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Boletín de la Asociación de Geógrafos Españoles N.º 72 - 2016, págs. 527-534
I.S.S.N.: 0212-9426

HUMAN ACTIVITIES AND INUNDATION RISKS IN THE PLAIN OF THE GUADALQUIVIR RIVER (IN THE REACH BETWEEN PALMA DEL RÍO AND SEVILLE, SPAIN)

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I. INTRODUCTION

Alluvial plains are a natural response to the dynamic fluvial balance between sediment input and output during floods in the course of the millenniums playing a key role in the fluvial dynamic during floods.

Despite the important physical function they perform in river systems and the high risk of flooding, floodplains have been important sites of human activity and economic development over the years.

These human activities have introduced important and irreversible modifications in the fluvial dynamics of streams and floodplains.

This paper presents the overall characteristics of the fluvial geomorphology of the Guadalquivir river in the province of Seville, Spain. Human activities conducted over the last fifty years are evaluated in order to understand the spatial and temporal dynamics of the geomorphological changes in the riverbed and inundation zones.

II. STUDY AREA, METHODOLOGY AND SOURCES

The Guadalquivir river with an average annual flow of 7,230 hm^3 and a watershed area of 57,527 km^2 represents the main basin in Southern Spain. Its water regime is clearly influenced by the weather fronts connected to Atlantic storms in November and March every year, resulting in an extreme seasonal (Cq: 13.8) and interannual (Cq: 7.9) variability, as well as flood flows ranging from 1,500 to 12,000 m^3/sec.

The study area comprises a larger reach of the stream of more than 80 km long and 6 km wide, stretching from the town of Palma del Río to the city of Seville.

A geomorphological map of the Low Guadalquivir (scale 1:50,000) based on aerial photogrammetry (scale 1:30,000) dated 1956 was used to carry out the study. This serves as a basis to identify the fundamental morphological elements of the alluvial plain (borders, inundation zones, high water riverbeds, abandoned meanders, alluvial terraces, tributaries).

At the same time, the evaluation of changes resulting of human activities in the selected time period of 55 years was performed by means of field research, study of photographs from 1956 (U.S. Army, scale 1:30,000), 1973 (CEFTA S.A., scale 1:25,000) and 1981 (FOYCAR S.A., scale 1:25,000), as well as with the help of multi-temporal orthoimages, Landsat 5 from 1990 (scale 1:100,000) from the Instituto Geográfico Nacional (MOPU) and SPOT from 1991 (scale 1:50,000) corresponding to the Seville metropolitan area (Environmental Agency - General Directorate of Land Management, Junta of Andalusia) and the colour digital orthography of Andalusia from 2007 and 2010/2011 (Cartographic Institute of Andalusia).

The Automatic System of the Hydrological Information for the Guadalquivir river (SAIH) at the Alcalá del Río dam (Water Management Agency of Andalusia, 2011) was considered as source of hydrological records and historical data.

III. HYDROMORPHOLOGICAL ELEMENTS AND THE NATURAL FUNCTION OF THE ALLUVIAL PLAIN OF THE GUADALQUIVIR RIVER IN THE SEVILLE PROVINCE

The alluvial plain of the Guadalquivir river comprises a flat area with altitudes between 8 and 50 m and it is demarcated by prominent slopes. At least since the Roman Age, the flows interact on this plain with following hydromorphological elements:

III.1. The river and its ordinary course

The Guadalquivir river runs through a single ordinary riverbed, on the average 100 to 150 meters wide and six to ten meters below the elevation of the alluvial plain. There are frequent seasonal oscillations of the flow with a minimum in September (32 m^3/sec.) and a maximum in the spring (300-400 m^3/sec.). Nevertheless, these flows do not exceed the bankfull flow rate estimated as 900 m^3/sec.

The course consits of two sections called estuary area and continental área. The estuary área is situated downstream toward the dam of Alcalá del Río and it is characterized by a middle gradient slope of 0.00044%. This area is influenced by tide and fluvial dynamic only during floods. On the other hand, the continental area is situated upstream and has a larger gradient of 0.039%. It is only affected by fluvial dynamic. In both cases, the extremities of course are formed by steep riverbanks.

The natural riverine vegetation plays an important role, fixing the loam-sandy material on the riverbanks and colonizing the ecosystems of the sandbanks with the riverine species of great ecological value.

They are numerous in this sector of the plain as well, having an effect both seasonal and annual, depending on their route and their watershed area. Among the tributaries flowing down from the Sierra Morena, the most important are the rivers Retortillo, Guadalbarcar, Rivera de Huéznar, Viar and Rivera de Huelva. All of them have large gradients, moderate average flow volumes (from 7.75 to 12.2 m^3/sec.) and high flow velocity. Among the tributaries on the left bank the river Genil plays a prominent role, contributing a large share of the annual average flow volume of the Guadalquivir (40 m^3/sec), as well as contributing to the decreasing of the river gradient as well as the enlargement of the plain. Other important tributaries of this riverbank are Corbones and Guadaira, both with more moderate flow volumes than those which flow down from the Sierra Morena, although they have high flow rates during floods (greater than 500 m^3/sec.). The tributaries represent a principal factor in the hydrological dynamics both of the river and the plain. They deliver 42.6% of the final flow volume of the Guadalquivir along with a significant fraction of its sediment load.

III.2. Abandoned riverbeds, Holocene terraces and floodplains

Abandoned riverbeds correspond to old meanders died down by the main current of the Guadalquivir river during floods. Their route could be identified in shallow elongated depressions situated between 1 and 1.5 meters below the surrounding terrain. Together with the main channel of the river, they play a predominant role in water circulation through the plain, functioning as overflow channels during floods. The origins of most of them date back to the Roman times (first century A.D) based on numerous archeological remains found in the estuary sector or in upriver banks from Alcalá del Río.

Until the second half of the last century their presence has been widespread on all parts of the alluvial plain ("Old Rivers") where, aside from the agricultural exploitation, they have been fulfilling the function of drainage for the inflows to the Guadalquivir river in its final stretches.

There are five levels of Holocene terraces setting up the boundaries of the inundated parts of the plain for various flood magnitudes. In the study reach, terraces are divided into two morphogenetic groups: the upper one corresponding to the Pleistocene to the Upper Holocene, +10-13 m (T13), +9-10 m (TH1) and +7-8 m (TH2) with respect to the water lamination level; and the lower one (Th1, Th 2, Th3), below the six-meter-level with respect to the river. The first group stays on the margin of all inundation, while the second one is linked to the historical dynamics of the meanders.

IV. HISTORIC HUMAN ACTIVITIES IN THE ALLUVIAL PLAIN AND THE STATE OF INTERVENTION IN IT IN THE MID-20TH CENTURY

Widespread human activities in the plain of the Guadalquivir river began in the Roman Age seeking agriculture and navigation benefits. However, the Roman presence prevented the construction of large human settlements above the main terrace (T13) as a natural limit for most frequent inundations at this time. This also explains the fact that the majority of towns and villages in the fertile plain have been constructed 10-12 m above the normal water level: Seville (*Hispalis*), Santiponce (*Itálica*), Alcalá del Río (*Ilipa Magna*), Cantillana (*Naeva*), Alcolea del Río (*Canania*), Lora del Río (*Axati*) or Peñaflor (*Celti*).

During the medieval and modern age, first settlements were formed in the floodplain as for example La Algaba, La Rinconada, Brenes or Tocina. This indicates a direct link between the origin of population centers and the use of the river waters for livestock farming (drinking troughs, cattle fords, charcoal production using woods near the banks. etc.). Already at the end of the 18th century the first large projects that altered the floodplain shape were conducted in order to provide sufficient depth for navigationand to manage the increased frecuency of floods. At the beginning, they were concentrated on the construction of artificial dikes and „cortas“ (meander cutoffs) downstreams of Seville but during the 20th century, new projects were initiated aiming to regulate the slope of the riverbed. During this time, the first permanent river crossings was erected; the retarding dams in the main riverbed was built to enable navigation on the Guadalquivir up to Córdoba and several canals for irrigation were all constructed. The situation became critical in the mid-20th century with the plain completely transformed. The most distinctive structural changes seemed to be the human interventions listed below:

a) The shortening of the riverbed has reduced the channel length downstream of Seville by more than 40 km and its continual dredging has regulated the river gradient. Moreover, the artificial displacement of the main stream towards the right river bank in the town of Seville has led to the old riverbed being used as a dock in the interior of the city. At the same time, there were already three dams constructed in the riverbed of the Guadalquivir (Peñaflor, Alcalá del Río and Cantillana). Further, a partial regulation of tributaries such as Rivera de Huelva, Viar and Genil with a total reservoir capacity of 298,37 Hm^3 was achieved by building five dams. As for the remaining hydrological basin upstream, the number of dams has been increased to 13 with a total capacity of 1,157.3 Hm^3.
   In addition to this, the first half of the 20th century included the construction of most of the necessary infrastructure network of canals and drainage ditches to irrigate the entire alluvial plain affecting all of its morphohydrological elements.
b) There were 461,185 people settled on the floodplain in 1950, spread out in 21 population centers belonging to 18 municipal areas in the province of Seville. It must also be highlighting the elevated density of roads and railways part of the transportation network. Ten bridges in total, three of them for the railways, and three dams with a crest road, connected the two river banks over a distance of more than 110 km. The whole floodplain has intensive agricultural production, due to the irrigation infrastructure, resulting in 110,000 ha of irrigable land. As for the urban land use, it is restricted to the area of the initial settlements with the exception of Seville, where a system of flood protection structures has allowed the expansion of the city towards the inundation zone.

V. FIRST CHANGES IN THE FLUVIAL GEOMORPHOLOGY (DECADE OF THE 1950)

The hydrological control and the impacts on the water downstream of Seville introduced the first geomorphological changes that affected unequally two different sectors to be called by us the estuarial and the continental zone. The first interventions intending to improve navigation and to avoid flooding in the Seville area resulted in: an increase in the river gradient and its depth; the disappearance of the areas of sedimentation in the meanders; reduced lateral mobility of the riverbed; a lower frequency of excessive flows, and greater and faster transmission of tides. An artificial transformation of the riverbed has been produced this way, enhancing its width and depth and causing a loss of 30 to 50 percent of the floodable area in the city of Seville. The second zone stretches upstream from this dam, enabling to the river to stay in a seminatural state, although it is affected by the Alcalá del Río dam and a riverbed incision upstream of Cantillana. From here, an absence of a dams on the tributaries coming down from the Sierra Morena enabled large loads of sediment to accumlate in the form of central and lateral sandbanks in the Guadalquivir river. In February 1963, the plain was affected by an extraordinary inundation estimated in 5,700 m^3/sec at the gauging station of the Alcalá del Río. The water caused flooding of the lower terraces (TH2 and the historical ones) and causing devastating damages in all surrounding towns with a total of 1,097 ha of inundated land and 15,316 evacuated persons.

VI. HYDROSYSTEM CONTROL OF GUADALQUIVIR RIVER DURING THE SECOND HALF OF THE 20TH CENTURY

It was after the flood of 1963, when the authorities responsible for managing the river basin set upon a change of priorities in the hydraulic interventions oriented until then on the irrigated land and the improvement of the fluvial connectivity steering the river regulation enhancement. The capacity of all the reservoirs was about 1,500 Hm^3 at that time, which is a large enough volume to modify the hydrological regime of the river but not large enough for its complete regulation, which is estimated to require between 8,000 and 9,000 Hm^3. The Spanish government released funds in the 1980's and 1990's to be invested in the construction of 13 dams with 1,632 Hm^3. However, these dams were never filled to the technical levels required for hydrological control purposes. Nevertheless, the quadrupled quantity of the water dammed up in the 1950's combined with the long periods of draught in the 1980's and 1990's created a false perception that catastrophic flooding had been eliminated. The construction on an artificial riverbed known as "Corta de la Cartuja" was completed in 1982, displacing the river from the city area and enabling urban development in the floodplain such as the Expo 1992 facilities. The main characterisitics of this area are following:

a) An increase of 50,7% of the total province population in 1991 within a surface area which only occuppies 4% of the total surface of the province.
b) Improved existing transportation infrastructure in comparison to previous century as well as increase in the number of roadways around the city and across the countryside.
c) A system of flood protection dikes, with the crest 6 to 12 m above the floodplain level which, today, is spread out on both sides of the new riverbed in Seville.
d) Expansion of agriculture work, including irrigation, requiring increased water extraction from the alluvial aquifer that is hydraulically connected to the river.
e) Due to the high demand for sand and gravel for use in construction projects, sand and gravel were excavated from the river bed.

VII. GEOMORPHOLOGICAL CHANGES AND THEIR REPERCUSSIONS

The abovementioned control of the hydrosystem of the Guadalquivir river generated an important transformation of the riverbed and the alluvial plain at the end of the 20th century. Incision of the channel and reduction of the river width are ongoing and widespread. This phenomenon has been observed in the whole lower continental stretch of the river by means of diachronic monitoring of the lateral sandbanks that formed two new terrace levels over a 30-year period. This process is more intense in the estuarial section, and downstream from dams:

a) At the Alcalá del Río dam, the incision is increasing downstream where the dikes along the riverbed reach a height of 8 to 10 m, while upstream a strong and immediate colmatation is produced.
b) At the Cantillana dam, there is an incision between 2 and 4 m deep extending downstream to Alcala. From here downstream, the effect at the level of the local dam basis originates a strong colmatation in the riverbed.
c) At the Peñaflor dam, an incision can also be found downstream up to Alcolea del Río and a deposition upstream in the riverbed up to the vicinity of Palma del Río.

In addition, a large number of dams constructed on the tributaries have altered the hydrological regime (decrease of maximum flow volume and disappearance of low water levels) as well as the sediment transport resulting in a strong development of river vegetation in the riverbeds.

Concerning the alluvial plain, the potential risk of inundation increased due to the alteration, or in many other cases, to the total disappearance of the morpho-hydrological elements indispensable for its correct functioning. This effect was seen clearly during the floods in December 1996 and January and December 1997, when the stream reached values between 3,200 and 3,670 m^3/sec. between Cantillana and Palma del Río. A flood which took place in this area in 1963 showed a similar behavior, although the flow rate was only about half the flow rate in the 1996 and 1997 floods. Conversely, floods caused no major problems downstream of Alcalá del Río and near the city of Seville, due to the successful functioning of the flood protection structures.

VIII. URBANISM AND NEW INUNDATION RISKS IN THE 21TH CENTURY

The perception of general security in the city of Seville during the last floods, together with the rise of land speculation, gave an impulse, at the beginning of the 21st century, to the politics of urban expansion in one of the districts close to the city. This happened despite the fact that the population of the floodplain in 2011 (900,000 inhabitants) just increased by 14 percent compared to that of the 1990's.

This phenomenon has been accompanied by a comparable build-up of infrastructure which consisted of two types of activities highlighting the different behavior of the plain during the floods. The first type consisted of flood protection structures: Bypass roads surrounding dams were constructed to the Northeast of the Palma del Río (2008) and Southeast of Lora del Río (2011).

The second class of projects was constructed near Seville and was intended to protect local territorial facility:

a) Elevated roads running 3 m above the surrounding terrain of the inundation zone and serving as an urban connection between populations of La Rinconada and San José (2010).
b) Flood walls with a filling material for the urban expansion and riverside walk in La Algaba (2009).
c) Elevated metropolitan road integrating the new "North Approach Road to Sevilla," A-8009 (2008).
d) Reforestation of the Guadalquivir riverbanks in the city of Seville on its right waterfront (Parque del Charco de la Pava), with a flood wall in the immediate vicinity of the river.
e) A new floodgate enabling the approach to the Port of Sevilla as an expansion and enlargement of the traditional anti-flood devices in the South direction (2010).

Two dams were constructed on the right-bank of the Guadalquivir river, the Guadiato and Viar rivers. The first one, denominated "Breña II" (823 Hm^3) is intended for agricultural irrigation, while the second one, "Melonares" (185 Hm^3), enhancing the basin storage capacity (5,593 Hm^3).

Nevertheless, the river is still not fully controlled during large floods. The need to increase flood storage capacity so as to attain full control of flooding continues to become more urgent.

This need was highlighted during the floods in 2009, 2010 and 2011 when flow rates increased by 3,300 m^3/sec. as reservoir storage was drawn down to prevent damage to the dams.

Due to these flow volumes, a similar situation like in 1996 occurred when water level increased between Cantillana and Palma del Río, and on the other side, the confluence of major regulated tributaries (rivers Genil, Bembézar, Guadalbarcar, Corbones, Retortillo, Huéznar and Viar).

At the same time, a spate of new buildings constructed in the inundation zone under the auspices of the local administration have raised the vulnerability of certain population centers (Lora del Río, Cantillana, Tocina) before the occurrence of this phenomenon. On the contrary, at the stretch between Alcalá del Río and Seville, dredging took place to improve the navigation on the river all the way to the port. This work, which resulted in the incision of the riverbed, facilitated water flow in the reach. Unfortunately, the increased flow capacity resulted in renewed pressure to increase urbanization in the few undeveloped areas of the floodplain.

IX. CONCLUSIONS

A great moment in the transformation of the floodplain has come in the second half of the 20th century, associated with the straightening of the river channel and the construction of new reservoirs which have quadrupled the storage capacity. This situation led to the false perception that development of the floodplain had a low risk and favored significant urbanization of the floodplain as well as the construction of large infrastructure works. The ordinary riverbed has reduced its width in most places, except for the estuarial stretch characterized by a dynamic between the incision and deposition. Here, zones of deposition and incision depend on the positioning of three dams built at the Guadalquivir river and on the magnitude of the suspended load.

The Guadalquivir river presents, downstream of the Alcalá del Río, an incision of more than 8 m. This results in a channel that can handle high flow rates up to 3,500 m^3/sec. On the other side, in the sector of Cantillana-Alcolea del Río, due to strong deposition, these flow rates, without being extraordinary, are surpassing the *bankfull* status and are taking up the whole inundation zone.