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Sediment fluidization events in a lake caused by large monthly rainfalls

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[1] In the last fourteen years (1986–1999), fluidizations of confined bed–sediments due to underground springs in basin BII of lake Banyoles (Spain) have been detected. As a result of periods of high precipitation, sediment confined at the bottom of karstic basins migrates from 45 m depth to approximately 25 m depth. Fluidization processes are associated to monthly rainfall 1.5 to 4.5 times larger than the long-term mean (1970–1999). As a result of a fluidization event, the water column of the lake maintains the particle volume concentrations of suspended sediment (pVC) as high as 44 μl/l, which is ~8–29 times larger than the usual values of pVC. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 4239 Oceanography: General: Limnology; 4558 Oceanography: Physical: Sediment transport

1. Fluidization Processes in the Main Basins of Lake Banyoles

[2] Lake Banyoles (42°07′N, 2°45′E) is situated in the north-east of Spain, in the Catalan prePyrenees, and 30 km west from the Mediterranean coast (Figure 1a). It is a small multibasin lake (surface area of 1.12 km^2) of mixed tectonic-karstic origin, composed of several basins. The main supply of water to the lake is through subterranean springs located at the bottom of the basins of the lake [*Abella*, 1980; *Casamitjana and Roget*, 1993; *Colomer et al.*, 1998]. An underlying fault (at the East of the lake), which acts as a barrier to ground water movement in a complex series of confined aquifers, forces the vertical discharge of the ground water flow through the bottom of the basins (Figures 1a and 1b). The aquifers are supplied by the percolation of precipitation in two watersheds located 20 km to the northwest of Banyoles (Alta Garrotxa, Figure 1b). The main basins of the lake, BI and BII (see Figure 2) have a maximum depth of 75 and 77 m, respectively [*Canals et al.*, 1990]. As a result of cumulative episodes of land subsidence, the basins have cone-shape structures as can be seen, for example, in the seismic profile at BI (Figure 2).

[3] Sediments in BI (Figure 2) are normally found in suspension (is a case of sustained hydrologic pressure, as also seen exceptionally in a karst pond in the Florida aquifer system, page 57 in the vol. 195 (March) of National Geographic, *Ringle and Skiles*, [1999]). In contrast, sediments in BII normally remain at the bottom of the basin forming a dense sediment bed, at 45 m depth. However, an increase in the amount of precipitation in the recharge area produces an increase of groundwater discharge that eventually resuspends the sediments (Figure 2 top right). The mean mass concentration of the fluidized sediment bed in BI ranges from 100 to 130 g/l meanwhile the sediment concentration in BII varies from 280 g/l at the beginning of a fluidization event to 180 g/l when sediments remain in suspension. During a fluidization process, the sediment resuspension is characterized by the formation of a dense sediment interface (see the flat signal in the echosounding and seismic profiles in BI and BII in Figure 2) that advances upwards from 45 m depth to ~25 m depth; the time evolution of the position of the sediment interface is shown in Figure 3 (bottom panel). The momentum of the underground spring and the characteristics of the sediment (mainly the particle size diameter) determine the maximum height that the sediment interface can rise to [*Casamitjana et al.*, 1996; *Colomer et al.*, 1998]. Also, the temperature at the sediment interface increases from 17.5°C at the beginning of the event to 19.4°C in the suspension state, which is caused by the enhanced circulation of incoming warm water within the fluidized bed.

[4] Since 1986 monthly temperature measurements were carried out at a station located at the center of BII, at intervals of 1 m depth. Moreover, since 1998 monthly measurements of pVC at the same depth intervals were done (data that will be discussed later on in the text). In this study the depth of the sediment interface identifying the top of the fluidized bed was found to be the depth of maximum inverse vertical temperature gradient (between 8°C/m and 2°C/m), i.e., warmer temperature below

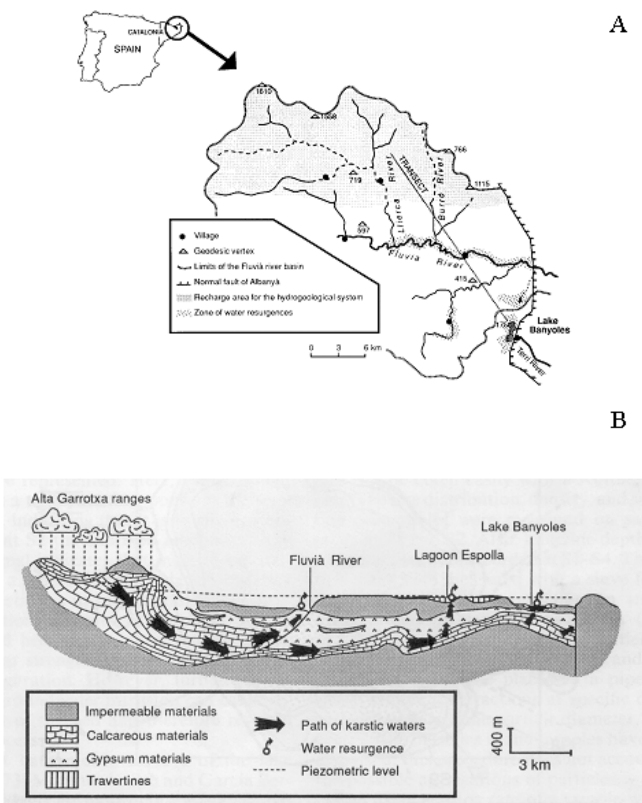

Figure 1. (a) General location map of Lake Banyoles and schematic representation for the hydrological system in the Lake Banyoles region. (b) Path of karstic water, along the transect marked in panel A [adapted from *Brusi et al.*, 1990].

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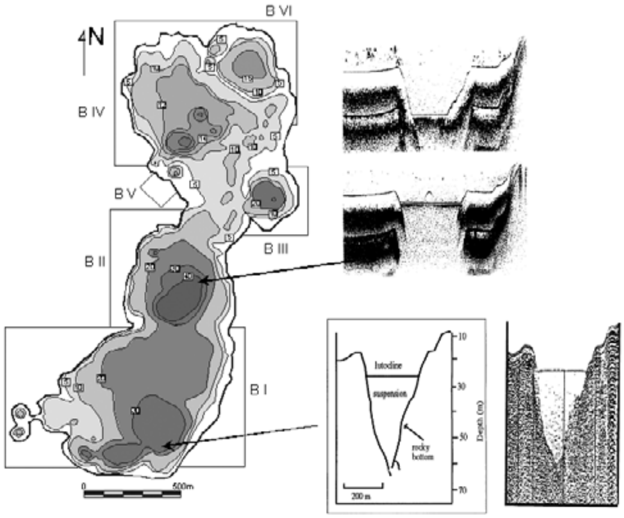

Figure 2. Bathymetric map of Lake Banyoles. Depth contours are in meters. The lake is composed of six basins (BI to BVI). The bottom right panel shows a schematic view of basin I of Lake Banyoles obtained from a seismic profile and its interpretative section [adapted from *Canals et al.*, 1990]. The top right panel shows two echosounding profiles, made during the F3 event, through basin BII for two different recharge volumes. Sediment in suspension is clearly delimited by an horizontal interface.

the sediment interface than the water above it. As a result of the extensive measurements carried out in the period 1986–1999 in lake Banyoles, six fluidization events (F3–F8) were detected (see Figure 3, bottom panel). Unfortunately, in the 70s and early 80s data were only taken intermittently. Consequently in 1976 and 1977 only two fluidization events (F1–F2) were detected (data not shown).

2. Fluidization Events and Monthly Rainfall in the Area of Study

[5] In Figure 3 (top) plots of monthly precipitation covering the interval (5 months) of a fluidization event are shown. More precesely, the month at which the fluidization of the confined sediments starts coincides with the 3rd month within the interval.

Table 1. Month of Initiation of the Fluidization Events with the Anomaly of Rainfall (%P) in the Area of Study

Event	Month-Year	%P
F1	December-76	–
F2	May-77	–
F3	October-87	+168.5
F4	April-88	+85.1
F5	December-91	+239.2
F6	June-92	+203.0
F7	December-95/January-96	+197.3/+350.7
F8	December-96	+133.8

Also, in Table 1 we list the month of initiation of fluidization (i.e., when the flat sediment interface at the top of the fluidized bed initiates the upward migration) and the percentage of monthly rainfall (%P) related to the long-term mean (1970–1999). Data were taken at the Darnius and Sant Privat d'en Bas meteorological stations which are located 15 km North-East and 10 km South-West, respectively, far from the area of the aquifer recharge (unfortunately no meteorological station is situated within the area of the aquifer recharge). Sediment resuspension events are preceded by months of high precipitation; the excess of percentage of rainfall ranging from 85 (F4) to 351% (F7), see Table 1 for details. Although it should be noted that F4 and F8 events do not present large values of precipitation (see also Figure 3 top and Table 1), it was enough to strength and maintain the fluidization. The F5 event corresponded to a monthly rainfall 239% larger than the mean long-term (Table 1). The rainfall was caused by a well defined synoptic weather situation in the Iberian Mediterranean coast, with "East" wind at the surface (from the Mediterranean sea) and cold temperature at the mid-troposphere above. On the contrary, the other events are associated to north-west Atlantic fronts.

3. Interannual Variability of Inorganic Particle Suspension in Lake Banyoles as a Result of Fluidization Events in BII

[6] As a result of the F8 event that ended on December-97, the water column in lake Banyoles (measured four months later on the 1st of May, 1998) had high particle volume concentrations, pVC, Figure 4. pVC was measured with a laser *in situ* scattering and transmissometry instrument (LISST-100) that determines pVC at

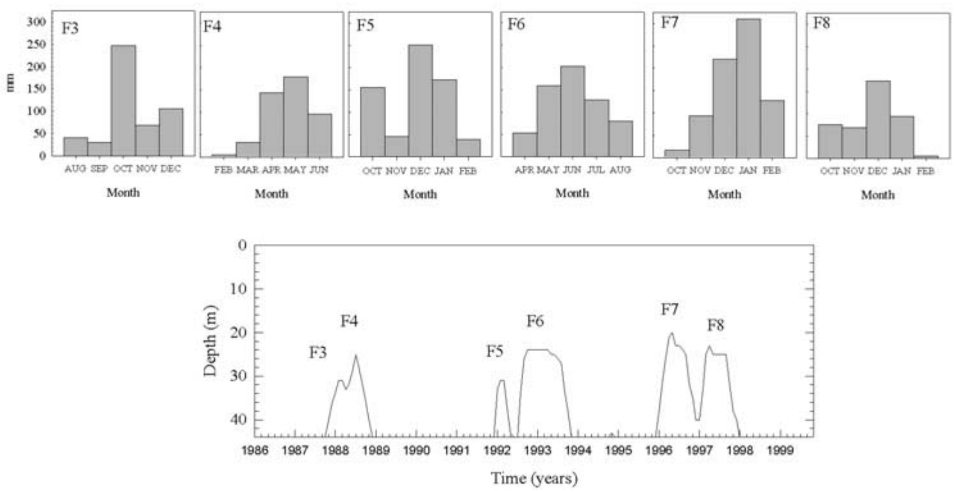

Figure 3. Top panels: Monthly precipitation in the area of study during the fluidization events (F3 to F8). Bottom panel: Variations of the sediment interface depth during the period 1986–1999.

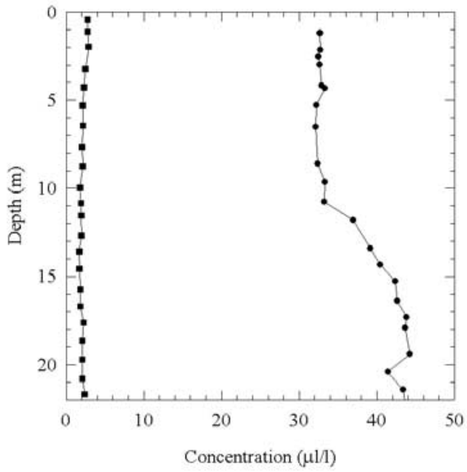

Figure 4. Vertical profiles of particle volume concentration (in μl/l) for May-98 (circles) and February-99 (squares) in basin BII of lake Banyoles.

different depths of the water column. LISST-100 measures the pVC of particles in 64 size classes logarithmically distributed in the range 1.2–250 μm by using the laser diffraction theory. The integration of this data gives the pVC of the measured sample. In addition, LISST-100 gives information of the depth at which the measure is taken, with a resolution of 5 cm, by means of a pressure sensor. High pVC values (32–44 μl/l) were measured on the 1st of May of 1998 in BII. In the next winter period, in February-99 (after a dry fall period), a whole depth-mixing column prevailed with values of pVC of 1.5–4 μl/l; the decrease in the pVC from May-98 to February-99 can be attributed to the sedimentation of particles in the water column. As a conclusion, fluidization events, which determine the water quality of the lake, have been found to be related to high levels of monthly precipitation.

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References

Abella, C. A., Comparative population dynamics of planktonic phototrophic bacteria (in Spanish), Ph.D. Dissertation, U.A.B., Bellaterra, Spain, 1980.

Brusi, D., J. Bach, and M. Sanz, Itinerari geològic de Banyoles (in catalan), Apunts 22, Eumo Editorial, 124 pp., Barcelona, 1990.

Canals, M., H. Got, R. Julià, and J. Serra, Solution-collapse depressions and suspensates in the limnocrenic lake of Banyoles (NE Spain), *Earth Surf. Proc. Land.*, *15*, 243–254, 1990.

Casamitjana, X., and E. Roget, Resuspension of sediment by focused groundwater in lake Banyoles, *Limnol. Oceanogr.*, *38*(3), 643–656, 1993.

Casamitjana, X., J. Colomer, E. Roget, and T. Serra, On the presence of aggregates in the basins of Lake Banyoles, *Geophys. Res. Lett.*, *33*(20), 2737–2740, 1996.

Colomer, J., J. A. Ross, and X. Casamitjana, Sediment entrainment in karst basins, *Aquat. Sci.*, *60*(4), 338–358, 1998.

Ringle, K., and W. Skiles, Unlocking the labyrinth of North Florida springs, *National Geographic*, *195*(3), 40–59, 1999.

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