# Restoration of a degraded torrential stream by means of a flood control system: the case of Arroyo del Partido stream (Spain)

J. A. Mintegui Aguirre, J. C. Robredo Sánchez,
C. De Gonzalo Aranoa & P. Huelin Rueda
*Escuela Técnica Superior de Ingenieros de Montes,*
*Universidad Politécnica de Madrid, Spain*

## Abstract

The Arroyo del Partido is a small torrential stream (307.67 km$^2$), draining into the El Rocío marsh, in the Doñana National Park (Spain).The DNP was declared a UNESCO Heritage site (1994), since it has an important role for bird migration between Europe and Africa. The last reach (7 km) of the stream was channelized in 1981, thereby the flowing conditions during floods changed. This fact caused the formation of a large alluvial fan over the wetland surface during the period 1982-2003, covering an area of 4.31 km$^2$, with a volume of $4.48 \times 10^6$ m$^3$.

In order to contain the advance of the fan into the marsh a flood control system was used. This control system consists of two check dams, one of them placed on the channelized reach, and a second one placed on a different stream, which receives the surplus flows of the Arroyo del Partido during floods. Between both streams a flood plain was reserved for sediments deposition and flood attenuation purposes. Reconstruction works were carried out in the summer of 2006. During the period 2007-09, works were monitored and adjusted on the basis of their behaviour in flood events, with the objective of restoring the former hydrological regime before the channelization.

*Keyword: major events, flood protection, hydrologic correction, ecological restoration.*

## 1 Introduction

Originally the Arroyo del Partido presented the classical scheme of a torrential stream (catchment area, gorge, alluvial fan and discharge channel). Then, during major floods, surplus flow was expanded over the fan surface before reaching the Doñana National Park (DNP) marshes, generating the former alluvial fan. After these flood events, the laminated and devoid of sediments flow was concentrated within several drainage channels discharging to the marsh with a uniform flow regime. The fan surface was cultivated only during the years in which the winter flood occurred. The irrigation plan Almonte-Marismas transformed this area for crop purposes in 1981, channelling the last 7 km of the stream before the marshes. This transformation forced the concentration of the flood into the channel, and thus the former alluvial fan behaves as an extension of the gorge, which has caused the formation of a new alluvial fan at the end of the new channel, inside the DNP marshes. Data pertaining to the evolution of the new fan surface and volume, up to July 2003, is presented in Table 1.

Table 1: Surface and volume increment estimation of the new alluvial fan over the DNP marsh between 1956 and 2003.

| Year | Surface ($m^2$) | Volume ($m^3$) |
|---|---|---|
| 1956 | 0 | 0 |
| 1982 | 152.241 | 5.338 |
| 1985 | 292.142 | 19.657 |
| 1993 | 1.042.800 | 250.460 |
| 1996 | 2.035.211 | 954.017 |
| 1997 | 3.325.798 | 2.547.588 |
| 1998 | 3.814.778 | 3.733.575 |
| 2000 | 3.929.143 | 3.899.220 |
| 2001 | 3.979.757 | 3.973.527 |
| 2002 | 4.195.430 | 4.297.024 |
| 2003 | 4.314.186 | 4.479.898 |

The analysis of that situation drove the following proposal. In order to recover the former hydrological regime of the Arroyo del Partido it is necessary to: 1) construct a check dam for soil erosion control at the beginning of the old alluvial fan, about 6 km upstream of the inflow into DNP marshes and 2) permit the flooding of the adjacent surface during major flood events, downstream of the check dam cross section, to recover the function of the former floodplain. The works on the hydraulic and hydrologic restoration of the Arroyo del Partido were conducted in 2006, designated as Action Number 3 (A3) of the Project Doñana 2005, which is a major project on Water Regeneration of the DNP Marshes. Due to its great environmental impact, an Executive Committee was created, and a Scientific Committee for its monitoring.

## 2 Objective

Since the old alluvial fan permitted the flood expansion prior to the DNP marshes, thereby promoting the flood lamination and sediments deposition, A3 is aimed at achieving the same effects. On this basis, a Flood Control System was implemented to regulate the flow draining into the marshes. This implies the need for a new flood-lamination-sedimentation area over the old alluvial fan, or at least a part of it.

Hereby we analyze the performance of the works carried out under the A3 on the last reach of the Arroyo del Partido stream during the period 2006-09; so that to adopt if necessary the appropriate adjustments to the works to ensure over time the hydraulic and hydrologic restoration of the degraded reach and its environment. This text discusses: a) the Arroyo del Partido Flood Control System project, b) the way in which the field works were conducted at the focus site, c) the actual possibilities to generate the new flood-lamination-sedimentation plain, and d) how the stream flood should be discharged into the DNP marshes, such that the stream contours are not altered by sedimentary processes.

## 3 Methods and site description: works and measures adopted under the A3 of Project Doñana 2005

The area where the Arroyo del Partido Flood Control System was located is shown in Figure 1. In the aerial photograph the Arroyo del Partido drains along the left-hand side of the image, and the Cañada del Pinar stream, having its own catchment, drains along the right-hand side. At the bottom of the image, from west to east, it the road that connects El Rocío and Villamanrique villages can be distinguished. The concerned area presents a slope towards the Cañada del Pinar stream, the reason why this last stream acted in the past as an additional drainage

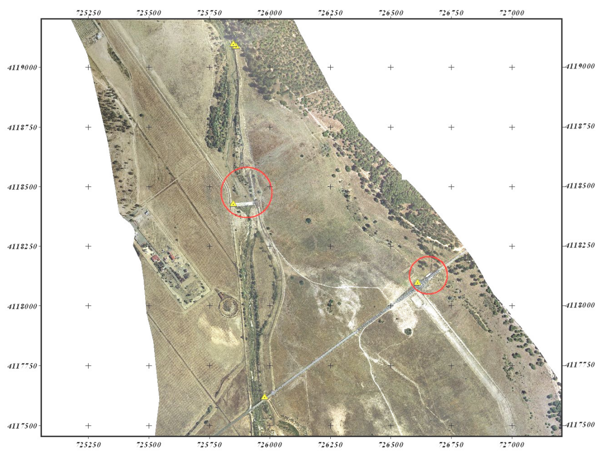


Figure 1: Aerial photograph (2008) showing the flood-lamination-sedimentation area recovered with the A3. The Arroyo del Partido drains along the left-hand side of the image and the Cañada del Pinar stream along the right-hand side. The road connecting El Rocío and Villamanrique runs along the bottom of the image. CD1 and CD2 are highlighted with circles. Triangles represent topographic landmarks, used for the levelling of the studied area.

channel for the floods coming from the Arroyo del Partido stream. The works implemented in order to achieve the aforementioned control system consisted of: a) the construction of a check dam on the El Partido channel at the beginning of the former alluvial fan (Check Dam 1 or CD1), controlling channel erosion processes upstream from its location, and distributing the stream flow between the Arroyo del Partido channel and the flood-lamination-sedimentation area, b) the construction of a second check dam on the Cañada del Pinar stream (Check Dam 2 or CD2), regulating the flood level in the floodplain, and c) the space available for flooding, flood lamination and sediments deposition, placed between both streams, and devoted in A3 for this purpose.

The CD1 height is 2.6 m above the current streambed. Originally the frontal spillway was 2.0 m high, 70.0 m long, and 2.0 m width, situated at an average altitude of 16.7 m. Thirty one weep holes, with 0.3 m in diameter, crossed the structure from the upstream to the downstream side, draining the water volume stored behind the structure. The weep holes were arranged in two rows (of 15 weep holes each) and a single bottom drain (Figure 2). The lateral spillway was placed immediately upstream of the structure along the left riverbank and coated with a rocky breakwater and a cyclopean concrete lining in order to prevent erosion when the diverged discharge flows into the flood-lamination-sedimentation area. The lateral spillway has a length of 140 m and its altitude ranges between 16.70 and 16.77 m.

The CD2 is 1.5 m high and was built immediately upstream of the bridge over the Cañada del Pinar stream, on the road connecting El Rocío and Villamanrique (Figure 3). Its spillway is 29.5 m long, 2.0 m high and 3.0 m width, with an average altitude of 14.62 m. The structure is crossed by 12 weep holes, 0.3 m in diameter, draining the volume stored behind the check dam, arranged in two rows (of 6 weep holes each).

The area comprised between both streams belonged to the former alluvial fan, before its channelization (1981). Accordingly, the A3 should recover its function. It is composed of two different areas:

a) The 57 hectares, triangular-shaped, surface upstream of the El Rocío-Villamanrique road. A geometric levelling of its perimeter was performed, since it was the first part of the plain being flooded, in order to estimate the behaviour

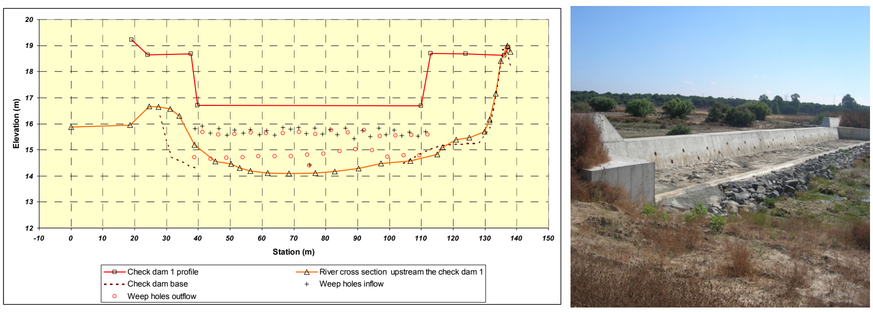


Figure 2: CD1 elevation view (left) in 2006 and photograph (right) in July 2007.

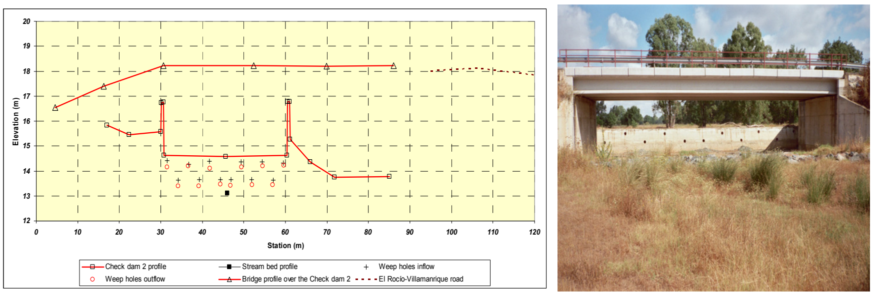


Figure 3: CD2 elevation view (left) in 2006 and photograph (right) in July 2007.

of the flood that occurred on July 19th, 2003. However, the greatest concern was focused on the geomorphologic response of the terrain surface of this area, when the Arroyo del Partido surplus flow comes from the lateral spillway of the CD1. For this reason, within the initial Flood Control System approach, we opted for a conservative flow allocation at the CD1. Using a design flow of a flood having a 100-year recurrence interval (358 $m^3 \cdot s^{-1}$), the flow would be distributed as follows: a 40% would discharge through the frontal spillway and weep holes, and the remaining 60% would flow through the lateral spillway.
b) The area placed downstream from the mentioned road, occupying 227 hectares, which can be flooded in the case of extreme floods. In such cases the road would operate as a discharge threshold of the stored water, flowing from the upstream surface (a) to the continuation of the floodplain area (b). A geometric levelling (October 18th 2008) of the road was conducted between both courses in order to establish the spill level of the road.

# 4 Results and discussion: behaviour of the works and regulations undertaken in the A3. Adjustments of the initial design

## 4.1 Stage-discharge curves of the El Partido flood control system at the Check Dam 1 and 2

The initial design of the CD1 (built in 2006) was tested, and it was found that the control system performed efficiently for major floods, but did not prevent minor flooding and problems related to sediments deposition in the eastern surroundings of El Rocío village, placed at the edge of the marshes. The stabilization of the new alluvial fan, formed over the marshes, was not solved either, because the flow reaching there was still too high. Moreover, the floods did not flood, as expected, the area devoted for that purpose. In these circumstances, as a step towards implementing the necessary adjustments of the CD1, the stage-discharge curves of the Flood Control System were determined at the CD1 and CD2. We only show here the stage-discharge curve at the CD1 (Figure 4, left chart), being the only one that suffered corrections.

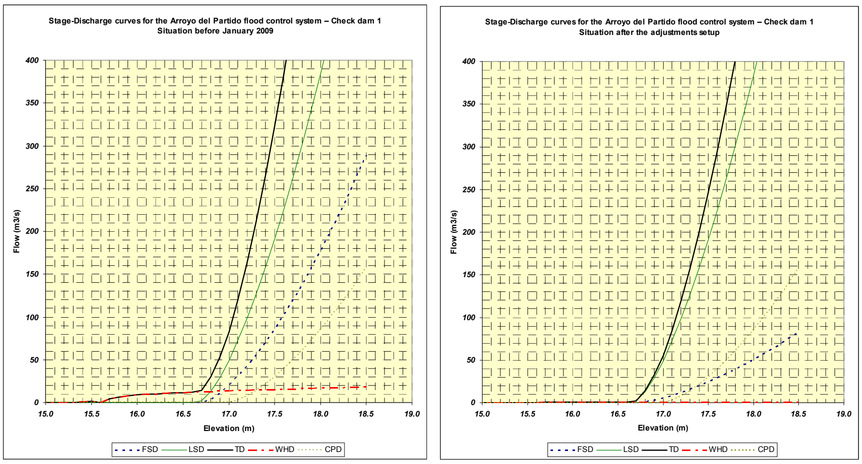


Figure 4: Flow allocation ($m^3 \cdot s^{-1}$) at the CD1 among the different discharge sections: left chart, with the initial design (2006), and right chart after the adjustments in January 2009. Frontal spillway discharge (FSD), Lateral spillway discharge (LSD), Total discharge (TD), Weep holes discharge (WHD), Cañada del Pinar discharge (CPD).

### 4.2 Adjustments of the Check Dam 1 and new stage-discharge curves of the Flood Control System

The adjustments of the CD1 were carried out after the summer of 2008, and were operational at the beginning of 2009. Their aim was the reduction of the flow crossing the CD1 to The Arroyo del Partido channel through its front face. With that purpose the following measures were implemented: a) to modify the initial frontal spillway section (2006), decreasing its draining surface, b) to cover the weep holes with gravel, delaying the discharge through them during floods.

Accounting these modifications, the new frontal overflow section became trapezoidal, 20 m long at the base and 24 m long at the crest, maintaining a height of 2 m (Figure 5). The new stage-discharge curves of the Flood Control System at the CD1, after the modifications are shown in Figure 4, right chart.

The effectiveness of these adjustments was tested by analyzing their behaviour during two flood events on February 1st and 5th of 2009 (Figure 6).

The results of the first flood were surprising. The pressure of the flow dragged the gravel blocking the weep holes through them, becoming those lasts operative again, as shown in the photograph in figure 5. The estimated flow distribution at the CD1in these events, is shown in the Table 2.

The photograph in figure 5 shows the situation of the CD1 at 13:00 h (local time) on February 2nd 2009, during the flood that started the previous day. At that time, the estimated hydrograph (figure 6) points out a flow rate of 15 $m^3 \cdot s^{-1}$. This value matches with the stage-discharge curve at the CD1 at the same time, as shown in the photograph in figure 5, where all the weep holes were draining at their maximum capacity and there is no discharge over the frontal spillway threshold.

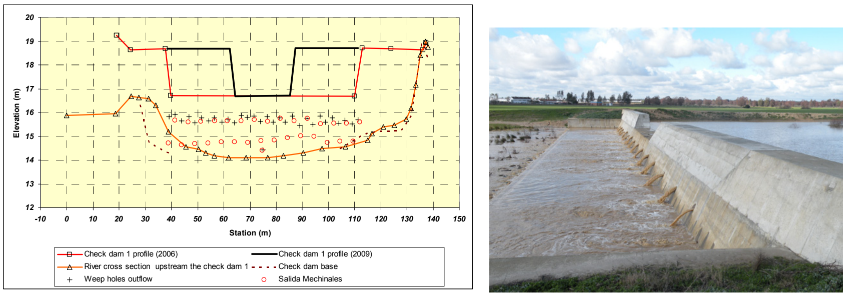


Figure 5: Left: CD1 elevation view with the final frontal spillway design. Right: Photograph of the CD1 at 13:00h on February 2, 2009, after the flood of the previous evening (image courtesy of C. Urdiales, DNP).

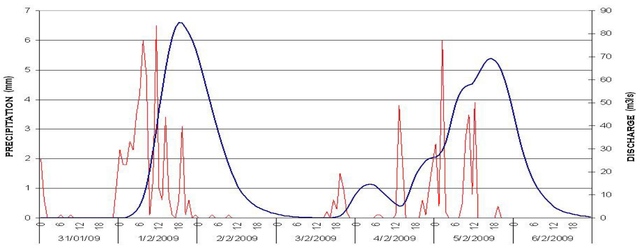


Figure 6: Precipitation at the Bollullos meteorological station (placed approximately at the centre of the Arroyo del Partido catchment) between January 31st and February 5th, 2009 (light grey line). Peak flow estimated at the CD1 upstream face on February 1st and 5th of 2009 (dark grey line).

Table 2: Flow distribution considering different discharge sections at the CD1 and the backwater effect at the beginning of the Cañada del Pinar stream during the floods of February 1st and 5th 2009.

| CD1 scenario during the flood | Peak flow ($m^3 \cdot s^{-1}$) | Peak flow distribution through different spill elements ($m^3 \cdot s^{-1}$) | | | |
|---|---|---|---|---|---|
| | | Weep holes | Frontal spillway | Lateral spillway | Backwater in Cañada del Pinar |
| Frontal spillway (2009) and operative weep holes. | 70*1 | 15 | 6 | 49 | - |
| | 85*2 | 15 | 9 | 58 | 3 |

*1 Estimated flow allocation on February 5 2009. *2 Estimated flow allocation on February 1 2009.

Figure 7: Flood in the Arroyo del Partido stream at 13:10 h local time on February 5 2009. Left: flow distribution at the CD1. Right: the flood flows downstream over the flood-lamination-sedimentation plain.

The left photograph in Figure 7 shows the flood on February $5^{th}$ 2009 at the CD1, at 13:10h (local time). As the hydrograph shows (Fig. 6), the stream flow at that moment was about 65 $m^3 \cdot s^{-1}$, where 20 $m^3 \cdot s^{-1}$ crossed the check dam front face (15 $m^3 \cdot s^{-1}$ through the weep holes and 5 $m^3 \cdot s^{-1}$ over the spillway threshold). The remaining flow, 45 $m^3 \cdot s^{-1}$, were diverged to the flood-lamination-sedimentation area over the lateral spillway, as shown in the same photograph, and ran downstream over the floodplain, as shown in the right photograph in Figure 7.

The analysis of these two floods allowed verifying the response of the drainage streambeds in the flood-lamination-sedimentation area when flooded. The analysis was possible due to the photographs taken while the area was flooded (Figure 7, right photograph); but more decisively due to the later topographical levelling, made on June 6-2009. With this survey, it was detected that the flood flow, discharged over the lateral spillway at the CD1, was adapted to the micro-topography of the plain, defined by the old drainage channels. The flood only caused little abrasion erosions at the base of the lateral spillway of the CD1. The profiles obtained for both floods are shown in Figure 8, together with the scheme of the Arroyo del Partido Flood Control System.

### 4.3 Drainage of El Partido floods into the DNP marshes, after being laminated and devoid of sediments at the area devoted for this purpose

Once the suitability of the flood-lamination-sedimentation area response was proved, it was analyzed the feasibility of a final stream discharge into the marshes in a uniform flow regime, in order to not alter the channel contours with sedimentary processes.

With this purpose a previous investigation (Urdiales, 1996) was taken into account. It was based on the (still conserved) profiles of the former Arroyo del Partido channel, running close the El Rocío surroundings. According to it, before the Arroyo del Partido channelization in 1981, the stream concentred the flow in a drainage channel with a very specific morphology, locally known as *caño*, to

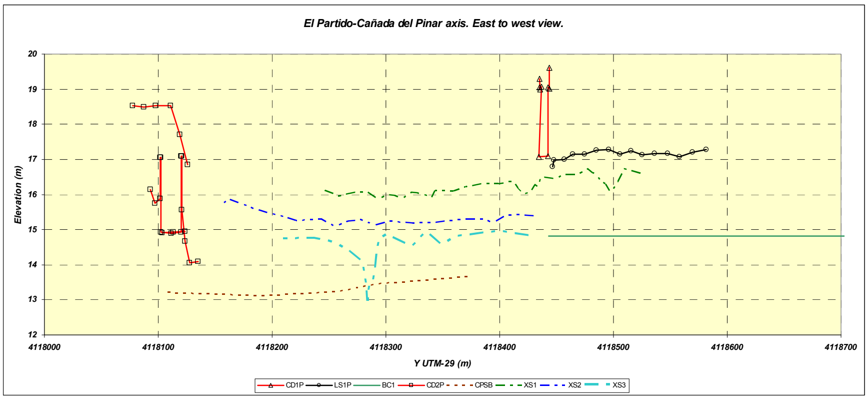


Figure 8: Elevation view (from East to West) of the elements composing the Flood Control System, and flood response on February 1 and 5 2009. From left to right: CD2 profile (CD2P); Cañada del Pinar streambed profile (CPSB); cross sections defined by floods in the flood-lamination-sedimentation area, surveyed on June 6 2009 (XS1, XS2, XS3); CD1 profile (CD1P); CD1 lateral spillway profile (LS1P); CD1 backwater curve (BC1).

flow towards the marsh. With the current Monitoring, it was detected that after the CD1 was constructed, which reduced substantially the flood flow reaching El Rocío village, a recovery of the Arroyo del Partido stream has been produced compared to the period between 1982 and 2006, especially regarding the recovery of the morphology of the former drainage system (caño), which was already lost. This fact ratified the modifications made to the CD1 to achieve the hydraulic and hydrologic restoration of the last reach of the Arroyo del Partido stream. Several cross sections along the last reach of the stream prior to the marsh inflow were levelled for confirmation. One of them is shown in Figure 9. The graph on the left corresponds to a 0.30 $m^3 \cdot s^{-1}$ flow. It was checked that in that situation the new alluvial fan was stabilized. The maximum evacuation capacity of this caño was estimated in 4 $m^3 \cdot s^{-1}$ (right graph in Figure 9), and this value was considered in the A3 for the CD1frontal spillway rectification. As a first approach, it was estimated that this flow corresponds to the bankfull stage of the channel, i.e. the evacuation capacity related with the dominant channel forming flow, linked with its compensation slope (García Nájera, 1943). This last was determined, by means of direct field survey, in 0.0016 $m \cdot m^{-1}$. Accordingly, it was considered that for flow rates under 4 $m^3 \cdot s^{-1}$, the sediment supply to the marsh remains beneath a moderated limit, since the flood remains into the drainage channel, and the sediment transport is essentially restricted to suspended load. Above this value, the best option is to permit the flood expansion across both overbanks. For this purpose it is necessary to ensure enough space, moving away any protection wall to the outer limits of the predictable flood expansion. In this way, the shear stress is insufficient to erode the banks and sweep away sediments into de marsh.

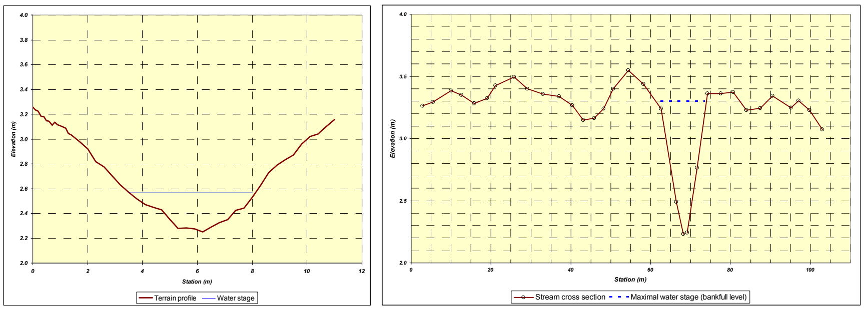


Figure 9: Left: Arroyo del Partido cross section, on the last reach prior to the marsh inflow, gauged on October 17 2008. Right: the same cross section, assuming a 4 $m^3 \cdot s^{-1}$ flow (bankfull level).

# 5 Conclusions

1) The conducted Monitoring consists on an approximation procedure to estimate the capacity of the A3 to move upstream the starting point of the alluvial fan to its ancient location and to reactivate its discharge channels to route the flood to the DNP marsh. This prevents from flooding and aggradation at the eastern side of El Rocío village, and maintains the current outlines of the marsh.
2) Regarding specifically the results related with the protection of the eastern side of the El Rocío village, the A3 estimates that: a) while the flood flow upstream the CD1 is lower than 20 $m^3 \cdot s^{-1}$ the situation will be under control. b) If the flood flow at the same location is lower than 100 $m^3 \cdot s^{-1}$, the direct discharge to the stream channel will reach a theoretical final value not greater than 5 $m^3 \cdot s^{-1}$, in the case that all the weep holes remain blocked (except for the bottom drain). This value, which could be seldom exceeded, ensures that the situation is also controlled. The flood discharge on February 1$^{st}$ and 5$^{th}$ 2009 was estimated over 20 $m^3 \cdot s^{-1}$ and no flooding or aggradation problems were detected on the eastern area of El Rocio village. Nevertheless, a planning is needed to ensure that the flood in the stream behaves as expected for a caño in this environment, i.e. concentring 4 $m^3 \cdot s^{-1}$ in the self drainage channel and expanding the surplus flow across both overbanks. So that it is necessary to remove any obstacle to the flow, preventing from the formation of new discharge channels westwards. This would promote undesirable situations around El Rocío village (in any case, not as serious as in the past). c) If the flood flow upstream the CD1 is greater than 100 $m^3 \cdot s^{-1}$, it has to be considered that the estimated flow getting to the surroundings of El Rocío village are reduced to less than the 15% of the reference rate before the construction and modification of the CD1 (2009). It is also noted that these flow rates, despite being high, have an order of magnitude that permits a planning and have a lower frequency. Another positive effect is that the A3 guarantees the ecological flow regime in the Arroyo del Partido stream, which contributes to its hydro-ecological recovery.

3) Regarding the functionality of the Cañada del Pinar stream, as an additional drainage of the flood-lamination-sedimentation area devoted in A3, it is noted that it was operative in the past. In this sense the floods on February 1st and 5th 2009 reactivated it without causing remarkable problems. As far as the Cañada del Pinar morphology remains as a caño, it is likely that the floods through it may behave in a similar way to the flow diverged from the lateral spillway of the CD1 over the flood-lamination-sedimentation area during the aforementioned floods. Therefore it is likely that the capacity of the Cañada del Pinar stream to drain the flood-lamination-sedimentation surface towards the marsh is compatible with the conservation of the current outline of the marsh, keeping away the threat of a new alluvial fan over the marsh.

## Acknowledgements

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