In this case, March had Ri values close to those for February (Fig. 4b). In November, the same increase in z_L from 25 m to 44 m would cause an increase in Ri of 11.7 times (Fig. 4b). In 2019, Ri values in February were close to those of February 1989, but in March Ri shifted to higher values than those in 1989 (Fig. 4c). In addition, in November, Ri values were higher than in 1989 (Fig. 4c).

4. Discussion

4.1. Change in rainfall

The rainfall data set demonstrates a large interannual variability. Similar interannual and interdecadal variations in the rainfall patterns in the Mediterranean area have been related to variations in the North Atlantic Oscillation index (López-Moreno et al., 2011). Xoplaki et al. (2004) revealed that regional precipitation steadily increased with a maximum in the 1960s and a decline since then of 2.2 mm $month^{-1}$ $decade^{-1}$ (i.e. an annual decrease of 26.4 mm $decade^{-1}$). These regional Mediterranean values are similar to the decreasing rates obtained in the present study. The second half of the twentieth century in the Mediterranean region has been characterized by the occurrence of many severe droughts (Nicault et al., 2008), which may explain the decrease in the piezometric level observed in the current study. Aquifers have shown different responses against rainfall variability (Lorenzo-Lacruz et al., 2017). They may present short-term responses (<6 months), medium responses (6–24 months) and long-term responses (>24 months). In the current study, medium-term responses (10 month accumulated rainfall) were observed. Also, Soler et al. (2007) found that the dormant pockmark B2 of Lake Banyoles became active after the 10 months accumulated rainfall surpassed by 2.51 times the monthly rainfall in the area of study. Based on different global and regional climate models, future scenarios over the Mediterranean region predict a pronounced decrease in the precipitation, especially in the warm season (Giorgi and Lionello, 2008; Pascual et al., 2015). These scenarios suggest a decrease in the rainfall from −10 % to −40 % depending on the period of the year, except for the winter months (December, January and February) when an increase of 10 % is expected. The forecasted decreasing rainfall will impact on the aquifer recharge of the lake and therefore on the groundwater discharge into the pockmarks.

4.2. Changes in land use

Furthermore, added to the observed decreasing rainfall trends, land use has also shifted in the region of study, and likely impacted the groundwater inflow to the lake. For example, decreasing flows in the Ter River (20 km south from the Fluvià River shown in Fig. 2c) during the last decades have been observed and interpreted as a consequence of farm land abandonment and subsequent forest-cover increase (Gallart et al., 2011). This land use has led to decreasing aquifer recharge in the region. Despite data for agricultural, industrial and urban groundwater use in the watershed and recharge area of the lake are scarce, direct water withdrawal in the watershed of lake Banyoles for human consumption averages 150 L s^{-1}, which is approximately the lowest amount of water entering the lake 158 L s^{-1} during the surveyed period (October 2017).

4.3. Impact of rainfall amounts and land use changes on the Lake Banyoles pockmarks activity

In order to determine the impact of both land use changes and rainfall variability on the lake pockmark activity, extensive limnological surveys in the lake have been conducted since 1986. They prove that the hydrodynamics of the quiescent pockmark B2 have experienced 13 active eruptive phases of subsurface sediment fluidization; with resuspension of previously deposited sediments associated to very intense groundwater discharges (Colomer et al., 2002). Pockmark B2 has been in quiescent mode since 2010 (Serra et al., 2020), whereas the giant pockmark B1 has undergone chronic eruptive sediment fluidization since measurements were first reported in 1988 (Canals et al., 1990; Roget et al., 1993; Serra et al., 2020). Textural and compositional analyses and depositional patterns of homogeneities of up to 75 cm in thickness indicate that they have been deposited by periodical, intense, fluidization events in the giant pockmark B2 during the last two millennia (Morellon et al., 2014) (Fig. 1). The sediment record illustrates a large change in the pockmarks activity at ~2800 cal yrs BP synchronous to a lake-level rise phase and a subsequent intensification of groundwater discharges (Morellon et al., 2014). The onset of these events was triggered by the intensification of groundwater discharges in the lake, likely caused by higher recharge during more humid climates and/or phases of agricultural expansion during Roman and Medieval times (Morellon et al., 2014). The Banyoles sediment record illustrates how groundwater fluxes in karstic lakes are very sensitive to surface expansion of farmland in the recharge area of the aquifers as soil permeability increases and a more rapid response of the aquifer to intense rainfall episodes in the recharge area (Gutiérrez et al., 2019; Morellon et al., 2014; Valero-Garcés and Moreno, 2011). Considering all the above mentioned factors, the compounding effects of decreasing rainfall, increasing severe drought episodes and land use changes can explain the decrease in the groundwater recharge in Lake Banyoles during the last decades. This phenomenon has been also observed in other groundwater-fed karstic lakes of the region, such as Estanya (Morellón et al., 2011). The presence of a sediment interface in lake pockmarks was also reported by Loher et al. (2016) in Lake Neuchâtel. They also reported the spilling of sediment over the pockmark rims caused by episodes of increased groundwater discharge. Andresen et al. (2021) also observed spilling of sediment from pockmarks in the shallow western Limfjord in northern Denmark caused by high groundwater discharges. Andresen and co-workers also reported groundwater discharge velocities of 1.5×10^{-8} m s^{-1}, 100 times smaller than those observed in lake Banyoles of 1.6×10^{-6} m s^{-1}.

Although data before 1990 are sparse, lutocline depths z_L in pockmark B1 were reported to oscillate between 27.7 (February 1986; Roget et al., 1993) and 24.0 m (September 1988; Roget et al., 1993). Discharge fluxes in the period 2000–2010 were similar to the precedent ones during the 1990s, (with a minimum in October 2004) with a flux of 413 L s^{-1}, which is 40 % lower than the maximum discharge flux found in June 1993. Concurrent to this data, in the period 1990–2020, the discharge fluxes in the pockmark B1 together with the available lutocline depths in B1 indicate that the lutocline depth increased as the discharge fluxes decreased. In October 2017, the discharge fluxes reached 158 L s^{-1}, coinciding with a lutocline depth of 40.09 m corresponding to a reduction of 77 % when compared to the maximum flux attained in June 1993. The lowest lutocline depths have been attained over the past decade, i.e. 2012 to date.

When the lutocline was located at the deepest position (high z_L), the groundwater head did not exceed the required hydrostatic pressure of the lake's water column (and the water discharge F_o was low) to be able to resuspend the sediment and the lutocline remained at the very bottom of the pockmark; this was the case in pockmark B2 with the lutocline situated at a depth of 46 m (Serra et al., 2020). When the lutocline was situated at the shallowest depth it indicated that the groundwater head did had the required hydrostatic pressure (also with a high water discharge F_o) to resuspend the sediment upwards the water column.

The documented changes in pockmark activity through measurements of the depth of the lutocline serve as a clear signal of large hydrological impacts of global change in limnological ecosystems. Compound effects of climatic (warming, change in wind patterns) and limnological (depth, residence time, shift in stratification) conditions drive zooplankton composition and dynamics in lakes (Havens and Jeppesen, 2018; Lévesque et al., 2017). The increase in residence time can have important ecological consequences due to the impacts on the pollutants and nutrients balance in the system. That is, larger residence times are expected to decrease the nitrogen content in the lake water as total nitrogen is stored through sediment burial (Tong et al., 2019) and increase the phosphate and chlorophyll *a* contents (Shalby et al. (2020). The severity of persistent droughts in the western Mediterranean, the predicted rainfall decrease in most climate change scenarios for the 21 st century (Michaelides et al., 2018) and the increased human water consumption as shown in this study are expected to play have a significant limnological and ecological impact on the lake.

4.4. Impact of climate on turbid hydrothermal plume development

All 2019 data present Ri above $Ri_c = 11$ (Narimousa, 1996), therefore confirming the inability of the hydrothermal plume developed in the pockmark B1 to penetrate the lake stratification. The constriction of the vertical development of lake hydrothermal plumes by thermal stratification was also found in lake Yellowstone (Sohn et al., 2019). In their case, the vertical development of the hydrothermal plumes reached a height of 70 m, greater than the vertical development observed in Lake Banyoles (Colomer et al., 2003; Serra et al., 2005). In addition, the hydrothermal plume in Lake Banyoles transports sediment upwards, whereas in Lake Yellowstone no sediment was transported and it was characterized by a lower salinity compared to that of the ambient water. Given that limnological scenarios suggest that lake stratification may last the whole year at the end of the 21st century (Serra et al., 2020), it is likely that the hydrodynamics of this lake system are about to be profoundly modified, as the hydrothermal plumes will be permanently confined to the deep waters of the lake. This confinement of the hydrothermal turbid plumes will restrict the sediment transport to the southern part of the lake, changing the sediment deposition processes. Other studies document that this change in the hydrogeological fluxes occurred several times during the Late Holocene. During the last 3000 years, periods of increased groundwater recharge in Lake Banyoles' pockmarks led to deposition of homogeneities, and phases of lower discharge to banded and laminated facies (Morellon et al., 2014). Past phases of increased aquifer recharge have been related to both, wetter climates and periods of higher soil permeability due to more agricultural activity in the area (Morellon et al., 2014).

5. Conclusions

The long-term decrease in the ten month accumulated rainfall during the last decades is responsible for the decrease in the piezometric level of the Lake Banyoles aquifer and in the groundwater fluxes into the lake pockmarks. The reduced groundwater flow has increased the residence time of waters five-fold from 0.682 years in 1993 to 3.2 years in 2019. The decrease in the lake-water residence time might bring subsequent ecological consequences in the balance of nutrients in the lake. As water withdrawal for human consumption has reached values similar to those of the lowest fluxes of water entering the lake, the residence time is likely to continue increasing.

Moreover, compared with the 1990–2010 period, during the last decade (2010–2020) pockmark B2 in Lake Banyoles has switched into a quiescent phase, while pockmark B1 has reached extremely low groundwater discharges. The low groundwater flux added to the stronger stratification of the water column of the lake has impacted the vertical development of the hydrothermal plumes, reduced their buoyancy, and impeded their penetration of the background stratification of the lake. Due to both the loss of buoyancy by the active hydrothermal plume in pockmark B1 and the lake warming as a result of increased temperatures, the sediments suspended from the lutocline have not been able to reach the surface lake waters, except during the winter months. Therefore, resuspended sediments will not penetrate the lake thermal stratification and sediments remobilization will be restricted to the southern part of the lake.

Depositional patterns and ecological dynamics will be altered by the hydrological changes in the watershed.

Author contribution

TS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing original draft. MM: Conceptualization, Writing review and editing. MS: Investigation, Methodology. BVG: Writing review and editing. FSA: Writing review and editing. JC: Conceptualization, Data curation, Methodology, Resources, Supervision, Validation and Writing review and editing.

Data section

Depths of the lutocline of the largest pockmark in the lake were obtained from the temperature water profiles. Measurements were carried out with a CTD profiler at the center of the pockmark. The lutocline depth was considered the depth were there was a sharp increase in temperature due to the presence of the sediment resuspended from the bottom of the lake. This data has been obtained by our research group and has not been published previously. Data on the flow velocity at the inlet was obtained by our research group and has not been published previously.

The dataset also contains rainfall data of the meteorological station in Castellfollit de la Roca. Data was collected by the meteorological station managed by the Catalan Meteorological Agency (Meteocat, www.meteo.cat). Furthermore, there is also data on the piezometric level of the aquifer of Lake Banyoles. Data was provided by the Catalan Water Agency (ACA, www.aca.gencat.cat). Piezometric levels were published previously in the work done by Gutiérrez et al. (2019).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2021.100913.

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