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Discussions

Towards an increase of flash-flood geomorphic effects due to gravel mining and ground subsidence in Nogalte stream (SE Spain, Murcia)

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Abstract. Transition from endorheic alluvial fan environments to well-channelized fluvial systems in natural conditions may occur in response to base-level fluctuations. However, human-induced changes in semi-arid regions can also be responsible for similar unforeseen modifications. Our results confirm that in-channel gravel mining and aquifer overexploitation over the last 50 years in the case study area have changed the natural stability of the Nogalte stream and, as a result, its geomorphic parameters including channel depth and longitudinal profile have begun to adapt to the new situation. Using interferometric synthetic aperture radar (InSAR) data we obtain maximum values for ground subsidence in the Upper Guadalentín basin of ~ 10 cm yr^{-1} for the period 2003-2010. In this context of a lowered base level, the river is changing its natural flood model to a more energetic one. A comparison of the 1973 flood event, the most dramatic ever recorded in the area, with the 2012 event, where there was a similar discharge but a sediment load deficit, reveals greater changes and a new flooding pattern and extension. In-channel gravel mining may be responsible for significant local changes in channel incision and profile. This, together with the collateral effects of aquifer overexploitation, can favor increased river velocity and stream power, which intensify the consequences of the flooding. The results obtained here clearly demonstrate an existing transition from the former alluvial pattern to a confined fluvial trend, which may become more pronounced in the future due to the time-lag between the drop in aquifer level and ground subsidence, and introduce a new scenario to be taken into consideration in future natural hazard planning in this area.

Keywords: ephemeral rivers, flash-floods, Nogalte fan, gravel mining, ground subsidence, InSAR.

1 Introduction

The high potential shown by ephemeral rivers in semi-arid areas to cause geomorphic channel changes and devastating flood activity is due to their intermittent spatial/temporal occurrence. Despite the low total annual rainfall, intense rainstorm episodes in SE Spain are usually followed by changes in channel position, river banks and longitudinal stream profiles

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(Conesa-García, 1995). These transformations are mainly produced by high-intensity convective rainstorms —500mm day $^{-1}$ rainfalls, with up to 200 mm h^{-1} during a ~15 min peak—, which can cause important floods with a return period of only 7-11yr (Bull et al., 1999). Conesa-Garcia (1995) states that these rainstorms generate important erosive and depositional effects due to the arid environmental conditions, and that even during smaller events a large amount of sediment may be mobilized. These effects in ephemeral streams are related to both geomorphologic and anthropogenic factors.

Several ephemeral streams in SE Spain including the Guadalentin River and Nogalte Stream have been the subject of many previous studies due to their powerful flash floods, catastrophic rainfall mechanism and related hazards (e.g. Navarro-Hervás, 1985; Hooke and Mant, 2000; Lopez-Bermúdez et al. 2002; Bull et al. 1999; Hooke et al, 2005; Ortega et al., 2009). However, their flood dynamics and geomorphological impacts have not been previously studied in detail (Gil-Meseguer et al., 2012). In particular, the significance of load discharge has been ignored in flood prediction and routing (Poesen and Hooke, 1997) due to the lack of records of in-flow sediment concentration.

This case study focuses on the stream and fan of the Nogalte Rambla (ephemeral or dryland stream), which has provided one of the most important examples of flash flood power in SE Spain in recent years. The catastrophic 1973 event destroyed new developments located on the rambla floodplain in the village of Puerto Lumbreras, with a death toll of 86 and the destruction of 120 houses. Immediately downstream, however, the floodwaters spread out over the alluvial fan and did not reach the distal fan outflow. Most studies (e.g. Heras, 1973; Navarro-Hervás, 1985; Conesa-García, 1995; López-Bermudez et al., 2002; Gómez-Espín, 2004) determined that the 1973 event should be considered exceptional in terms of return period (~500 yr).

On October 28, 2012 a new event occurred that was smaller in precipitation magnitude, but similar in discharge. Despite its smaller impact on the Nogalte upper basin and Puerto Lumbreras village, it produced greater damage along the distal fan area. The extent of the flooded area in 2012 was 116 km^2, much greater than in 1973 event, and a week later 24 km^2 were still under water (Gil-Meseguer et al., 2012).

A post-flood field survey and record of the flood effects allowed us to recognize the resulting hydrodynamic and morphosedimentary features in the Nogalte fan and surrounding areas. Important differences were observed between the flood behavior and its subsequent effects in the 1973 and the 2012 events. These significant changes in the extent and distribution of flooded areas, as well as in the erosional and depositional results, led us to analyze why this flooding pattern was modified.

Drastic land use modifications and intense anthropic development have taken place in the area over the last 30-40 years. One of the human-induced changes with the greatest impact was the shift to intensive irrigation agriculture, which has led to important aquifer overexploitation. Some recent studies highlight the significant land subsidence occurring in the Guadalentin Basin due to groundwater overexploitation (Gonzalez and Fernandez 2011; Rigo et al. 2013). Extensive in-channel gravel mining is another anthropic factor impacting stream changes.

The main purpose of this paper is to evaluate the relative importance of these factors and identify to what extent they are responsible for the recently detected flood behavior leading to a modified stream flooding model.

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We considered three working hypotheses; (1) Most of the changes detected in flood patterns obey natural dynamics and the response can only be linked to changes in rainfall pattern or sediment availability; (2) There is a relationship between the gravel mining in the Nogalte stream in the last 30 years and physical changes in channel and flood dynamics; (3) Channel changes are the result of ground subsidence resulting from aquifer overexploitation.

2 Methodology

To characterize the behavioral changes and geomorphic impact of flooding in the Nogalte area, a detailed field analysis including channel measurements, flood stage indicators, sedimentary sections and the resulting morphologic features was combined with geomorphological interpretation of aerial photos, LIDAR derived DEM and ground deformation measured by radar interferometry (InSAR).

We reviewed the information available on the 1973 flood from field data, historical photographs and eyewitness reports, and analyzed the field area affected by the 2012 flood, gathering information on water levels and the effects of flooding to compare it with the 1973 event. Stratigraphic sections were interpreted at sites where records of both events were preserved. We made measurements of the banks by positioning GPS along the whole length of the main channel of the Nogalte rambla from the apex to the fan area where the channels become blurred.

To identify changes in the Nogalte channel and neighboring streams through the Upper Guadalentin Depression, we analyzed geomorphological parameters including channel width, longitudinal stream profiles and the location and extension of gravel mining, using a combination of aerial images from 1956, 1981, 2004, 2007, 2009 and 2011 provided by Cartomur (www.iderm.es), and 4 m resolution LIDAR derived DEMs (LIDARMUR: IDERM, http:// iderm.imida.es/iderm/index.htm).

Radar interferometry (InSAR) was used to measure ground motion in the Guadalentín Basin during the period 2003-2010. 27 ENVISAT ASAR (5.6 cm wavelength) images acquired from ascending track 373 were processed using a small baseline approach (Berardino et al., 2002, Hooper 2008). First, the 27 SAR images were focused and cropped using ROI_PAC (http://www.roipac.org/) and then 74 interferograms were computed using DORIS software (http://doris.tudelft.nl/) to analyze a ~30 x 45 km^2 area. The topographic phase contribution was removed using a 90 m digital elevation model from the Shuttle Radar Topography Mission (SRTM) (Farr and Kobrick 2000). The orbital information used in the processing was provided by the European Space Agency (DORIS orbits).

StaMPS/MTI software (http://homepages.see.leeds.ac.uk/~earahoo/stamps/index.html) was then used to perform pixel selection and interferogram unwrapping. This analysis led to a total 42842 pixels selected in the study area. A ground subsidence map and profiles were drawn up and compared to the drainage network and flooding distribution.

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3 Geological setting and geomorphology of the Nogalte area

The case study area is located in the Upper Guadalentín Depression (Murcia, SE Spain) in the Internal Zones of the Betic Cordillera (Fig.1). The depression is a Quaternary sedimentary basin developed along the Eastern Betic Shear Zone (EBSZ: Larouzière et al. 1988; Silva et al. 1993a) bounded by mountain fronts controlled by the activity of the Alhama de Murcia Fault. The oblique (reverse-strike slip) movement of this fault induced tectonic inversion of the landscape during the Pliocene and Quaternary associated with active uplift. The sinking of the footwall produced the infill with continental deposits overlying Miocene marl and metamorphic rocks from the Alpujárride units (phyllites, quartzites and dolomites).
Pleistocene and Holocene sedimentation consists of alluvial fan deposits, predominantly composed of conglomerates, sands and silts up to 200 m thick. The distal fan deposits merge to palustrine and playa-lake environments, defining a narrow NE-SW endorheic zone infilled with silts and clays (Silva et al., 2008).
The current morphology in the depression is defined by the large Nogalte and Lorca alluvial fans. The Nogalte fan consists of coarse material and shows large distal growth incising previous fan deposits. The Lorca fan was fed by overflooding of the Guadalentin River producing mainly clay deposition. The lateral coalescence of the Lorca and Nogalte fans determines a low elevation area occupied by the Béjar Rambla fan which currently displays high activity in spite of its smaller drainage basin. The low gradient of the distal fans favor the development of a palustrine area that hinders its drainage. This Upper Guadalentín Depression remained endorheic until an artificial channel was built connecting the Nogalte area to the Guadalentin-Segura drainage system. This channel acted as a diversion for flood waters, but in spite of this the Nogalte floods continued to infill the endorheic area, and only a few flood events reached the Viznaga channel.
The Nogalte drainage basin covers an area of 171 km^2 terminating in a fan with an area of 32 km^2. The upper to medium reach drains though a narrow, entrenched, flat- bottomed valley, confined in poorly resistant metamorphic rocks. Vegetal cover is scarce, so the system headwaters are highly erodible. The flow regime is ephemeral, dry during most of the year with intense precipitation episodes, and can be considered as natural as no flood control or large check dams have been built in the basin.
In the upper Nogalte basin the sediment types and grain-sizes display considerable fluctuations in longitudinal channel profiles, related to temporal variations in sediment supply from the hillslopes (Michaelides and Singer, 2014). In the fan the sedimentation is very active, displaying a clear example of flow spreading (flood-out) where the stream dominates its central axis, and the water is redistributed radially from the channel banks (Conesa and Alvarez, 2003; Ortega et al., 2009). The average width of the upper constrained stream valley is 50-160 m with a mean slope of 0.019 m m^{-1}. The width of the main channel in the fan lobe is 60 – 400 m with a slope of 0.014 m m^{-1}. According to Navarro-Hervás (1985), the low bifurcation index (1.06) and relief index (0.026) facilitate slow initial drainage of the water followed by sudden flash flooding.
To characterize alluvial fan differences the longitudinal profiles of the main streams in the depression were obtained using high resolution (0.25 m vertical resolution) LIDAR-derived DEMs (Fig. 2) showing these profiles for two stream sets. One is formed by streams draining towards the depression axis from its steeply sloping sides (mean slopes 0.023 and 0.014 m m^{-1}),

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while the Guadalentín and Viznaga rivers, representing basin evacuation collectors, show a slope one order of magnitude lower (0.005 and 0.003 m m^{-1}respectively). A significant exception is the Tiata Rambla (Fig. 2), developed on the Lorca fan surface, with a profile displaying an atypical low slope (0.005 m m^{-1}). The sediments in this fan consist of the thinner overflow and dispersion deposits from floods triggered by the Guadalentín River, while the other neighboring streams are dominated by gravel sediments.

4 Hydrology of the 2012 event. Was the flood behavior comparable to the 1973 event?

More than twenty large floods have been recorded in this area since 1568 (Gómez-Espín, 2004; Ortega, 2007). However, the 1973 event is considered the most catastrophic (Heras, 1973; López-Bermúdez and Gutierrez, 1983, among others). A Mesoscale Convective System (MCS) affecting the whole of southeast Spain was the origin of intense, persistent rainfall on three consecutive days (Capel-Molina, 1974). Antecedent rainfall was a significant factor, with 200 mm recorded in the three days before the event. Intense precipitation (although under 100 mm day $^{-1}$ and with a 50-year return period) led to a peak discharge with an estimated range of 1974 m^3s^{-1} - 2100 m^3s^{-1} (Table 1). Significantly, Heras (1973) claimed that the estimated solid discharge was c. 813 m^3s^{-1}, or 40% of total discharge, producing a large log-jam at the 100 m long village bridge and justifying the severity of the damage caused.

The October 28 2012 flood event studied here was provoked by a convective rainfall episode driven by an Isolated Upper Level Low (IDHL) with 180 mm of rainfall in 24h, 25% of the total in one hour, and intensity 119.6 mm h $^{-1}$ (Gil-Meseguer et al. (2012). In a previous study, some of the present authors (Ortega et al., 2006), estimated the precipitation in Puerto Lumbreras to be 190 mm day $^{-1}$ for a 500-year return period. Therefore the rainfall in the 1973 event was lower than estimated for this period, but the 2012 event may be assigned to a 500-year return period.

The resulting peak discharge recorded in 2012 was somewhere between 1500 and 2489 m^3s^{-1} depending on the author (Table 1). This may be considered as a high magnitude event compared with the T500 return period proposed by Conesa-García et al. (1996) for a discharge estimated as 1859 m^3s^{-1} and 1900 m^3s^{-1} (Pernia et al., 1987). Benito et al. (2012), however, consider it a moderate to high flood, slightly less than 1973.

The comparison of the 1973 and 2012 flood events, which most authors classify as exceptional, shows the different rainfall mechanisms (MCS vs IDHL) and amounts of water precipitated before the flooding event (Fig. 3). Although a similar peak discharge is given for both floods, in the cumulative hydrograph both show around 2000 m^3s^{-1}, the persistence of a high discharge over time was different.

In the 1973 event, the high entrainment capability of previously wetted soils in the watershed could explain the high amount of solid discharge transported. The load value of c. 40% referred by Heras (1973) may be too high, considering that based on the boulder size he reported (0.60 - 1.60 m diameter) the Manning coefficient would have to be around twice the 0.049 value he used. The solid discharge would therefore be less than 40%, although high enough in each case to be a relevant issue to establish differences between the flood results.

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In fact, both hydrographs, despite showing similar peak discharge, show differences in cumulative water and persistence in time, with worse effects in the 1973 than in the 2012 flood event, at least in theory. Nevertheless, although the differences in antecedent rainfall may have been of great significance, we do not consider this to be enough in itself to explain all the differences observed in the hydro-morphological dynamics of this most recent flash flood. As already observed, in the 1973 flood the major changes were located in the upper catchment and fan apex due to the high bedload transported, but the effects of the 2012 flood event were concentrated in the medium to lower fan reaches.

5 Gravel mining effects in hydro-morphological flood dynamic

One of the most significant recent human-induced changes in the Nogalte Rambla is the extraction of gravel for construction. The Nogalte active channel has been intensively exploited for gravel mining by both digging and machine head-cutting since 1981, as can be observed in aerial photos, especially from 2002 onwards. According to our measurements obtained using LIDAR and a high–resolution DEM the gravel pits exploited in the streambed affected around 30% of the channel during the period 1981-2009 (Fig. 4 B and C). The width of the Nogalte channel has changed between the first aerial photos taken in 1956, where no gravel pits are shown, and the most recent photos from 2009. There is a significant reduction in the area occupied by the channel in map views (Fig. 4 C) between 1956 (~ 23 km^2) and 2009 (~ 19 km^2). It can be seen that the channel tends to narrow along the whole length of the stream, but this is especially notable in relation to the active mining in each section. Values for these changes reach 39% in the sections where gravel extraction is the greatest and -7% in sections with less impact (Fig. 4D).

The field data obtained from the channel depth after the 2012 flood together with the high-resolution DEM measurements allowed us to quantify recent Nogalte channel entrenchment. The results of the field analysis (Fig 5) indicate a variable channel incision rate in the fan apex reach. Entrenchment values in the Nogalte fan are very irregular in the first few kilometers of the stream course due to local gravel removal. Bank undermining appears to be closely related to recent gravel pits, where down-cutting can reach values of up to 6 m.

Mean entrenchment values throughout this upper fan section are around 2.2 m. Temporal variations in the longitudinal profile and channel slope could not be measured due to lack of information prior to the 2012 flooding event. Our field results show that the longitudinal stream profile (Fig. 5) is rapidly homogenized and flattened by river dynamics, which coincides with the results of the research conducted by Singer and Michaelides (2014) in the confined Nogalte valley reach.

We also compared mean entrenchment in the Nogalte Rambla with incision values obtained for other nearby streams using a high-resolution DEM derived from LIDAR data. In the Nogalte Rambla reaches where the values are not affected by recent gravel pits, detected incision is much lower at around 1.7 m. If the sections with gravel pits are also considered, mean entrenchment values of up to 2.2 m are obtained. In the neighboring streams, mostly unaffected by mining, the entrenchment values are lower, but still significant: Béjar: 0.91 m, Viznaga: 1.56 and Guadalentin: 1.6 m.

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These results show that the whole fluvial network is undergoing significant entrenchment. This is an important factor to explain the significant distal effects and extent of the 2002 flash flood event, and allows aspects of the flow dynamics to be reconstructed and explained, taking recent anthropogenic interference into account.

The section of the Nogalte Rambla flowing through the village of Puerto Lumbreras is artificially channeled and the induced increase in water velocity hindered deposition, favoring greater incision and bank erosion immediately downstream at the fan apex (Fig. 6A). Sedimentary sections surveyed (Fig. 7), show c. 2-3 m thickness for the 1973 deposits with boulders, while the 2012 sediments consist of only 20 cm on top of the previous flood deposits.

A couple of kilometers further downstream, a gravel quarry (area 137,138 m^2, depth 4 m and estimated total volume of gravel extraction 5.4 x 105 m^3) acted as a major interference in the channel, inducing significant backward erosion with intense upstream undermining and widespread pit remodeling (Fig. 6B and Fig. 4B, reach 2). The partial bedload retention in the mining hollow involved sediment deficit downstream compensated by new material eroded from the stream banks. Reaches with channel widening and lateral flow expansion have been established, alternating with newly entrenched reaches, causing the collapse of a railway bridge further downstream.

Channel incision decreased towards the distal part of the fan, the channel was widened with lateral flow and the formation of thin but extensive sandy bars and silt deposits. However, the flow was still concentrated and had high depth and velocity values (Fig. 6C) when it reached the flat endorheic playa, favoring flow continuity towards the northern depression outlet (Fig. 8).

In this context, the formerly endorheic area displays a change in flood dynamics with major erosive effects upstream reshaping an entrenched channel in the apical fan reach followed by an increase in water velocity and flow depth in the distal fan lobes. During the 1973 flood event the Escucha chapel located in this lower area (Fig. 8), was only affected by stagnating floodwaters with low water velocity and fine-grained deposition. In contrast, the 2012 flood waters reached this area with high flow depth values (>1.5 m. see Fig. 6C), and the water velocity may have reached 1 m s^{-1}, as suggested by the resulting scours and bars compared with similar features studied in other flood events (Ortega et al., 2014). In this case, instead of the flow stagnating, the floodwaters continued downstream, unable to retain such a high flood volume on the broad, flat endorheic area (Fig. 8). A new floodway developed, reshaping a wide flood corridor connected to the Viznaga diversion channel, as the artificial outlet of the endorheic depression was no longer functional.

Also significant for the flooding extension in this area was the confluence with water arriving from the Béjar fan system (Fig. 8), which was also seriously affected by rainfall. Recently-built industrial estates limited infiltration, concentrating flows, and this together with extensive gravel extractions favored undermining along the rambla channel and even led to the collapse of the A-7 highway bridge (Fig. 6 D, E and F). Several braided streams converged here and joined the water from the Nogalte Rambla extending over both distal areas towards the common outflow (Fig. 8). The resulting flow, already channeled, continued north and finally encountered the artificial Viznaga Rambla.

From the flood description we can deduce the relative importance of human activities such as gravel mining in exacerbating flow concentration instead of dispersing the water along the fan. The 1973 flood event produced rapid deposition as soon as

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the floodwater spread out, depositing its large load with the decreasing gradient on entering the Upper Guadalentín Depression. The large sediment load was therefore significant in the upper basin and fan apex. Thus the role of the solid discharge may have been determinant in the behavior of each flood, both because the 2012 flood did not transport a large amount of upper catchment sediment, and also because the gravel pits induced load deficit in the channels along the fan.

6 Changes in drainage system induced by groundwater overexploitation

A third factor that needs to be taken into account is the InSAR detected ground subsidence due to groundwater overexploitation and how this may affect the observed change in flooding pattern.

To analyze the InSAR detected ground deformation with this lower water level we developed an average velocity map for ground deformation rates using InSAR analysis for the period 2003-2010 (Fig. 9A). The measurements are in the satellite's line of sight (LOS) with an angle of 23º from the vertical and thus they are mostly sensitive to vertical displacements. The deformation pattern is elongated in a ~N45ºE direction, parallel to the Upper Guadalentín basin. Maximum deformation rates of ~10 cm yr $^{-1}$ are located at the center of the basin (red dots), in agreement with previous results (Gonzalez and Fernandez 2011; Rigo et al. 2013). Deformation ends at the south between the Béjar and Nogalte channels, but continues towards the northeast following the Guadalentín River, outside the case study area.

To compare the measured ground deformation with the flooding pattern detected during the 2012 event, we projected the deformation along the four main channels in the region: the Guadalentín River and the Viznaga, Béjar and Nogalte streams (Fig. 9B, profiles A to H). These cross-sections and longitudinal profiles along the main rivers show that the largest area of sinking occurs along the Guadalentín River with deformation rate values between 2.5 and 10 10 cm yr^{-1}, together with the Béjar Rambla channel, with a maximum deformation rate of ~ 7 10 cm yr^{-1}, increasing towards the center of the basin. The Nogalte channel does not show any deformation pattern, suggesting either the absence of deformation along this channel or deformation below the stability threshold of the InSAR measurements (~1 cm yr^{-1}). The Viznaga channel surrounds the area of the valley affected by more rapid subsidence, but in this case the velocity profile shows that the sinking may be less than 1 cm yr^{-1}.

The areas depicted with different subsidence rates show a roughly similar morphology to that of the alluvial fans (Fig. 10). The maximum subsidence area corresponds to the Lorca fan, with values of 7-10 cm yr^{-1}; the smaller area corresponding to the Béjar Rambla presents lower values (4-7 cm yr^{-1}); and the Nogalte fan shows no subsidence.

In order to understand the significance of this subsidence we analyzed the recent evolution of the hydrogeological configuration. The Upper Guadalentín Depression unconfined aquifer developed in the highly permeable conglomerates and sands of the Plio-Quaternary alluvial fan deposits. Given the growth of intensive agriculture, the aquifer began to show evident signs of overexploitation in 1972, and was officially declared overexploited in 1987. Water withdrawal (43.3 hm^3 year^{-1}) was four times higher than natural input (11.5 hm^3 year^{-1}), which has resulted in a drop of up to 200 m in groundwater piezometric surface (IGME, 2009).

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Earlier hydrogeological maps showed a northeast underground flow, with a 0.85% gradient, fed by the lateral alluvial fans (IGME, 1975). In contrast, the 1993 map shows that over-exploitation had led to a 150 m water table drop (IGME, 2009), with the resulting endorheic aquifer flowing towards the depression center (Fig. 11A). The lowering of the water table intensified in 2008 and the underground flow inverted southwards (Fig. 11B); a trend that continued in 2012 (Fig. 11C) according to the latest data published (CHS, 2014).

These results indicate that the current state of the aquifer described (Fig. 11 C) does not show any apparent relationship with the ground deformation map derived from InSAR analysis (Figs. 9 and 10) for the 2003-2010 period. However, this deduced ground deformation appears to be reflected better in the 1993 groundwater contour map. As shown in Fig. 11A, the highest groundwater-flow gradient corresponds to the Lorca fan, the lowest gradient coincides with the Nogalte fan, and the Béjar fan presents an intermediate value.

This configuration can be inferred if we consider a delay occurring between the groundwater table drop and its effect on surface subsidence. A time delay could explain the current absence of subsidence in the Nogalte fan area, since the piezometric drop there only became evident recently during the period 2008 to 2012 (Fig. 11B and C). Other InSAR studies of aquifer-related subsidence in the Guadalentín Depression also suggest non-linear time-delayed flow processes (González and Fernández, 2011) and more recently Boni et al. (2016) conclude a similar delay.

Lithology is another important parameter to consider when interpreting differences observed in ground subsidence analysis. The dissimilar behavior of the Lorca and Nogalte fans may derive from their geological characteristics. As described in the longitudinal stream profiles (see Fig. 2B) there is a significant difference in fan slope due to lithology. The Lorca fan is fed by the Guadalentín River, which well-defined floodplain favored clay sedimentation. The greater compressibility of these deposits may explain the higher subsidence rate than that found in the Nogalte fan, which is composed of coarse sediments. Delayed compaction during land subsidence was also explained by González and Fernández (2011) due to the presence of low permeability materials.

An additional factor justifying the larger subsidence rate in the Lorca fan is its current disconnection from its feeding stream, the Guadalentín River. The channelization of this stream diverting it from the Lorca fan apex not only avoids overbank flooding towards the fan but also prevents the underground connectivity responsible for its groundwater recharge. Moreover, a large dam upstream has drastically reduced the flow through the Guadalentín River.

The important accumulation of the 2012 flood waters in the distal fan endorheic area may have acted as a driving factor for subsidence manifestation. Floods often trigger change in metastable state systems (Schumm, 1973), that means an external factor favors to overcome a threshold and determines a new equilibrium regime. Distal endorheic areas are composed of silts and clays with interbedded sand and gypsum deposits. These characteristics favor collapsible soils that are metastable under dry conditions, but lose strength when wet.

The appearance after the flood of a large crack in the soil (Fig. 12), hundreds of meters long and several meters wide and deep, may evidence ground settlement. The crack developed in the lower reach of the Béjar Rambla where coarse deposits transitions to distal clays. In fact, the local name for this site ("Bujeos" or holes) is coherent with the occurrence of especially

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compressible clays in this area. More detailed studies are needed to test the response of these materials and their potential role in the subsidence delay process detected.

7 Discussion

In addition to the characteristics of the rainfall event itself, two other significant causes must be taken into account to understand the changes in the unusual hydro-morphological dynamics of the 2012 flash flood studied here: human activities such as in-channel gravel mining and severe ground subsidence due to groundwater withdrawal. Both of these involve channel stability control factors: the first leads to a deficit of load material in the drainage system and the second to the loss of substrate support resulting in base level lowering. They may justify the geomorphological changes observed, i.e. the tendency to stream entrenchment and the unexpected extent of the flood.

Although the September 2012 total flood volume was only medium-high, the rainwaters were concentrated into a two hour period. Sudden, highly intensive rainfall with no antecedent precipitation is a determining factor hindering sediment entrainment from the catchment, as this requires existing available material previously prepared by wetting and disaggregation. Flood duration is a decisive factor in erosion. Costa and O´Connor (1995) suggested that the long duration of flood flows together with stream power explain the driving forces for significant geomorphic changes. Ortega and Garzón (2009) tested the effects of a high magnitude flood in the Rivillas River (SW Spain) showing that a long duration peak discharge generated more effective impacts. The comparison between the 2h duration of the 2012 flood with the c. 6h peak discharge plus the antecedent rainfall effect in 1973 (see Fig. 3), should be enough to explain the rapid rainfall concentration and the low entrainment capability of the 2012 event.

The fact that the 2012 rainfall was concentrated into a small time period, and soil moisture was low due to the summer drought, may have led to faster flood propagation downstream. This load deficit could however have been quickly corrected downstream from Puerto Lumbreras by renewed channel erosion of the channel banks followed by channel bed accretion as the response proposed by Schumm (1977) for load deficit adjustment on bedload streams. The brief time span of the precipitation would have displaced the flood slightly downstream, but would not have induced the significant morphodynamic changes described at much greater distances.

The Nogalte Rambla is prone to shifting in sedimentation areas and flood dispersal within its fan, but we found no previous references to deep, high energy flood propagation downstream from the endorheic area. A flood model proposed by Conesa and Alvarez (2003) even considered that, due to its more concave profile, the vulnerability for flooding was greater towards the southern edge of the fan axis. The only reference found to previous flood propagation downstream from the endorheic area is the 1948 flood in which 240 mm rainfall in only five hours was recorded in Puerto Lumbreras resulting in a flash flood that affected an area of 7900 ha (Perez and Gil, 2012). The flooded area was smaller than the 116 km^2 of the 2012 event, and affected mainly the lower part of the depression, as the floodwater arrived mostly from the Lorca fan through La Tiata channel, not from the Nogalte Rambla.

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The significance of load discharge for channel incision was pointed out by Segura-Beltrán and Sanchis-Ibor (2013) in a similar Mediterranean ephemeral stream environment. They showed that even when large floods are responsible for transporting high amounts of sediment, channel incision only occurs when there is a supply deficit, similar to what happened in their case study following basin afforestation. As also indicated by Hooke and Mant (2000), large events in this area are responsible for major channel changes, although they frequently only mobilize riverbed material.

A more serious effect on stream pattern may derive from in-channel gravel mining. The consequences of in-channel gravel extraction are well described in the literature, as the gravel pit produces a nick point migrating upstream (e.g. Scott, 1973; Schumm et al., 1984; Kondolf, 1997; Wohl, 2000). Moreover, hungry waters (Kondolf, 1997) prompt the propagation of channel bed and bank erosion downstream to recover the sediment deficit. The river system has negative feedback; any change introduced affects both upstream and downstream (Schumm, 1977). There is inertia between cause and effect, and the higher average shear stress caused by incision can aggravate degradation Martin-Vide et al., 2010). The result is an adjustment of the stream profile and variations in channel width, depth and slope along the longitudinal profile.

In this present case study, gravel mining may explain the considerable channel entrenchment observed as it concentrates flow and contributes to increased erosion and removal of entrained sediments. These consequences have intensely affected the Nogalte and Béjar Ramblas watercourses, and have even caused a bridge collapse in active incising reaches. The loss of material has induced upstream entrenching to fill the hole generated, but the removal of this material from the system will also be reflected downstream. According to Martin-Vide et al. (2010), in semi-arid braided rivers the loss of alluvial material resulting from incision may be as much as twice the volume of gravels mined. As we have observed in this case widespread entrenchment also occurred downstream, although less abruptly than upstream. Channel adjustments are dependent on the reach-scale sediment budget (Wishart et al., 2008) and display greater discontinuity and complexity in comparison with water discharge sediment fluxes (Rice, 1998).

The other important factor conditioning this flash flood results is the subsidence caused by aquifer overexploitation. The thick surficial quaternary aquifers defined and fed by the lateral fans have experienced a 200 m drop in water level. Our results of the subsidence velocity quantified by InSAR for the 2003-2010 period define a spatial correlation between the piezometric gradient of the 1993 groundwater map referred above. This gap between the water extraction and the terrain results observed implies a time-lag between the water table depletion and the subsidence occurring on the surface. The delay can be explained by the current disconnection between surficial waters and the groundwater table, now forming a deep aquifer that delays rainfall recharge. In fact, after the 2012 flood no recharge at all was registered on the aquifer piezometers (CHS, 2014).

In terms of how subsidence could affect the flood pattern evolution studied here, it should be noted that the ground sinking defines a considerably lower base level for the drainage network. The drop of up to 60 cm that took place from 2003 to 2010 for the area between the Bejar Rambla outflow and the upper Viznaga channel (Fig. 9) implies a significantly increased gradient in relation to the Nogalte fan. This would facilitate concentration of the water towards subsidence points, stimulating a change in drainage configuration.

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According to the hydrogeological maps (Fig. 11), higher groundwater flow gradients occur towards the depression axis. Soil consolidation related to the reduction of interstitial pressure on fine sediments promoted ground subsidence inducing water concentration and channeling towards the most depressed points. This area coincides with the Nogalte-Viznaga connecting corridor, which was revealed as an active floodway during the last flash-flood. As a result, a better connection was facilitated between the previously endorheic area and the artificial Viznaga channel. A link between what has been, until the present, an endorheic depression and the Guadalentín River downstream needs to be considered, and subsequently the transformation of the former palustrine configuration into an organized fluvial axial floodway for the depression.

8 Conclusions

The flash flood event analyzed is characterized by short duration and clear water discharge, with hardly any bedload input. This can be attributed first to its torrential character as an event of high rainfall intensity but short duration that promoted rapid surface runoff, as it occurred at the end of the summer drought and with no previous soil humidity. In addition, the net loss of solid load produced by intense in-channel gravel mining needs to be taken seriously into account. A major gap exists in managing flood impacts on these Mediterranean areas due to the lack of solid discharge data (Poesen and Hooke, 1997). The long-term impact of such events needs to be considered especially as their time-space occurrence does not allow immediate manifestation of their hidden but severe effects.

However, one of the most dangerous consequences of the anthropic factors leading to widespread system instability may be ground subsidence from aquifer overexploitation, due to its imperceptible but retarded character. Compaction of the special clays material together with sustentation loss due to groundwater extraction undoubtedly favors subsidence, but this effect is neither uniform nor immediate in this region. The metric scale ground subsidence that has been detected affects the stream base levels promoting entrenchment and displacement upstream of an erosive wave. The base level drop can severely modify the drainage pattern, erosion and sedimentation areas.

Management of alluvial fan floods in semi-arid areas is extremely complex. Despite their apparent inactivity, ephemeral streams and alluvial fans are fragile systems, but precisely for this reason they enter a metastable phase during those long periods with minor local events, storing potential energy capable of triggering catastrophic changes during extreme events.

After a catastrophic flash flood like the one analyzed in this case study, there is increased social pressure for the construction of ‘flood-defenses’. Engineering work may be needed to protect certain reaches, but should always be considered after first assessing the side effects it may generate. Management interventions usually serve to maintain sediment budget deficits (Wishart et al., 2008) and as a result delay the benefits of natural morphological adjustments. The best way of controlling erosion is to promote sedimentation in favorable incipient deposit sites (Schumm, 1977).

As already discussed above, flood regulation by upstream dam construction and stream channelization restricts fan connectivity with its feeding river and facilitates the lowering of the water table and related ground subsidence. Recognition of overall catchment processes in the long-term is required rather than reacting in the short term at reach scale, a result of the

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human tendency to resist natural channel changes (Kondolf and Piegay, 2002). Land planning at watershed level is essential together with an extensive local information campaign stating present and future terrain conditions and their management implications.

Our analysis suggests the existence of metastable ground conditions in the case study area resulting from a time-lag in the manifestation of subsidence as an effect of groundwater extraction, implying significant consequences for the management of this land area, naturally arid but exposed to strong anthropogenic pressure. It should be noted that the impacts described here may be masked and not manifested for long periods of time, until they are triggered by the occurrence of an event of catastrophic magnitude.

10 Acknowledgements

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Tables

Table 1: Estimated peak discharge and rainfall during the 1973 and 2012 events in Nogalte channel. Data taken from several sources

Author/s	1973 Event		2012 event	
	Rainfall (mm/24h)	Discharge ($m^3 s^{-1}$)	Rainfall (mm/24h)	Discharge ($m^3 s^{-1}$)
Heras, 1973		2100	-	-
Capel-Molina, 1974	96	-	-	-
López-Bermúdez & Gutierrez, 1983	-	2000	-	-
Gómez-Espin, 2004	100	1974	-	-
Benito et al., 2012	-	2000	212	1500
Gil-Messeguer et al., 2012	-	-	180	2356
CHS, 2013	-	-	162	2489

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Figures

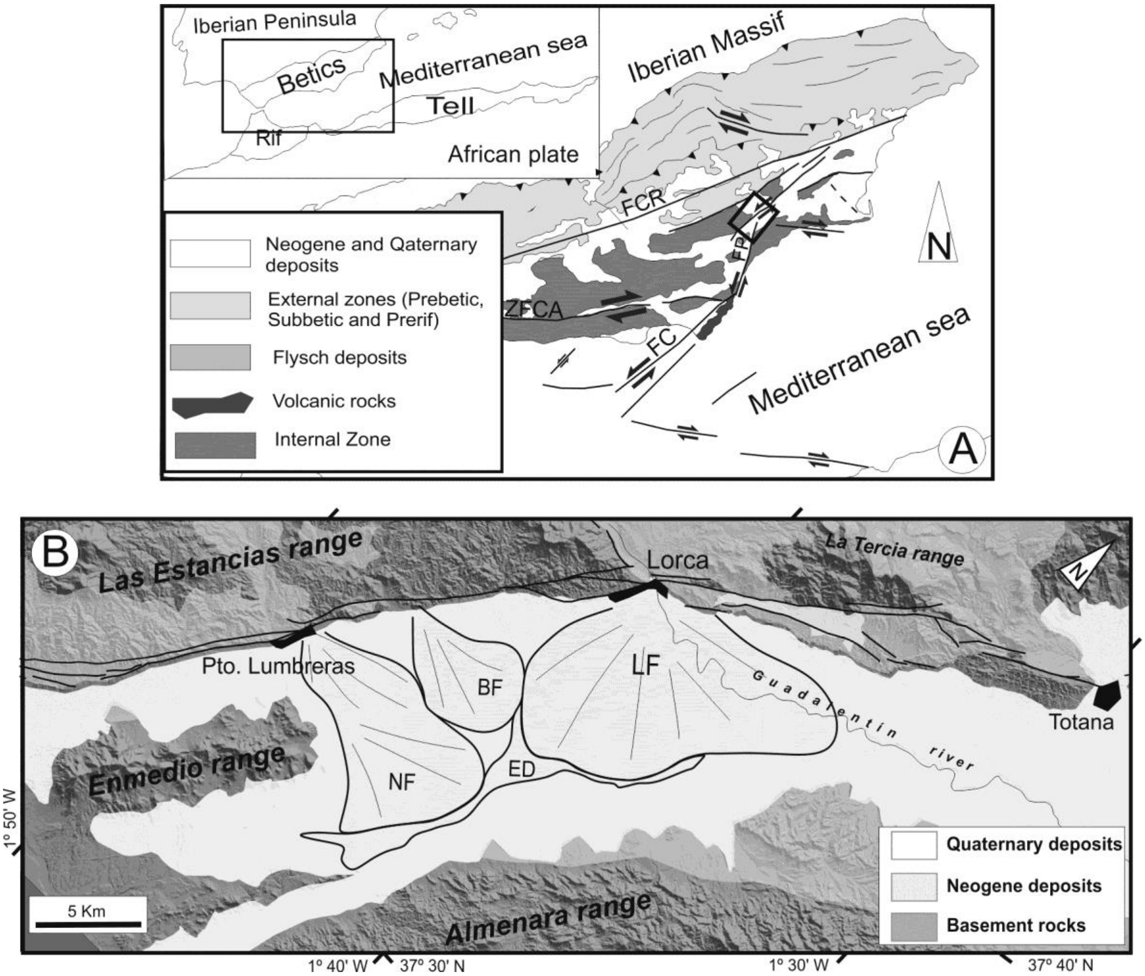

Figure 1. A. Geological setting of the study area. Black square points the situation of the Guadalentín valley into the Eastern Betic cordillera. B. Schematic geological map showing the western part of the Guadalentín Upper Depression and the three main alluvial fans; LF: Lorca fan, BF: Béjar fan and NF: Nogalte fan. ED: endorheic deposits (Lacustrine and fluvio-palustrine environment).

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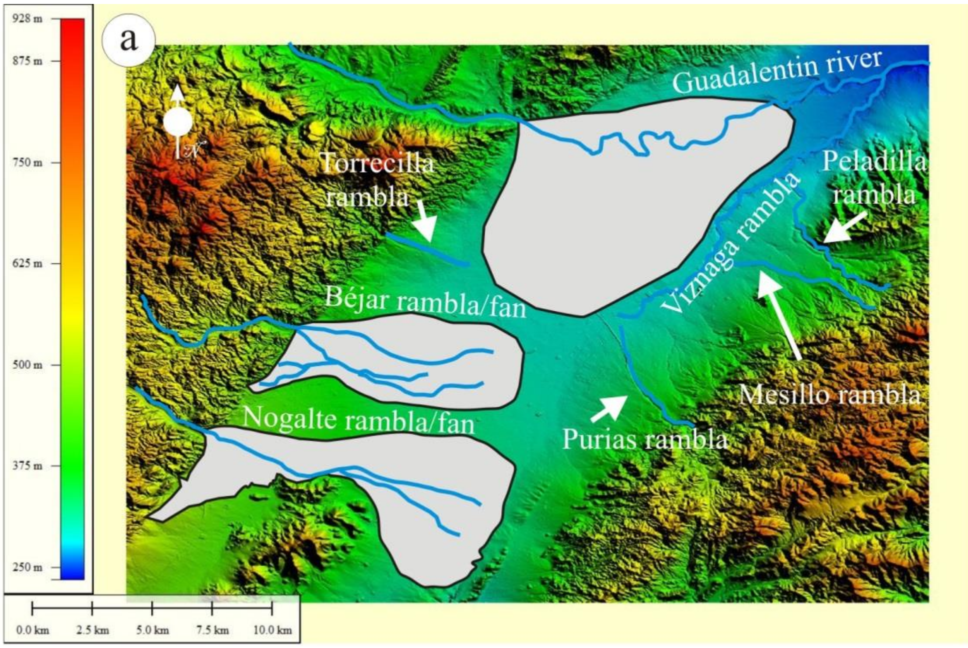

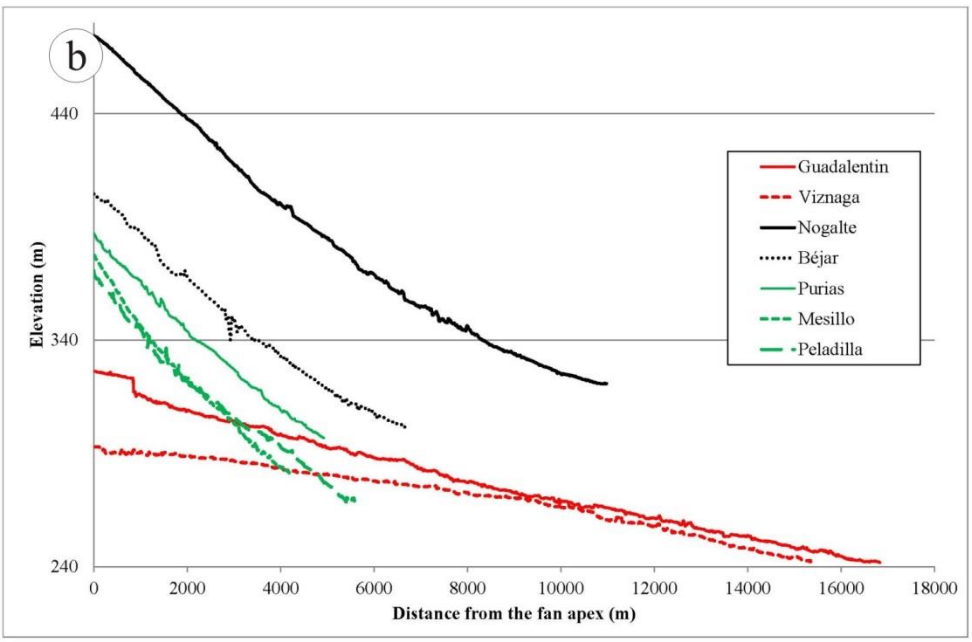

Figure 2. A. Location of the main streams in Guadalentín Upper Depression. B. Longitudinal profiles of the main streams. Black lines: tributaries of the left margin. In green: tributaries of the right margin. In red: streams in the Guadalentín valley axis.

525

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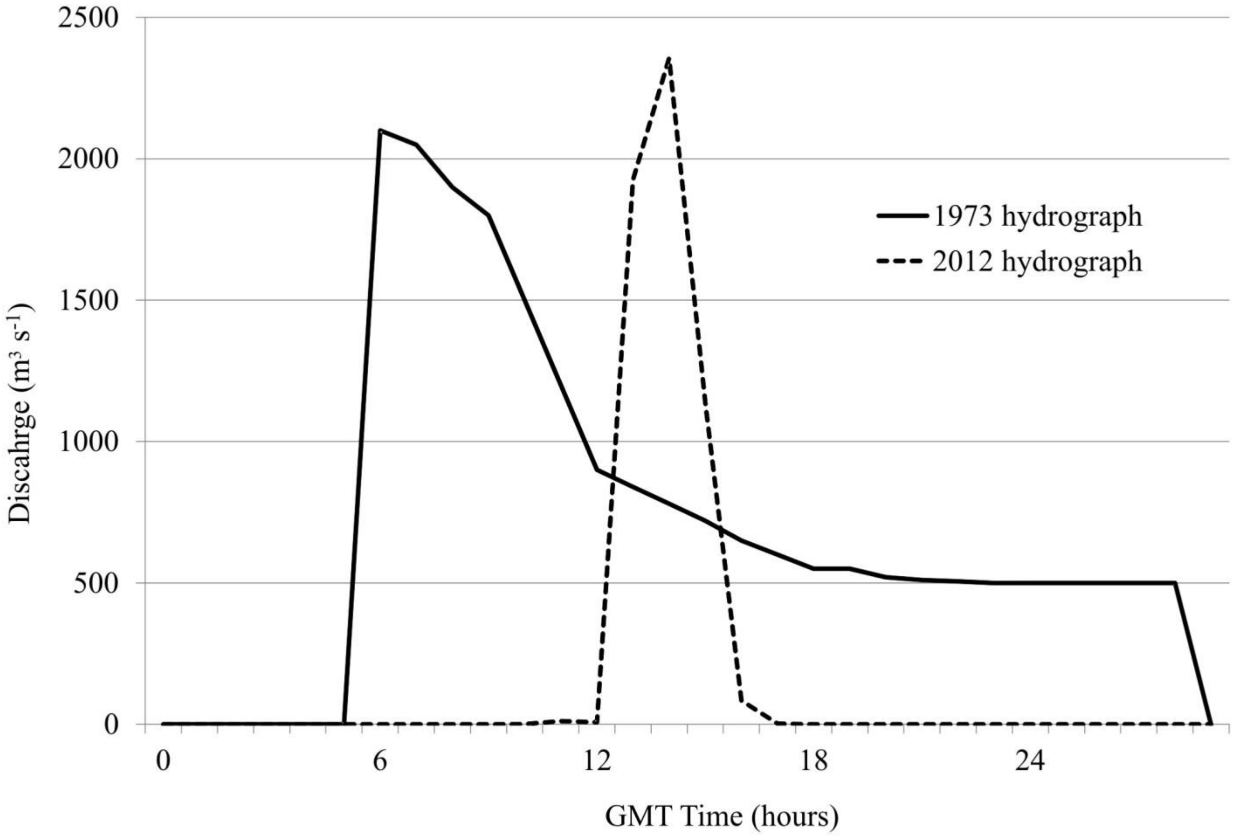

Figure 3. Peak discharge recorded by SAIH system for the Nogalte Rambla in Puerto Lumbreras during the 28 September 2012 flood and comparison with the hydrograph of 1973 event.

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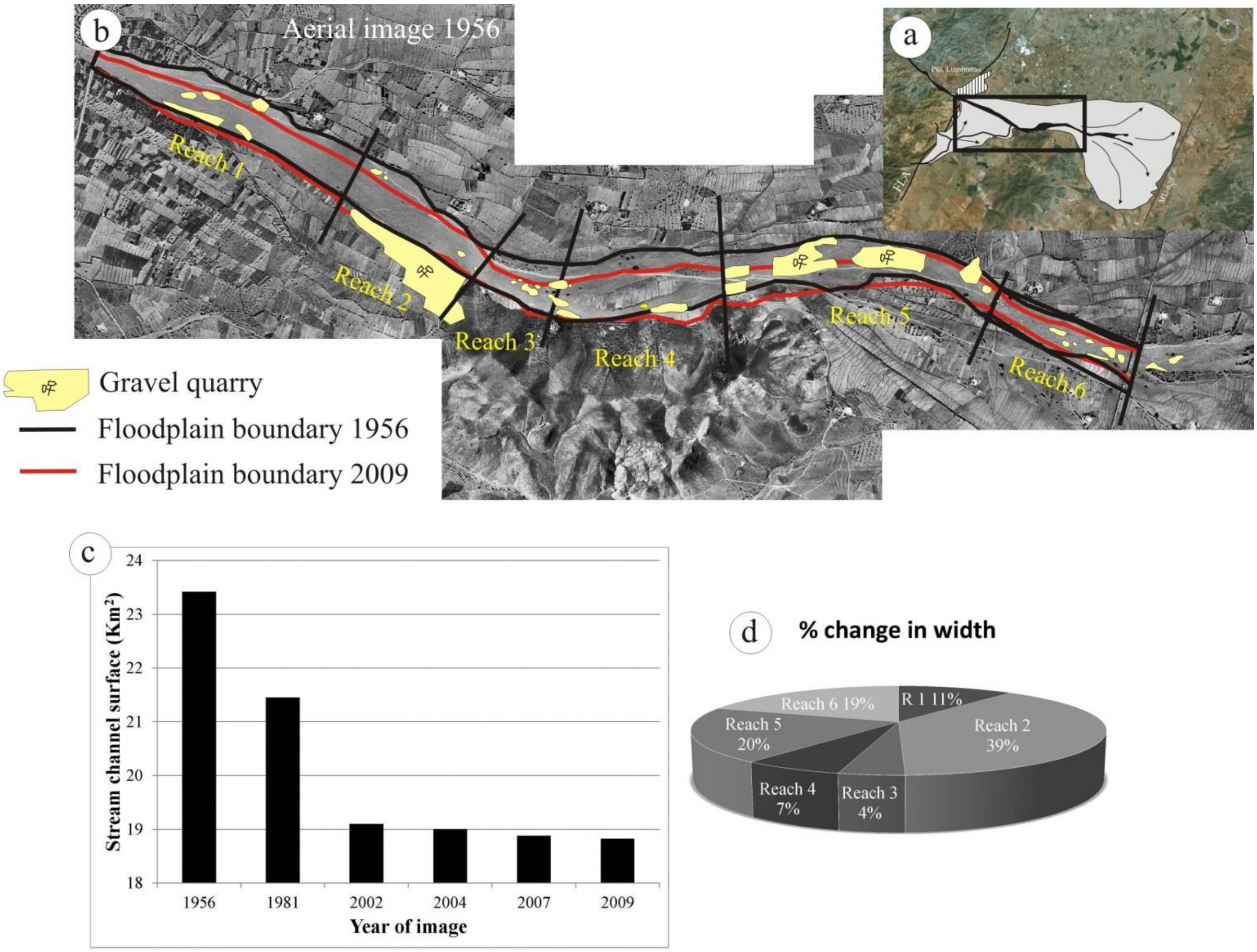

Figure 4. A-B. Location of the studied channel reaches and entrenchments showing channel bank boundaries change between 1956 and 2009 and related gravel quarries. C. Recent evolution in stream channel area. D. Percentage of channel width change for each reach.

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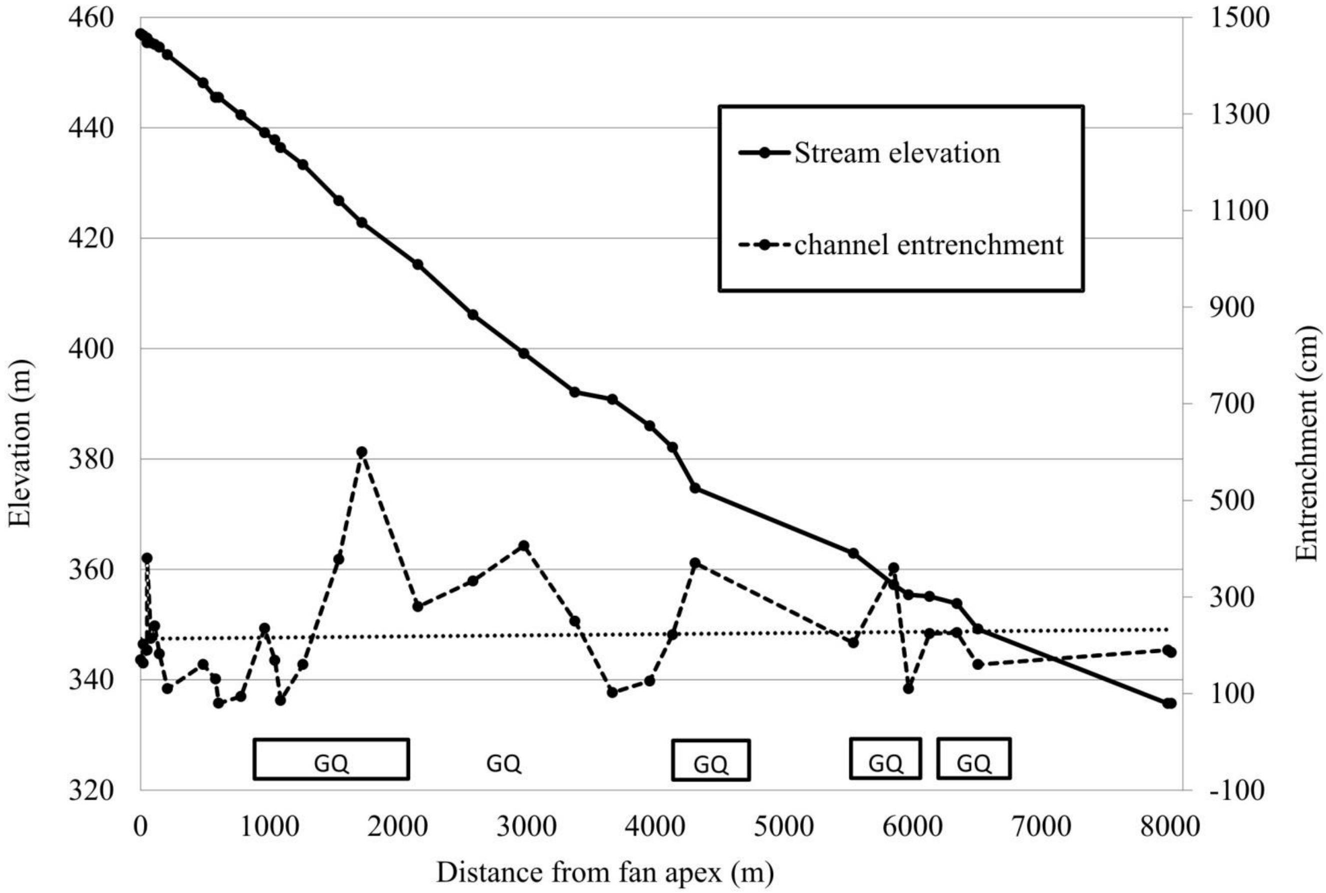

535

Figure 5. Nogalte River longitudinal profile and its channel banks entrenchment and related presence of gravel quarries (GQ).

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Figure 6. Pictures from the 2012 flood effects. A. Entrenchment of 2.5 m below Puerto Lumbreras Bridge. B. In-channel gravel quarry in Nogalte fan apex showing 4.5m channel entrenchment. C. Escucha chapel in Nogalte distal fan area showing the 1.5 m high water mark from 2012 event. D and E. Gravel mining impact on A-7 highway bridge after 2012 event; pillars are exposed in 2m. F. Headwards erosion due to gravel mining in the Béjar Rambla.

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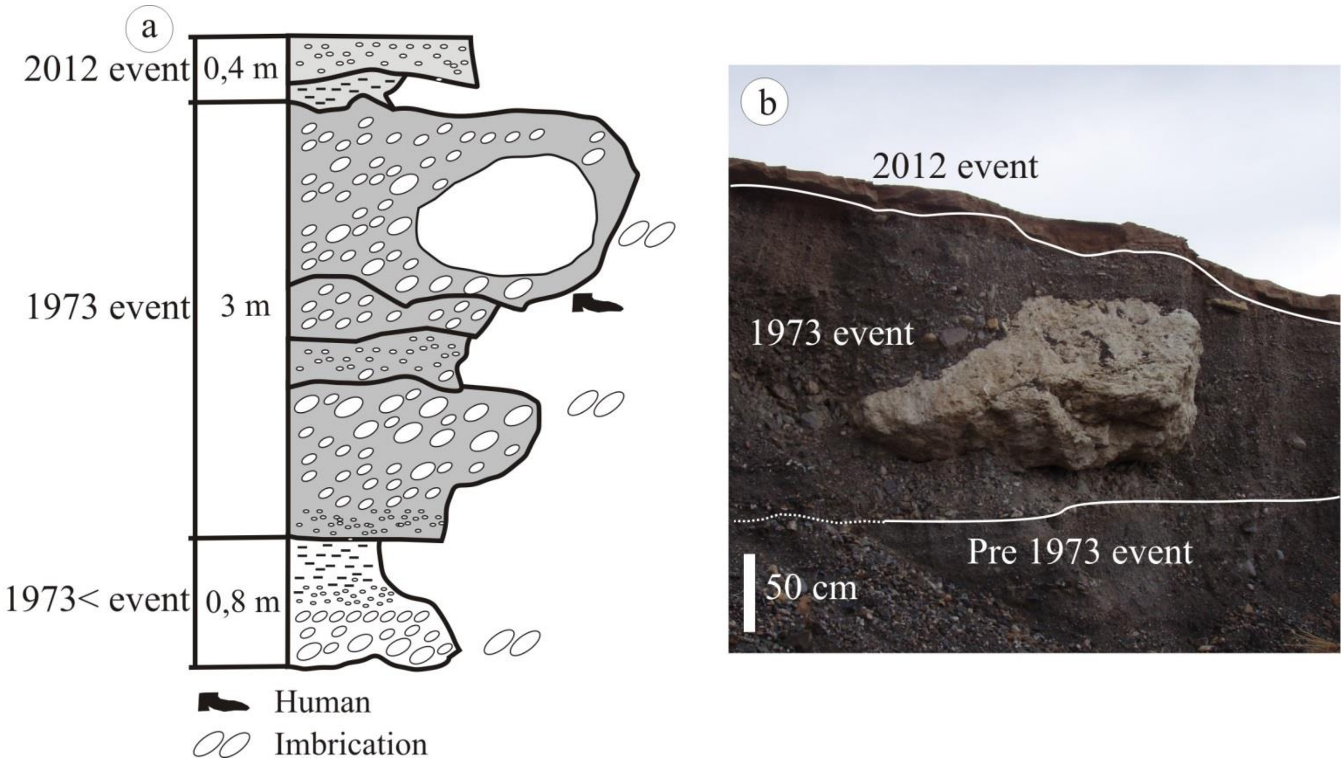

545 **Figure 7. Sedimentary section from 2012, 1973 and older floods recorded in the banks of Nogalte Rambla at Puerto Lumbreras.**

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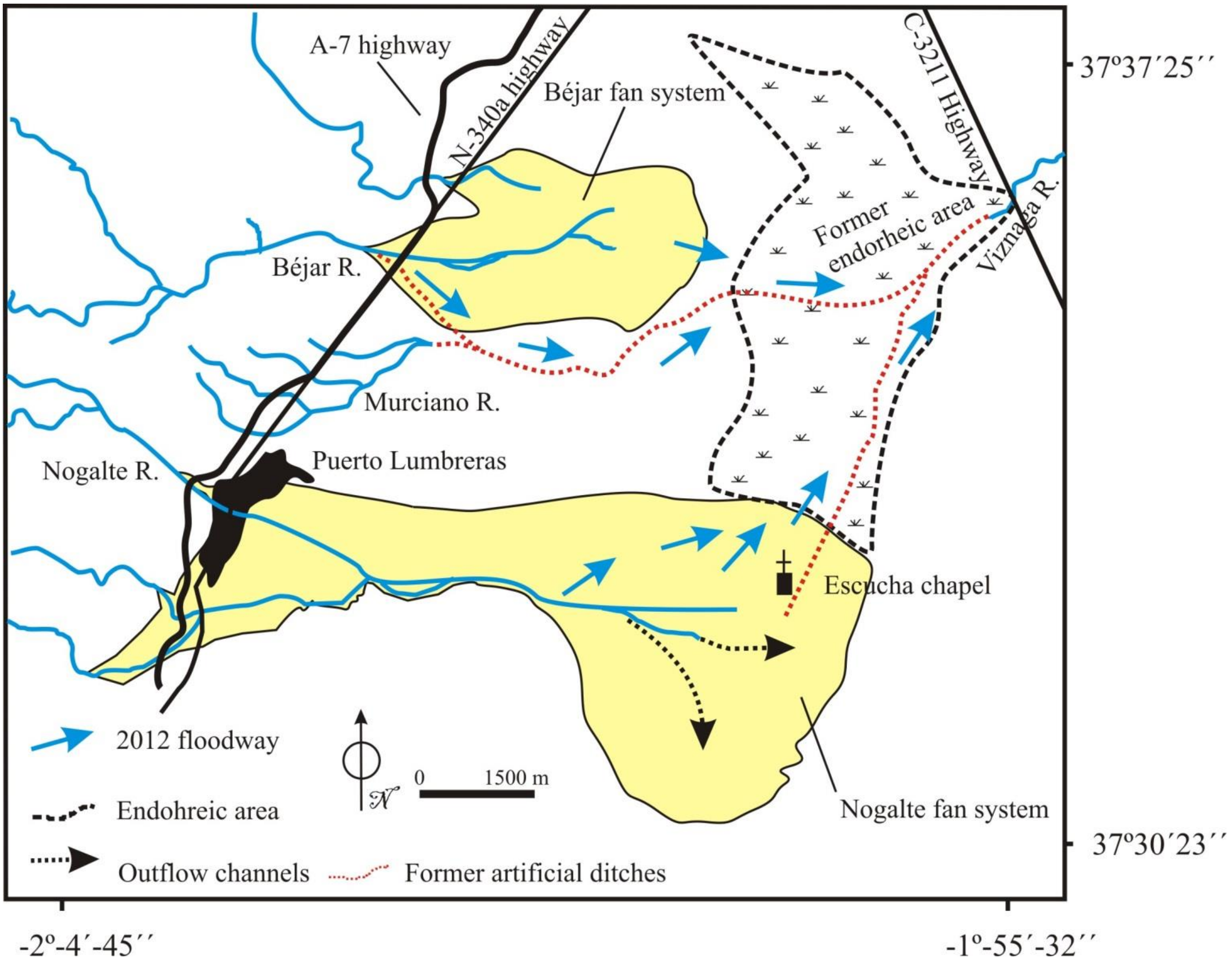

Figure 8. Evolution of the 2012 flood from medium Nogalte fan and Béjar stream (blue arrows) following former artificial ditches through Viznaga Rambla, flooding endorheic areas at the end of Nogalte distal fan (Escucha Chapel) and confined areas around C-3211 highway.

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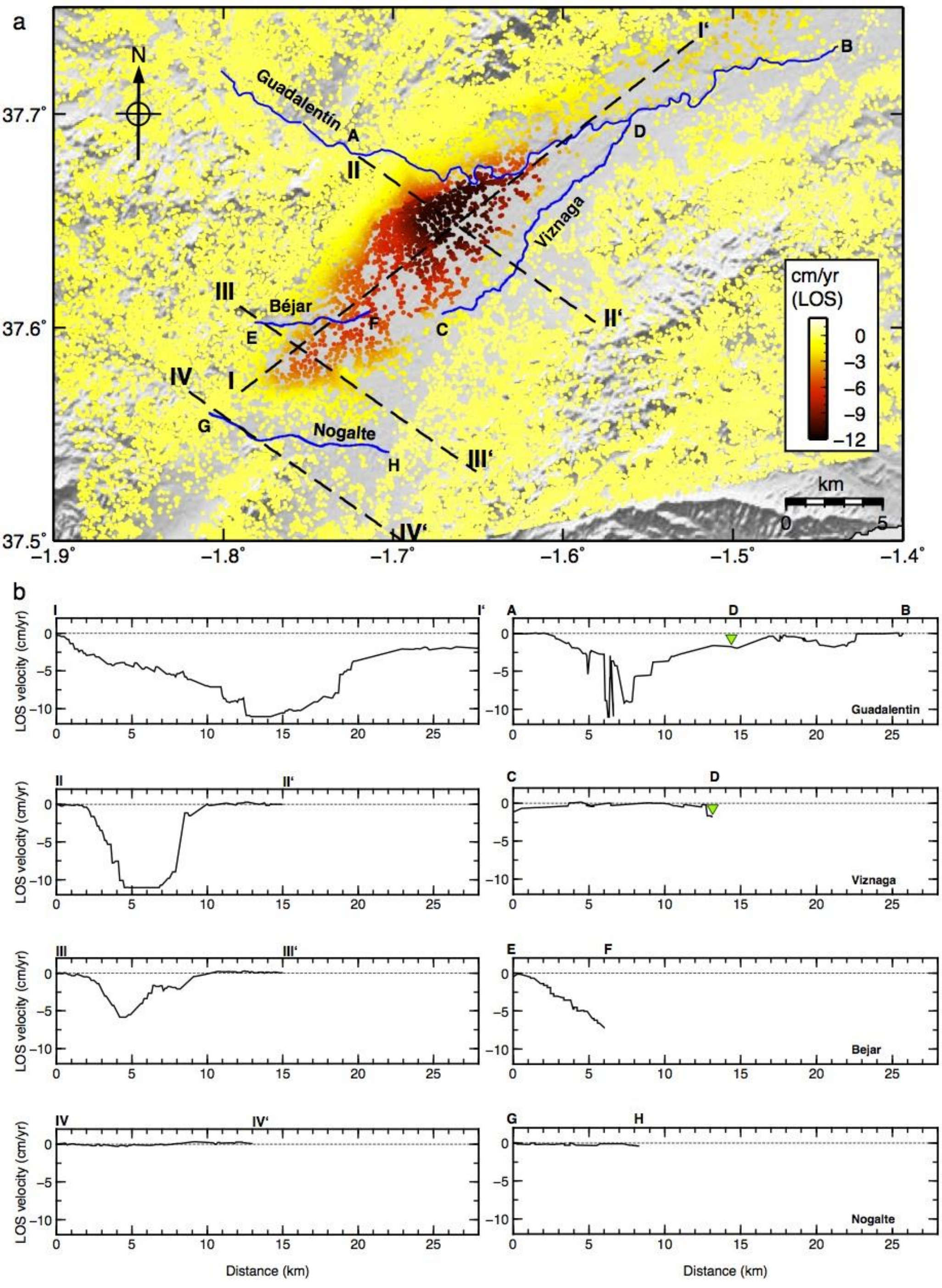

555 **Figure 9. A. Ground deformation measured by InSAR: colored dots represent InSAR velocities for the period 2003-2010 in the satellite's line-of-sight (LOS, ~23º from the vertical). The four channels analyzed in this work are represented by black lines. B. Cross sections: ground deformation velocities measured along the 4 discontinuous white lines in A (profiles with flags I – IV) and along the 4 channels identified in the map (profiles with flags A – H).**

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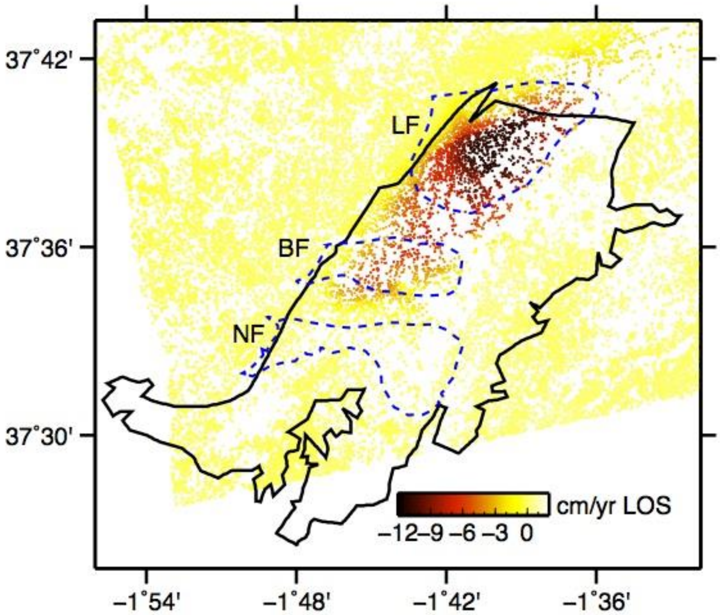

Figure 10. Map showing ground deformation in the studied area. The solid black line delineates the Alto Guadalentín aquifer. The dashed black lines indicate the approximate location of the three fans shown in figures 1B and 2 (LF-Lorca, BF-Béjar and NF - Nogalte fans).

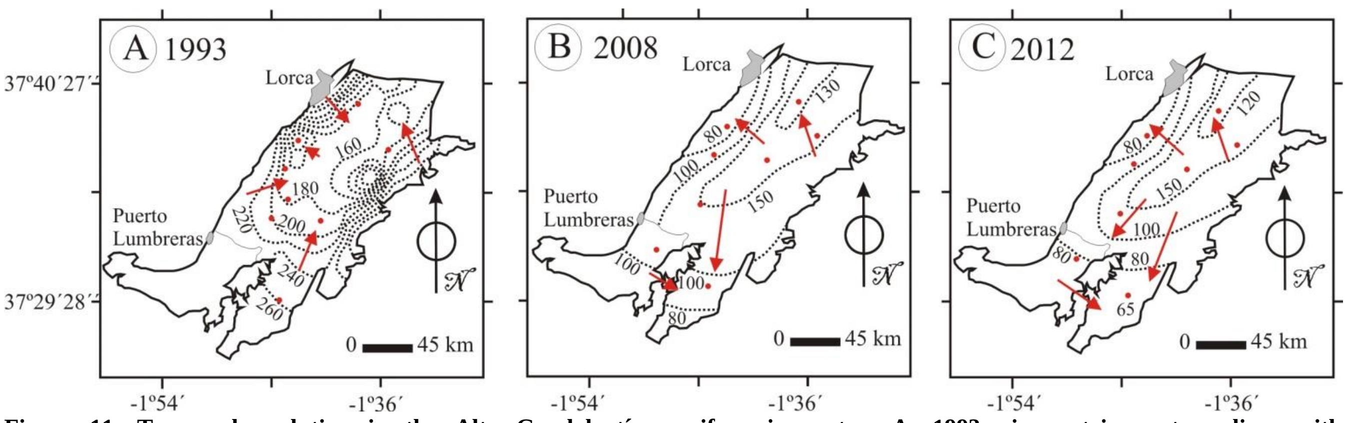

Figure 11. Temporal evolution in the Alto Guadalentín aquifer piezometry. A. 1993 piezometric contour lines with overexploitation signs. B. Aquifer in 2008 with inversed groundwater flow. C. Drop in groundwater surface in 2012 (Source: modified from IGME, 2009 and CHS, 2014).

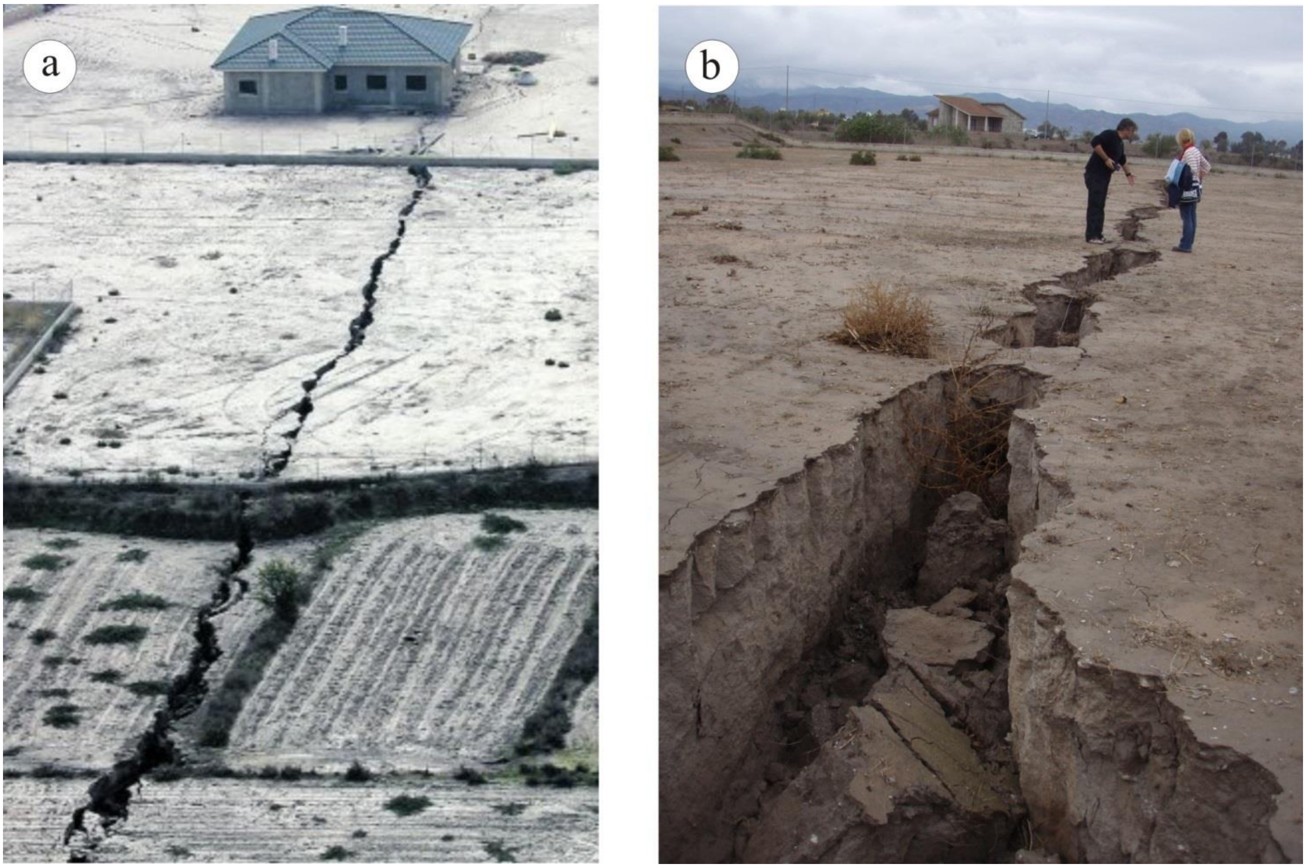

Figure 12. Compaction on clay soils interpreted as due to compressibility after groundwater overexploitation. A.Large crack development on vertisols on Béjar fan distal area (Source: La Verdad de Murcia). B. Crack detail up to 150 cm width and 2 m height.