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Recent morphological changes (2009-2022) on the floodplain of the Guadalporcún River, province of Cádiz (Southern Spain)

Cambios morfológicos recientes (2009-2022) en la llanura de inundación del río Guadalporcún, provincia de Cádiz (Sur de España)

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Abstract

In 2009 and 2013 two avulsion events occurred in the Guadalporcún River, a tributary of the Guadalete River, SW Spain. Google Earth and Geamap images acquired between 2002 and 2022 were examined and a timeline of events constructed. Exposed floodplain materials to a depth of up to 2 m reveal about 80 cm of sandy alluvium resting on a firm buried soil formed on older sandy alluvium with occasional pebble and boulder clasts. The avulsions, likely caused by logjams, breached the natural levee, and formed channels, less than 1 m deep in 2009 and more than 2 m deep in 2013. In 2013 the buried soil played an important role in the retreat of a knickpoint, the main process in avulsion channel formation. Following each avulsion event, a local landowner repaired the levee and levelled the floodplain, filling the avulsion channel with building rubble. The occurrence of two avulsion events separated by a few years shows that reestablishment of the original channel after the 2009 event was temporary and that similar events are likely to occur in the future.

Key words: Avulsion, floodplains: evolutionary changes, anthropogenic intervention, Guadalporcún River, Andalucía.

Resumen

En 2009 y 2013 se produjeron dos avulsiones en el río Guadalporcún, un afluente del río Guadalete, al suroeste de España. Se examinaron imágenes de Google Earth y Geamap adquiridas entre 2002 y 2022 y se construyó una cronología de los eventos. Los materiales de la llanura de inundación expuestos a una profundidad de hasta 2 m revelan unos 80 cm de aluvión arenoso que descansa sobre un suelo enterrado firme formado sobre aluvión arenoso más antiguo con clastos ocasionales de guijarros y cantos rodados. Las avulsiones, probablemente causadas por atascos de troncos, rompieron el dique natural y formaron canales,

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de menos de 1 m de profundidad en 2009 y más de 2 m de profundidad en 2013. En 2013, el suelo enterrado jugó un papel importante en el retroceso de un punto de contención, el proceso principal en la formación de un canal de avulsión. Después de cada evento de avulsión, un propietario local reparó el dique y niveló la llanura de inundación, llenando el canal de avulsión con escombros de construcción. La ocurrencia de dos eventos de avulsión separados por unos pocos años muestra que el restablecimiento del canal original después del evento de 2009 fue temporal y que es probable que ocurran eventos similares en el futuro.

Palabras clave: Avulsión, llanuras de inundación: cambios evolutivos, intervención antrópica, río Guadalporcún, Andalucía.

1. Introduction

Floodplains are among the most active geomorphic environments in river catchments. Large floodplains, with levees, meanders, cutoffs, oxbow lakes, and avulsion channels, have attracted considerable attention in the geomorphic literature (e.g., Dunne and Aalto, 2013). Small floodplains have attracted less attention. These often lack meanders and associated landforms, with floodplain features being confined to levees, backplains, and avulsion channels.

Avulsion is a well-known process on floodplains where the whole channel abruptly shifts to another position on the floodplain (O'Connor *et al*., 2003; Slingerland and Smith, 2004; Bridge and Demicco, 2008). Avulsion occurs when an event (usually a flood) of sufficient magnitude occurs along a reach of a river that is at or near an avulsion threshold

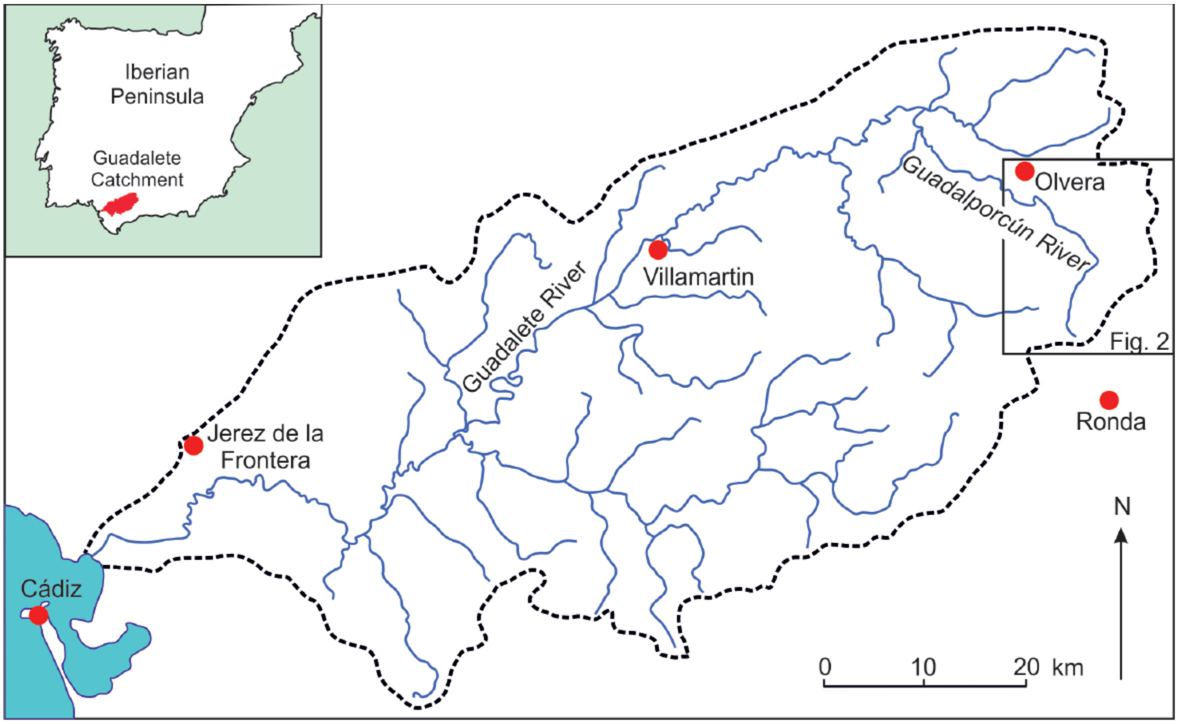

Figure 1. Main drainage lines in the Guadalete River catchment. Location of Figure 2 is shown on the right.

Figura 1. Principales líneas de drenaje en la cuenca del Río Guadalete. La ubicación de la Figura 2 se muestra a la derecha.

(Jones and Schumm, 1999). Avulsion usually involves a change in the ability of an existing channel to carry sediment and discharge. Such changes may be caused by sedimentation in the channel resulting from increased sediment load or blockages by vegetation and log jams. The river forms a crevasse channel that diverts flow onto the floodplain (Miall, 2014).

Between 2009 and 2013 there was a series of floods in the Guadalporcún River valley. Channel avulsion occurred on one small section of the floodplain. Attempts by a local land holder to return the channel to its former position succeeded briefly, but avulsion occurred again in 2013. Another attempt to restore the original channel was made and was finally successful in 2018. These changes provided an opportunity to study details of recent floodplain changes and to assess the impact of anthropic intervention on channel changes in this part of the Guadalporcún floodplain. The paper describes the floodplain morphology and stratigraphy, and the avulsion events. After the period of this study the river has been returned to its previous course.

2. Study area

The Guadalporcún River is a tributary of the Guadalete River, which flows into the Atlantic just northeast of the city of Cádiz in Cádiz Province, southern Iberian Peninsula (Figure 1). The highest parts of the catchment boundary are between 800 and 900 m asl and lie on the eastern edge of the Guadalporcún River catchment, east of Setenil de las Bodegas. The Guadalporcún River exits the study area at about 390 m asl. Upstream of the study area the Guadalporcún River drains an irregular dissected plateau consisting mainly of Tortonian and Messinian limestone, marls, calcarenite, calcareous sandstones, clay, silts, sands, and conglomerate (Cruz-Sanjulián, 1990; del Olmo Sanz and Serrano, 1990; Medina and Jerez Mir, 1990; Serrano, 1990) (Figure 2). The valley floor consists of a series of narrow floodplains (Qa on Figure 2) separated by V-shaped valley segments. The same pattern of narrow floodplains and V-shaped valley segments extends downstream from the study area.

The climate is warm, temperate, and typically Mediterranean. The average annual temperature in Setenil de las Bodegas is 15.5 °C with lows below freezing and highs approaching 40 ^{o}C. Annual rainfall averages 737 mm, with most falling between October and May. Data are from https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/setenil-de-las-bodegas_spain_2510915.

The study area is a small part of the Guadalporcún River valley south of the village of Olvera (Figure 2) and just upstream of the area described by Martínez Sánchez *et al*. (2019). For most of the study area the Guadalporcún River flows adjacent to steep bedrock slopes on the left (southwest) side of the channel, with the floodplain being confined to the right side (Figures 3, 4). Slopes adjacent to the floodplain on the northeast are gentler. Before the avulsion the only part of the floodplain on the left bank of the river was downstream of the convergence point (Figure 3). The floodplain studied here has two landowners. On Figure 6A the boundary between the two properties is marked by a straight row of trees that separate areas with slightly different tones.

3. Methods and Sources

Following a visit to the site and conversations with the land holders of the upstream part of the floodplain in the study area it was decided to map the changes that occurred, and to characterise the sediments.

Thirteen images acquired between 2002 and 2024 were examined (Table 1). These allowed comparison of channel locations before, during and after the flood events. Liz Aylmer and Jenny Stock, the land holders of the upstream part of the floodplain, also made available

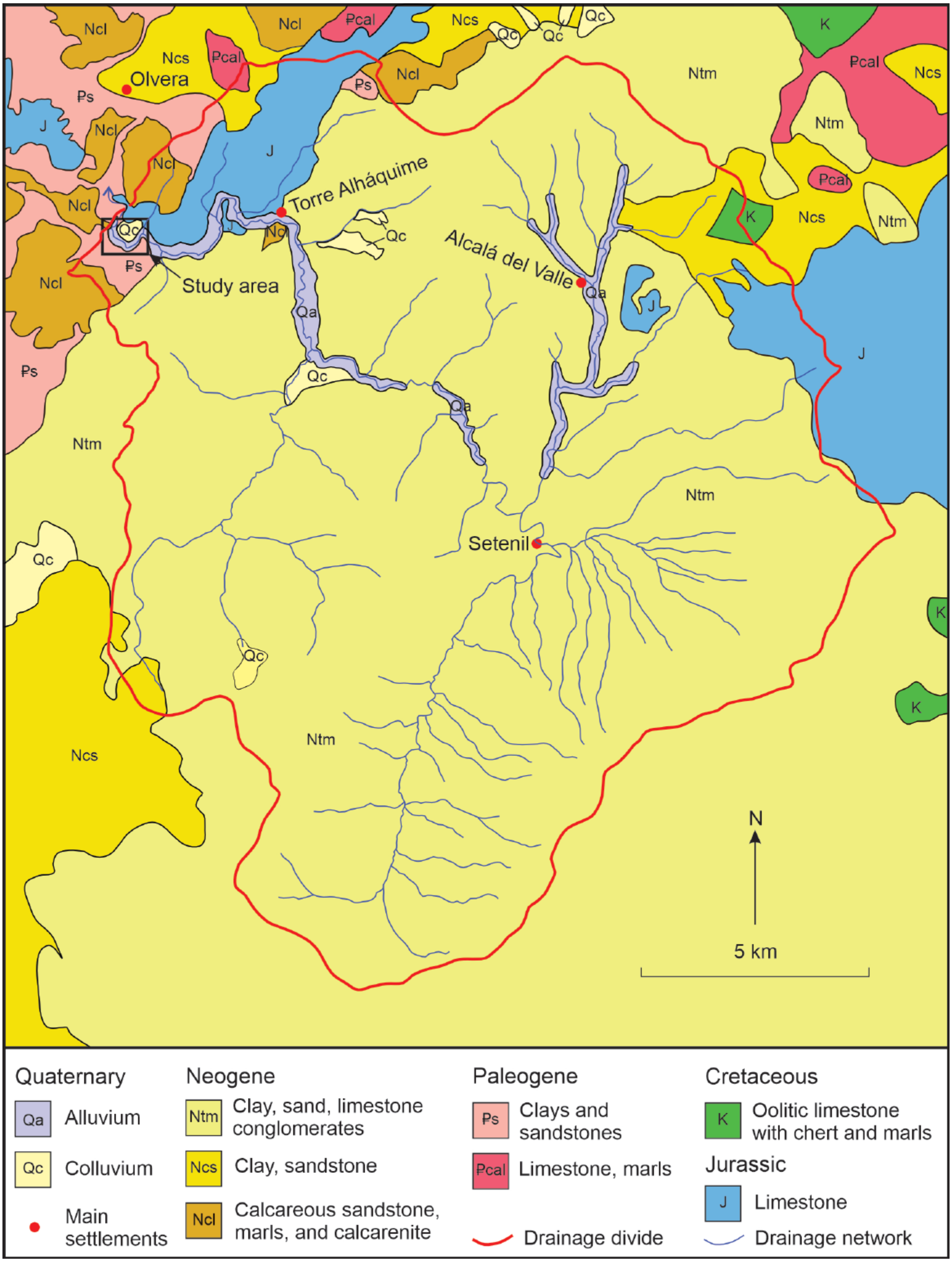

Figure 2. Lithology of the upper Guadalporcún River catchment. The study area is in the northwest.

Figura 2. Litología del alto Río Guadalporcún. El área de estudio está en el noroeste.

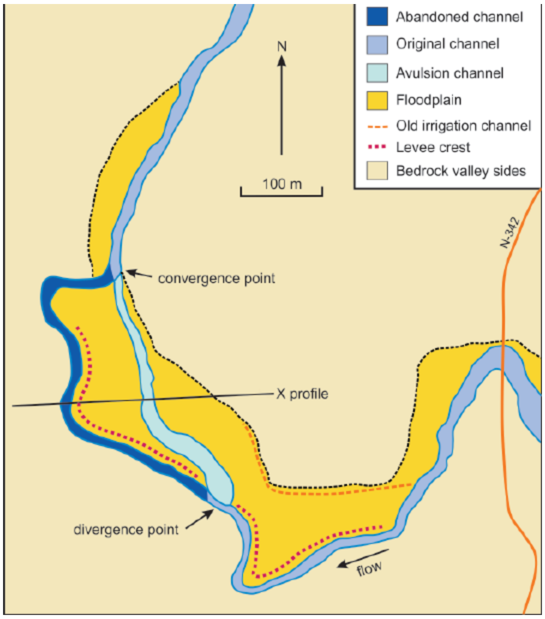

Figure 3. The main features of the study area. The X-profile is in Figure 4.

Figura 3. Principales características del área de estudio. El perfil en X está en la Figura 4.

photos and videos taken during flood events. Together these allowed a timeline of events to be constructed; this timeline was confirmed by Liz and Jenny.

Several field visits provided observations of channel and floodplain conditions at various times. Sections on the banks of the avulsion channel exposed floodplain materials to a depth of up to 2 metres, allowing materials to be examined and Munsell colours, field textures and other attributes described.

4. Results

4.1. Floodplain morphology and sediments

The floodplain has a simple morphology with a levee about 10 m wide and 1-2 m high adjacent to the channel on the right side (Figures 3, 4). The levee is not present for the whole length of the study area and is confined to the right bank of the channel. The left bank is adjacent to bedrock hillslopes, so no levee is formed. A cross profile of the floodplain (Figure 4) shows that the Guadalporcún River is higher than most of the floodplain and is separated from it by a well-developed levee. There is no evidence of splay deposits within the floodplain stratigraphy. However, at and near the divergence point the avulsion produced a thin cover of boulders and stones up to 15 cm in diameter that were derived from the channel upstream from the divergence point.

The banks of the avulsion channel expose more than 2 m of floodplain sediment (Figure 5, Table 2). Unit 1, 50-55 cm thick, is alluvium with a weakly developed soil consisting of AB and BC horizons. The lower boundary is sharp and represents a former floodplain surface. Unit 2, also alluvium, has a firm upper horizon with a blocky structure and a diffuse lower boundary (bA). These characteristics suggest that it is a well-developed buried soil 30-40 cm thick. Horizons bB and C are the lower parts of this buried soil. The lower boundary of unit 2 is sharp and wavy. The basal unit 3 extended below the water level at the time of observation.

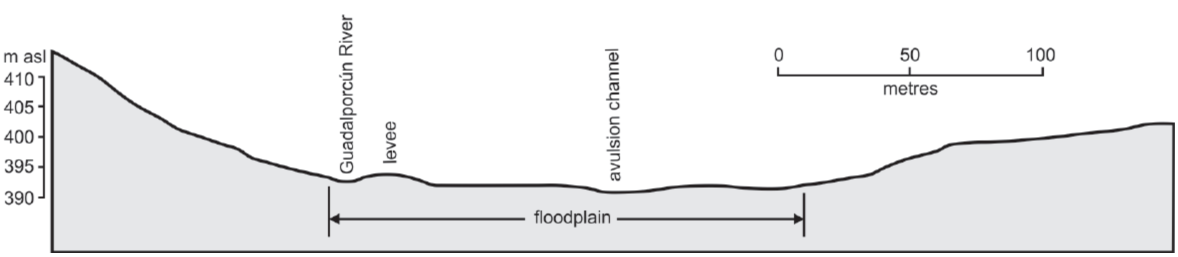

Figure 4. Cross profile of the floodplain (location shown on Figure 3).

Figura 4. Perfil transversal de la llanura de inundación (ubicación mostrada en la Figura 3).

Table 1. Images used to map changes
Tabla 1. Imágenes utilizadas para cartografiar cambios.

Date	Source	Attribution
2002	Google Earth	Maxar Technologies
2008	GeaMap	
2010	GeaMap	
17 Jul 2011	Google Earth	Digital Globe
10 Apr 2012	Google Earth	Landsat/Copernicus
1 Nov 2013	GeaMap	
2013	GeaMap	
28 Jul 2015	Google Earth	Landsat/Copernicus
27 Jan 2016	Google Earth	Digital Globe
3 May 2016	Google Earth	Europa Technologies
2016	GeaMap	
6 Jul 2018	Google Earth	Europa Technologies
15 Mar 2021	Google Earth	Maxar Technologies

GeaMap images were obtained from the Cartographic viewer of Spain web site http://geamap.com/. This site specifies only the year of imagery. Google Earth images were obtained using the historical imagery function in Google Earth. The attribution column gives the source of the image data as listed on Google Earth.

Table 2. Description of sediments.
Tabla 2. Descripción de los sedimentos.

<table>
<tr><th>Unit</th><th>Soil horizon</th><th>Thick (cm)</th><th>Colour</th><th>Description</th></tr>
<tr><td rowspan="3">1</td><td>AB</td><td>20</td><td>Light yellow brown 2.5Y 6/6</td><td>Friable sand; weak medium blocky structure; many grass roots; some organic staining.</td></tr>
<tr><td colspan="4">Diffuse boundary</td></tr>
<tr><td>BC</td><td>35</td><td>Pale yellow 2.5Y 8/4</td><td>Friable to loose sand; some fine gravel particles; massive structure; some roots.</td></tr>
<tr><td colspan="5">Sharp boundary</td></tr>
<tr><td rowspan="5">2</td><td>bA</td><td>30-40</td><td>Brown 7.5YR 4/6</td><td>Slightly friable to firm clayey sand; well-developed medium to coarse blocky structure; some organic staining.</td></tr>
<tr><td colspan="4">Diffuse boundary</td></tr>
<tr><td>bB</td><td>80-90</td><td>Light yellow brown 2.5Y 6/6</td><td>Friable sand; some fine gravel particles and rare matrix-supported pebbles and cobbles; massive structure.</td></tr>
<tr><td colspan="4">Distinct boundary</td></tr>
<tr><td>C</td><td>10-15</td><td>Light gray 7.5YR 8/1</td><td>Loose sand to fine sand, some pebbles and gravels; structureless</td></tr>
<tr><td colspan="5">Sharp wavy boundary</td></tr>
<tr><td>3</td><td></td><td>40-50</td><td>Brown 7.5YR 4/6</td><td>Clay to fine sandy clay with rare gravels and pebbles.</td></tr>
<tr><td colspan="5">Water level</td></tr>
</table>

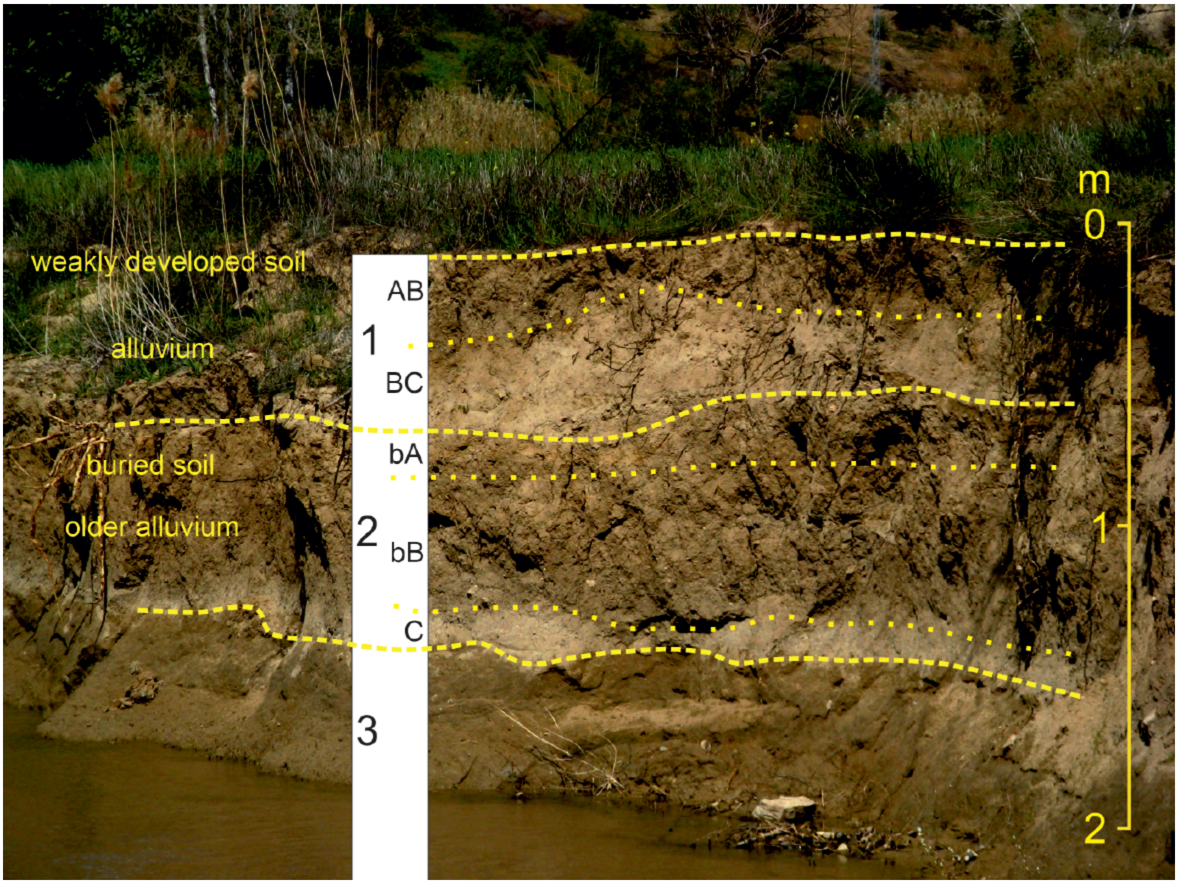

Figure 5. Floodplain sediments exposed on the bank of the avulsion channel in 2014.
Figura 5. Sedimentos de la llanura de inundación expuestos en la orilla del canal de avulsión en 2014.

The same general stratigraphy is present along all banks of the avulsion channel and under the levee where it was cut by the avulsion. In the latter case the unit covering the buried soil is up to 1 m thick. Unfortunately, these exposures are no longer available because the river has been forced back into its original course and the floodplain has been graded to allow resumption of cultivation.

4.2 Floodplain changes

The general timeline is set out in Table 3. Between 2002 and 2008 there is no evidence of avulsion, although there were floods during that period. The main path for flood waters reaching the floodplain appears to have been the old irrigation channel shown on Figure 3. During floods this channel carries water onto the floodplain, but no erosion appears to have resulted from either the 2009 or 2013 floods. Figure 6A shows the floodplain in 2008 about a year before the first flood; the old irrigation channel is marked by the irregular line of trees extending to about halfway down the floodplain.

On 22 December 2009 a flood broke through a low levee on the right bank at the divergence point (Figure 3) and flowed across the lowest part of the floodplain. By 24 December flood waters had covered the entire floodplain, and by 26 December the flood waters had receded, leaving a shallow (> 50 cm) channel on the floodplain. The flood also left an incipient gully near the convergence point, and a knickpoint began to develop (Figure 6B). Most flow

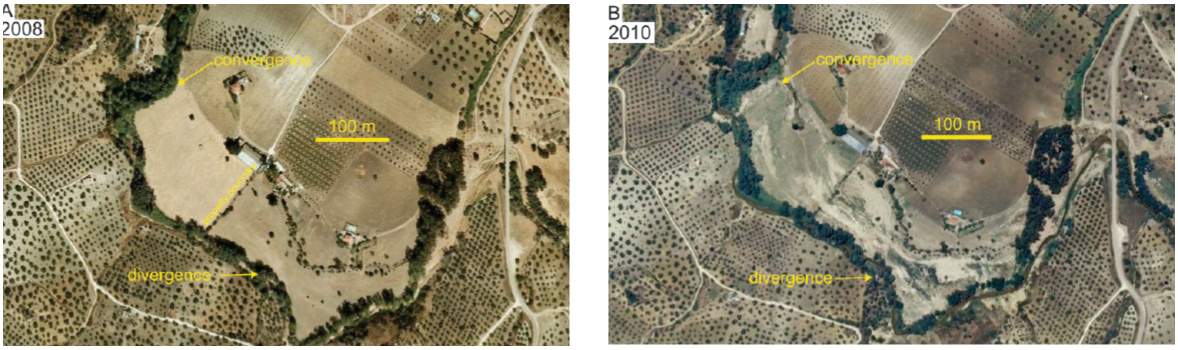

Figure 6. A. GeaMap image from 2008 showing the area before the flooding events. B. GeaMap image from 2010 showing the area following earthworks on the floodplain and at the divergence point. The remnants of the downstream end of the avulsion channel can be seen leading to the convergence point. Cropping on the floodplain resumed after this date.

Figura 6. A. Imagen de GeaMap de 2008 que muestra el área antes de las inundaciones. B. Imagen de GeaMap de 2010 que muestra el área después de los movimientos de tierra en la llanura aluvial y en el punto de divergencia. Se pueden ver los restos del extremo aguas abajo del canal de avulsión que conducen al punto de convergencia. El cultivo en la llanura aluvial se reanudó después de esta fecha.

was returned to the original channel. The base of the floodplain channel was formed by the buried soil within the floodplain sediments. In April 2010 the levee was artificially rebuilt at the divergence point and during the following months the shallow avulsion channel was artificially filled (Figure 7). This work was carried out by the owner of the downstream part of the floodplain as a means of returning his land to crop production.

Another major flood occurred in March 2013. On 20 March 2013 the repaired levee at the divergence point was breeched and the avulsion channel on the floodplain was re-established (Figure 8A). By 4 April 2013

Table 3. Timeline of major events 2009 – 2018.

Tabla 3. Cronología de los principales eventos 2009 – 2018.

Year (month)	Events
Post 2004	River crossing bulldozed at the future convergence point
2009 (December)	Flood broke through the levee and formed a shallow channel across the lowest part of the floodplain
2010 (February)	Avulsion channel established
2010 (April)	Earthworks at the divergence point to re-establish original river course
2010	Floodplain smoothed and cropping restarted
2013 (March)	Flood broke through and re-established the avulsion channel, which deepened into April
2013 (December)	Failed attempt to block avulsion channel at divergence point
2014	Filling of downstream end of avulsion channel with building rubble
2015	By June “wetland” ponds established
2016 - 2018	Avulsion channel artificially filled with building rubble and the river was redirected into its original course.
2018 (July)	Sometime before this the avulsion channel was filled
2021 (March)	By this time the floodplain was artificially smoothed, and cropping resumed

Figure 7. Rebuilding the levee and diverting the river back to its original channel at the divergence point in April 2010.

Figura 7. Reconstrucción del dique y desviación del río a su cauce original en el punto de divergencia en abril de 2010.

Figure 8. A. The divergence point on 20 March 2013 looking downstream. The original channel continued to flow on the left but most water flowed down the avulsion channel on the right. B. The divergence point on 4 April 2013. The new channel has cut about 1 m below the old channel, which was then abandoned. B also shows the nature of the original levee (photos: Jenny Stock).

Figura 8. A. El punto de divergencia el 20 de marzo de 2013 mirando corriente abajo. El canal original siguió fluyendo por la izquierda, pero la mayor parte del agua fluyó por el canal de avulsión de la derecha. B. El punto de divergencia el 4 de abril de 2013. El nuevo canal ha cortado aproximadamente 1 m por debajo del antiguo canal, que luego fue abandonado. B también muestra la naturaleza del dique original (fotos: Jenny Stock).

the avulsion channel was eroded to about 2 m depth below the floodplain surface; this led to the original channel being abandoned because it was left standing about 0.5-1 m above the bed of the new channel (Figure 8B). The new channel was up to 20 m wide near the divergence point and narrowing to about 5 m wide at the convergence point (Figure 9A).

Figure 9. A. GeaMap image showing the avulsion channel in mid-2013. Note the light-coloured flood sediments along the old irrigation channel. B. Google Earth image from 2022. The downstream property has been levelled, the levee at the divergence point has been repaired and the river has been returned to its former location. The avulsion channel fill shows as slightly darker tones. The avulsion channel on the upstream property is lined with low trees but has not been levelled.

Figura 9. A. Imagen de GeaMap que muestra el canal de avulsión a mediados de 2013. Tenga en cuenta los sedimentos de inundación de color claro a lo largo del antiguo canal de riego. B. Imagen de Google Earth de 2022. Se niveló la propiedad aguas abajo, se reparó el dique en el punto de divergencia y se devolvió el río a su ubicación anterior. El relleno del canal de avulsión se muestra como tonos ligeramente más oscuros. El canal de avulsión en la propiedad aguas arriba está bordeado de árboles bajos pero no ha sido nivelado.

Following the 2013 flood all floodplain changes were a consequence of artificial interventions. The landowner of the downstream property began to fill the downstream part of the avulsion channel, using building rubble from the nearby village of Olvera. Filling began at the downstream end and led to ponding of the channel at the upstream end. This work was accompanied by repair of the levee at the divergence point. By 2021 the Guadalporcún River was back in its original channel and the whole of the downstream property had been graded and cropping resumed (Figure 9B).

5. Discussion

5.1. Floodplain stratigraphy

No evidence of lateral accretion was found and there are no buried channels in the sections examined. The floodplain in the study area appears to have been formed mainly by vertical accretion and falls within confined vertical accretion sandy floodplains (A2) of Nanson and Croke (1992).

Faust *et al*. (2000), in a study of floodplain stratigraphy about 65 km southeast of Olvera, stress the importance of distinguishing true soils formed *in situ* in alluvium from transported humic deposits, which they call soil-sediments. As noted above, unit 2 (Figure 5) is interpreted to be an alluvial deposit with a soil formed *in situ*. The presence of only one buried soil contrasts with the area studied by Faust *et al*. (2000), where they found evidence for two episodes of *in situ* soil formation in floodplain sediments.

The buried soil within the floodplain alluvium (Figure 5) marks an important hiatus in the accumulation of the sediments. It would have formed on alluvium during a period of slow sediment accumulation. The light to very light yellow friable to loose brown sandy material (unit 1) overlying the buried soil is interpreted to be a result of accelerated erosion caused by human activity, sometimes called post settlement alluvium or legacy sediment (James, 2013). James *et al*. (2020) note that anthropogenic sedimentation on river floodplains is global in scale, with regional variations in timing and magnitude. It is also difficult to distinguish between erosion that is anthropogenic and that which is caused by climatic variations (Walsh *et al*., 2019).

No dates for the alluvium in the study area are available. Faust *et al*. (2000) report dates from sediments in their study area; based on pottery fragments, their uppermost soil unit (buried at 0.3 m) dates from about 1000 years ago, coinciding with the period of Moorish agriculture. The oldest buried soil (buried at 1.40 m) was formed about years ago (from pottery and AMS radiocarbon ages). This soil is recognisable in southwestern Spain, so the buried soil, unit 2 in Figure 5, may well be the same age.

Cultivation may have been established in southern Iberia by 7,000 BP (Shennan, 2018), and certainly by 5,000 (Zapata *et al*., 2004). Stephens *et al*. (2019) show that extensive agriculture was established in the Iberian Peninsula by 6000 BP, and intensive agriculture by 4000 BP. Romans were growing olives and vines in the Guadalporcún River catchment by the first century A.D. (Rodríguez-Ariza and Moya, 2005). Lang *et al*. (2003) and James and Lecce (2013) show that it wasn't until Roman times that sediments resulting from intensive agriculture began to be deposited on floodplains in Europe, so it is likely the alluvium overlying the buried soil began c. 2000 years ago. This impact continues to the present.

5.2. Floodplain changes

The channel diversion described here was not a cutoff, because there are no shifting meanders in the study area. It was an avulsion, where flow was diverted to a different position on the floodplain (Bridge, 2004). River avulsion takes place in two phases, setup, and trigger (Phillips, 2012). In most cases the setup phase leads to the riverbed being higher than the adjacent floodplain because of the formation and consolidation of levees, and sedimentation on the riverbed. This situation existed in the study area before the avulsions of 2009 and 2013 (Figure 6, Figure 9). The pre-avulsion channel bed was perched about 1 m above the floodplain and separated from it by a well-developed levee covered with trees that made it stable.

Triggers are events that divert flow from the channel to the floodplain. In the case of the study area overtopping and then breaching and failure of the levee in 2009 was most likely caused by blocking of the old channel by a log jam. The 2013 avulsion was probably facilitated by the loose fill of the artificial levee, which was constructed of loose sand and tree logs. In 2009 the avulsion channel was less than 1 m deep and formed by erosion of the alluvium (unit 1) above the buried soil. In 2013 the avulsion channel was more than 2 m deep and formed by knickpoint retreat within unit 2 from the convergence point (Figure 10). Knickpoint retreat is a common process in the development of avulsion channels (Slingerland and Smith, 2004); in this case the knickpoint may have been initiated by a bulldozed river crossing at the convergence point. In both 2009 and 2013 the avulsion channel (c. 340 m) was shorter than the original channel (c. 430 m), so was steeper, which would have enhanced the erosion potential. Upstream of the area studied here, erosion during the flood events was confined to floodplain sections. There was no associated slope erosion that would have led to an abrupt increase in sediment carried by the river.

The artificial rebuilding of the levee at the divergence point leaves the levee liable to breaching in future flood events because it is weaker than the natural levee. Levelling of the floodplain, especially filling of the avulsion channel with building rubble, is also problematic because the development of any future channel will bypass the filled channel and erode the less resistant alluvium adjacent to the building rubble. Reestablishment of the original channel is at best temporary.

Figure 10. Knickpoint on the avulsion channel on 31 March 2013. Note the light-coloured alluvium at the top on both sides of the channel. Upstream from the knickpoint the water is flowing on top of the buried soil. The original and natural levee, with trees, can be seen on the top right. (Photo: Jenny Stock).

Figura 10. Knickpoint en el canal de avulsión el 31 de marzo de 2013. Obsérvese el aluvión de color claro en la parte superior a ambos lados del canal. Aguas arriba del knickpoint, el agua fluye sobre la tierra enterrada. El dique original y natural, con árboles, se puede ver en la parte superior derecha. (Foto: Jenny Stock).

6. Conclusions

Avulsion is a well-known and well-studied feature of alluvial landforms. The two avulsions in the Guadalporcún River valley (2009 and 2013) followed the common sequence of events from breaching of the levee to the formation of a new channel mainly by knickpoint retreat. The alluvium, mainly derived from agricultural land in the catchment, played a role, especially the buried soil that controlled the retreat of the knickpoint. An unusual aspect of the avulsions is that attempts to return the flow to the original channel were successful and the land was returned to cropping. However, these efforts were short lived in the period 2009 to 2013 and are likely to recur in the future.

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Disclosure statement

No potential conflict of interest was reported by the author.

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