Hydrological and geomorphological criteria to evaluate the dispersion risk of waste sludge generated by the Aznalcollar mine spill (SW Spain)

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Abstract Following the Aznalcóllar pyrite mine disaster (Seville, Spain) which caused the spilling of some 4.5 hm^3 of acid water, the floodplains of the rivers Agrio and Guadiamar were rapidly cleaned of waste sludge. However, despite the efficiency of cleaning activities, there is still evidence of a fine superficial layer of sludge and some soil contamination, with the consequent risk of remobilisation of the pollutants by water erosion. There is much concern that these contaminated sediments may affect the precious ecosystems of the Doñana National Park and the Guadalquivir marshlands. This report describes the evaluation of the risk of mobilisation of the waste sludge through (1) detailed geomorphological analysis, indicating potential areas of erosion-sedimentation on the floodplains of the rivers Agrio and Guadiamar, and predicted dynamics of the waste sludge, and (2) evaluation of the potential dispersion of the waste sludge provoked by future flood events, including hydraulic calculations to model channel flow and the analysis of the texture of the sludge to obtain critical transport and sedimentation values. Findings suggest that the waste sludge is likely to be transported and deposited within the Doñana National Park during future flood events.

Keywords Heavy metals · Mine spill · Sludge · Spain

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Introduction

On 25 April 1998, the rupture of the dam containing the tailings reservoir of the pyrite mine of Aznalcóllar caused the spilling of 4.5 hm^3 of acid water and pyrite ore. The resulting sludge, containing high concentrations of heavy metals (mean particle size 12 μm), is of a solid content of some 0.88 hm^3 and 2.97×10^3 Mg mass (personal communication at the Junta de Andalucía 1998). The accident provoked the inundation of the floodplains of the rivers Agrio and Guadiamar and was close to affecting the Guadalquivir marshlands posing a substantial threat to the ecosystems of the Doñana Natural and National Parks. The tailings flood led to the sedimentation of a layer of sludge in the reach and floodplain of the Agrio-Guadiamar system, covering 2616 ha from the failured dam to the start of the Guadalquivir marshlands. This corresponds to a total volume of 1,981,844 m^3 of pyrite-contaminated sludge (ITGE. Cartografía y cubicación de lodos mineros en la cuenca del río Guadiamar. Aznalcóllar-Entremuros, unpublished report, 1998). The estimated amounts of metals of environmental concern in the toxic mud released by the Aznalcóllar mine tailings spill were in the order of 16,000 tons of zinc and lead, 10,000 tons of arsenic, 4,000 tons of copper, 1,000 tons of antimony, 120 tons of cobalt, 1,000 tons of thallium and bismuth, 50 tons of cadmium and silver, 30 tons of mercury, 20 tons of selenium and other metals (Grimalt and others 1999). Heavy metal pollution mostly affected the superficial soil layers (0–20 cm), although in some coarser soils pollution may penetrate down to at least 50–80 cm (Cabrera and others 1999). The principal soil pollutants were Zn, Pb and Cd, which penetrated the soil in the solution phase of the spill, whereas Cu, As, Sb, Bi and Tl penetrated predominantly as part of the soil phase (Simon and others 1999). Water samples taken a few weeks after the accident ~20 km downstream of the mine showed a low pH of 3.8, which contrasts with the prevailing alkaline conditions (pH ~8) upstream and in the adjacent Guadalquivir River (van Geen, and others 1999).

Once flooding was stopped in the channelled Entremuros reach approaching the Guadalquivir marshlands (Fig. 1), cleaning activities commenced and continued until November 1998. This represented an outlay of over 30 million Euros. The cleaning tasks were highly effective and served to remove practically all the sludge spilt in the accident. However, sludge traces in the form of a fine surface film and a layer of contaminated soil remain. After the cleaning tasks, about 100 samples were taken along the Guadiamar River valley (Ministerio de Medio Ambiente and Junta de Andalucía, 'Niveles de contaminación residual del cauce', unpublished report). In the river channel, the results showed that in 73% of the samples As content exceeded 52 mg kg^{-1} (with 53% over 100 mg kg^{-1}), and in 83% of the samples, Zn content exceeded 700 mg kg^{-1} (with 61% over 1,200 mg kg^{-1}). In the floodplain, 53% of the samples exceeded an As content of 52 mg kg^{-1} (with 37% over 100 mg kg^{-1}), 57% exceeded a Zn content of 700 mg kg^{-1} (with 29% over 1,200 mg kg^{-1}), 28% exceeded a Pb content of 350 mg kg^{-1} (with 19% over 500 mg kg^{-1}), and 28% exceeded a Cu content of 250 mg kg^{-1} (with 3% over 500 mg kg^{-1}). This, together with the severe changes suffered by the reach and floodplain of the Agrio-Guadiamar system because of the effects of the heavy machinery used in the clean-up process, points to the possible remobilisation of the remaining waste sludge by readjustment of the river channels and the effects of natural floods (Gallart and others 1999). Indeed, this disaster has revived the existing debate concerning the state of degradation of the Guadalquivir marshlands and the need to hydrologically regenerate the basin to restore the main rivers and streams feeding the wetlands.

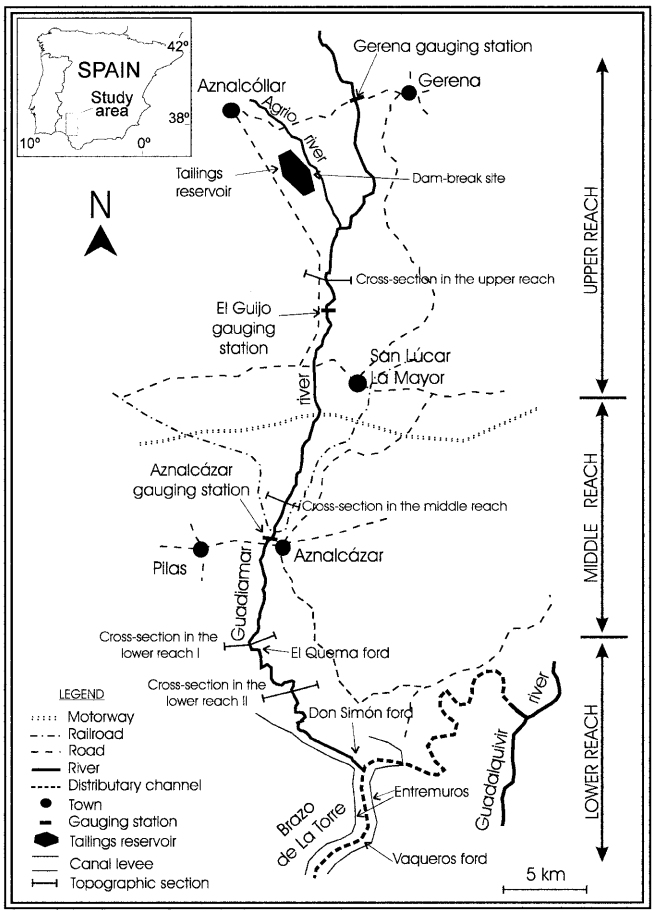

Fig. 1
Location of the Guadiamar lower course, downstream of the tailings reservoir, and division of the upper, middle and lower reaches

Fortunately, this type of environmental disaster is not a common worldwide event and thus provides a unique opportunity for the evaluation of the mid- and long-term consequences of spilling a large quantity of pollutants over a few hours. For previous information on the transport and dispersion of waste mining materials one would need to consider mining areas where spillage occurs in limited quantities over long periods of time. It is known that most of the heavy metals generated by the mining industry are transported in the solid phase, indicating the importance of fluvial geomorphological processes in their transport and sedimentation (Lewin and Macklin 1987; Miller 1997). Consequently, fluvial geomorphological processes are considered to be the main indicators of the potential dispersion of contaminants in this area of high environmental value.

The main objectives of the present study were as follows:

1. to explore the development of the river dynamics of the Guadiamar by establishing a detailed geomorphological map including both existing conditions of the natural regime (prior to 1950) and the different anthropogenic changes suffered by the floodplain up until the present;
2. to evaluate the incidence of the hydrological and hydraulic regime of the Guadiamar as an agent of transport, and dispersion of residual waste sludge following sludge clearance;
3. to establish areas of the Guadiamar prone to flooding under natural conditions for different flood return periods;
4. to suggest appropriate measures to prevent the short- and mid-term diffusion of pollutants;
5. to evaluate the measures proposed in the 'Doñana 2005' restoration plan and the Guadiamar reconstruction project, and to analyse the fluvial dynamics and geomorphology of the river in its natural or quasi-natural regime as a model of the hydraulic system to be achieved within the hydrologic regeneration projects 'Doñana 2005' and the 'Green belt of the Guadiamar'.

Study area

The Guadiamar basin lies in the south-east of the Iberian Peninsula where the river originates in the Sierra Morena and flows towards the Guadalquivir depression to finally drain in the Guadalquivir marshlands. The affected area includes the final reach of the River Agrio and the mid-lower reach of the Guadiamar; from the confluence of the River Agrio with the Guadiamar to the point where the Guadiamar joins with the Brazo de la Torre in the Guadalquivir marshlands (Fig. 1). At the administrative level, the study area falls within the east Seville province, near the border with the Huelva province.
The contaminated sludge spill occurred in the final reach of the Agrio, the main tributary of the Guadiamar just before the confluence of the two rivers. Under natural conditions, the Guadiamar is one of the principal water supplies of the Guadalquivir marshland and Doñana National Park. However, the latter regions were substantially affected by channelling of the river from its arrival at the marshlands to its outflow in the Brazo de la Torre.
The Guadiamar basin (1,879 km^2) harbours three gauging stations located at (Fig. 1) the bridge on the road to Gerena, upstream from the affected area (up to this point the drainage basin is 92.5 km^2), the Guijo gauge (574 km^2 basin) and the Aznalcázar gauge (1,319 km^2 basin). The sub-basin of the River Agrio (228 km^2) is regulated by a dam of some 40 hm^3 capacity, a few kilometres upstream from the Aznalcóllar mine, which considerably affects its hydrological regime (Gallart and others 1999). According to the River Guadalquivir water authorities (Confederación Hidrográfica del Guadalquivir), the main hydrological data available on the river Guadiamar are registered in the Aznalcázar gauging station records and are as follows: mean flow 6.6 $m^3 s^{-1}$ (annual volume 209 hm^3 and mean annual rainfall 667 mm) with a standard deviation of up to 5.3 $m^3 s^{-1}$, indicating high inter-annual irregularity. High flow occurs from January to March (mean discharge 13 $m^3 s^{-1}$), whereas June to October is the low flow period (mean discharge 3 $m^3 s^{-1}$). Peak flood discharges are 2,160 $m^3 s^{-1}$ for a 500-year return period, 1,520 $m^3 s^{-1}$ for a 50-year return period, and 860 $m^3 s^{-1}$ for a 5-year return period.
The affected reach of the Agrio–Guadiamar River cuts through Tertiary and Quaternary materials of the Guadalquivir depression, although the upper part of the basin flows through Hercynian materials of the Devonian and Carboniferous in the Ossa-Morena del Macizo Ibérico zone (Torres 1975; Leyva and Pastor 1976; Leyva and Ramírez 1976; Muelas and Crespo 1976; Coullaut and others 1978). The Guadiamar forms a wide valley with a valley floor incised at 80–60 m on a polygenetic surface developing a sequence of terraces on the left margin and alluvial fans on the right.
Cartographic analysis of the natural dynamics of the River Guadiamar by the interpretation of aerial photographs taken in 1956 suggests its division into three sectors or reaches:

Upper-reach
This stretch comprises the final part of the Agrio River and a reach of the Guadiamar from its junction with the Agrio to the bridge on the Sanlúcar la Mayor road (Fig. 1). It is characterised by a floodplain presenting areas of scarce lateral development (200–300 m) in both rivers because of the proximity of the present river channel to the lower stream terraces (Fig. 2). Observed in the floodplain are several crevasse splays and numerous abandoned channels of scarce functionality during floods. This reach has a wide river channel, which is fairly straight (sinuosity 1.13) and has a mean slope of 0.00146 $m\ m^{-1}$. During low water periods, the main channel divides into several secondary channels and flows between gravel and sand bars.

Middle reach
This next reach extends from the bridge on the Sanlúcar la Mayor road to the Vado de Quema, or Quema ford (Fig. 2). Within this reach, the River Guadiamar is fed from the right by lateral streams of considerable size with flat valley floors, such as the streams Ardanchón, Molinero, de San Cristobal and Arcarayón. With respect to the previous reach, there is a sudden drop in mean slope (0.0006 $m\ m^{-1}$) and an increase in sinuosity (1.3). In this part of the River Guadiamar, the floodplain, 450–800 m in width, is also bordered by low terraces on the right and by alluvial fans on the left (Fig. 2). The plain is cut by small abandoned channels, similar to those of the former reach, and by high flow channels hydraulically linked to the main channel, which clearly act during flood periods. Overbank deposits and crevasse splay are found associated with the concave curve of the meanders and depressed areas between levees. The river channel is narrower than that of the upper reach, approaching 50 m, and is frequently bordered by natural levees on both sides of the channel. Sand bars form associations with lateral supply from streams on the right.

Lower reach
The lower reach of the Guadiamar River extends from the Quema ford to its confluence with the Brazo de la Torre of the River Guadalquivir (Fig. 2). Natural regime fluvial dynamics are mainly characterised by increased floodplain width connected to wide, topographically almost flat surfaces and to poorly drained areas (wetlands and close depressions), indicating the start of the marshlands. In this area, the mean slope of the river diminishes with respect to the previous reach and is $\sim$0.00015 $m\ m^{-1}$, whereas sinuosity is maintained or even slightly increased. In the floodplain, two types of abandoned channel are found: (1) channels of diffuse morphology and scarce functionality and (2) high flow channels with sharp banks that are functional during floods. In natural conditions, the latter were tributary channels feeding the marshland, such as in the case of the Caño Guadiamar. In the lower reach, the main channel maintains the characteristics of the middle reach, is 30–50 m wide and is entrenched within the alluvial plain at some

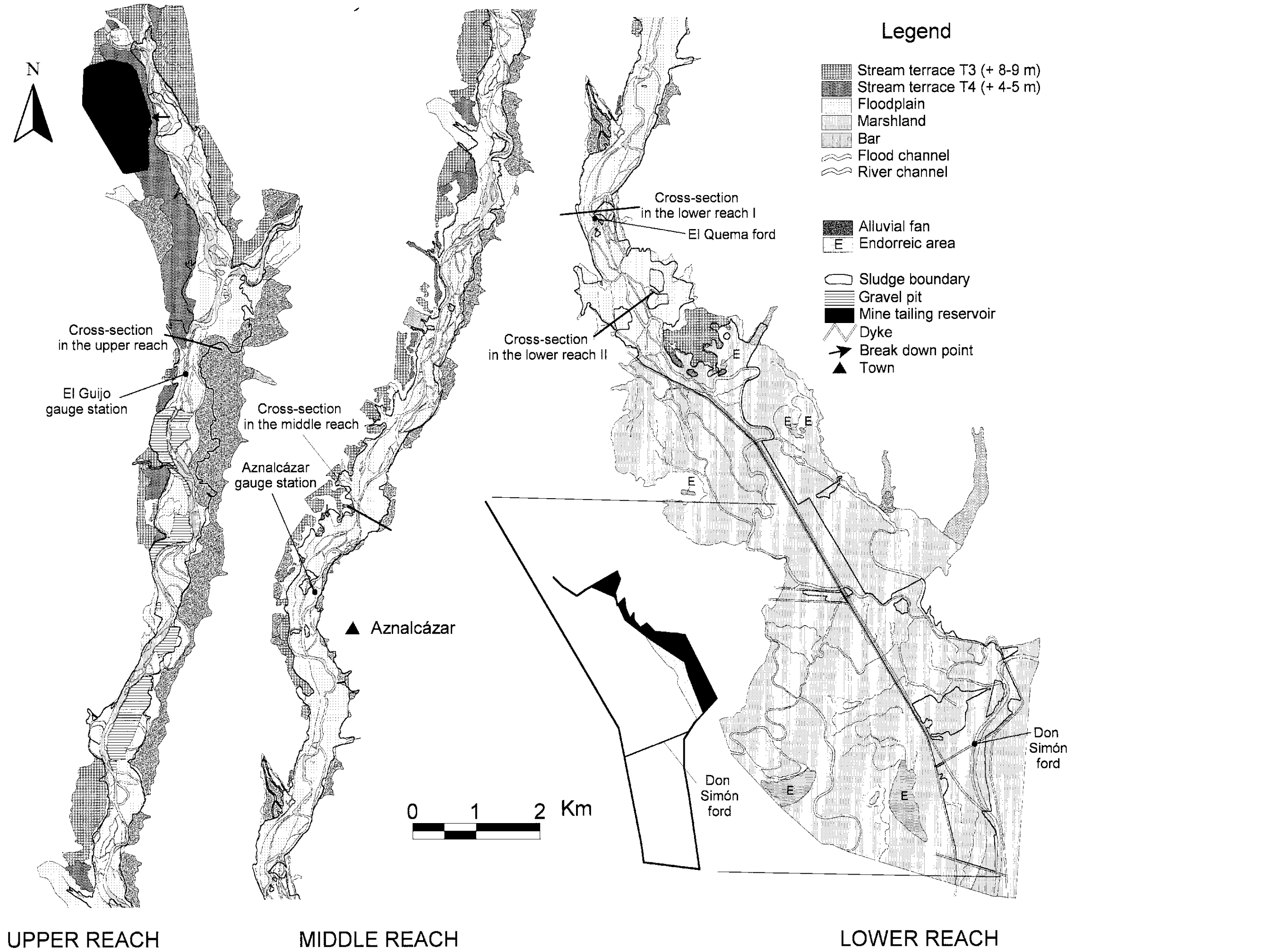

Fig. 2
Geomorphological maps of the Guadiamar-Agrio course affected by the contaminated sludge, along the *upper*, *middle* and *lower reaches*. Maps show information related to a semi-natural regime (from aerial photographs taken in 1956, 1:30,000 in scale) as well as anthropogenic modifications (from aerial photographs taken in 1993, 1:20,000 is scale; 1998, 1:15,000 in scale, and 1998, 1:10,000 in scale). The *inset* contour of the Entremuros area shows the results of the two-dimensional modelling with the location of areas with flow velocity lower than 0.1 m s^{-1}, in which sedimentation is likely to be produced according to the Hjulström diagram, for a discharges of 1,065 $m^3 s^{-1}$ (10-year return period; *black*), and for a discharge of 500 $m^3 s^{-1}$ (*grey + black*)

3–4 m. There are no sand bars in this reach. Crevasse splay deposits are associated with both the main channel and high flow channels.

From 1956 to 1998, few changes in fluvial dynamics in response to natural processes were observed throughout the Guadiamar basin (Figs. 2, 3 and 4). The only outstanding natural changes correspond to the upper reach and are related to the generation/destruction of channel bars. Recent major fluvial changes are mostly related to human activities. Prior to the mine spill, the anthropogenic modifications incurred may be summarised as follows:

- Mining activity associated with the Aznalcóllar tailings mine and gravel and sand mining activities in the floodplain and stream terraces. These activities were conducted in the upper reach and substantially affected the courses of the Agrio and Guadiamar.
- Channelling of the final stretch of the Guadiamar (known as Entremuros) causes the artificial cutoff and straightening of certain reaches and the hydrological separation of the Guadalquivir marshlands from the Guadiamar River (Fig. 3).
- Increase in agricultural activity mainly in the form of irrigation crops along the Guadiamar valley.

Methodology

The methods employed in the present investigation fall into two main categories:

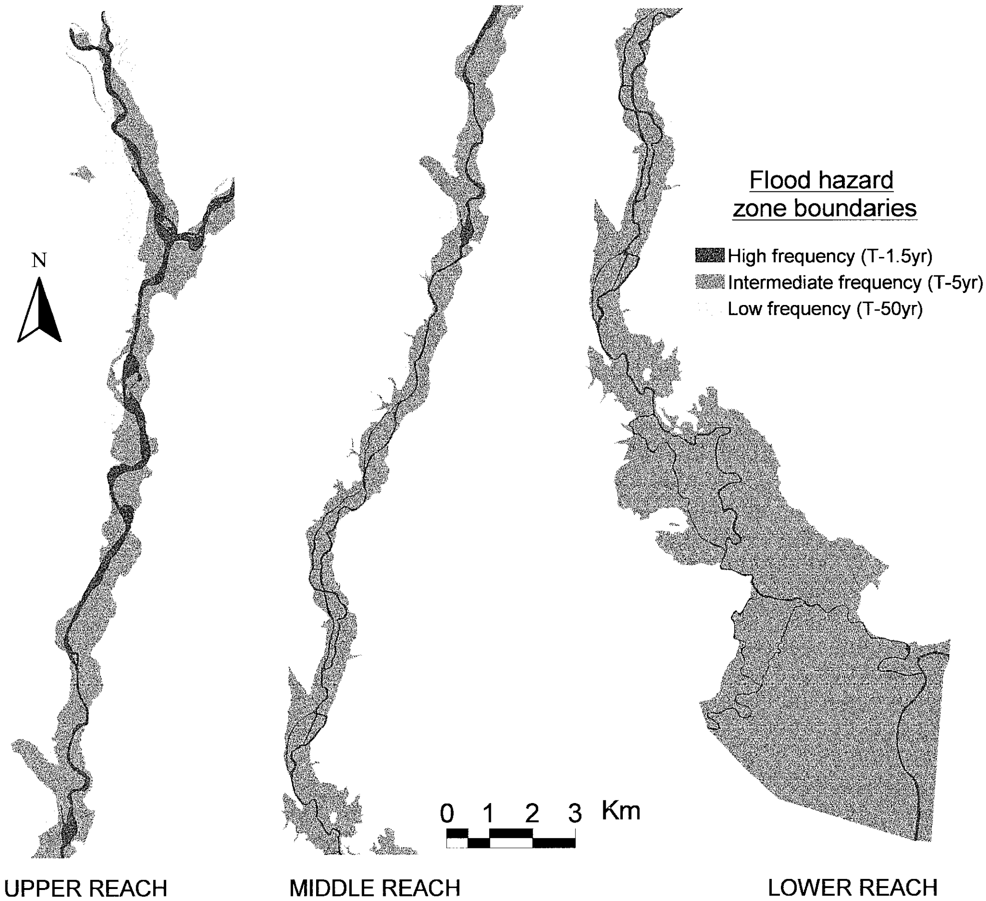

Fig. 3
Flood hazard map for natural regime based on geomorphological and hydraulic criteria along the *upper*, *middle* and *lower reaches*. Man-made structures along the lower reach (Entremuros) were not considered

1. Geomorphological analysis. Serial geomorphological cartographs were drawn up to give rise to 1:10,000 maps, both of the natural regime and of the anthropogenic modifications of the area affected by the mine spill. Sequential aerial photographs from flights conducted in 1956 (scale 1:30,000), 1993 (scale 1:20,000) and 1998 (scale 1:15,000) were used together with data obtained from the 1998 flight (scale 1:10,000). Analysis of these cartographs served to generate data on natural processes, fluvial architecture, natural areas of sedimentation/erosion of the channel banks, and on potential changes in the Agrio-Guadiamar fluvial system.
2. Hydrological analysis. This involved the analysis of gauge station records and transverse topographical sections of characteristic reaches of the Guadiamar. These data were used to estimate discharges, return periods and flow velocities, which, together with a sedimentological study of sludge samples, provided data on the risk of remobilisation of the remaining waste sludge. For the final reach of the Guadiamar River, a two-dimensional model was used to run discharges associated with different return periods in an attempt to identify areas of potential erosion/sedimentation. Analysed data from the gauging stations and the transverse topographical sections were used to characterise the geomorphological units in terms of peak discharge required for flooding and return periods giving rise to a third cartographic series at a scale of 1:10,000, which indicates the risk of flooding of the Guadiamar River (Fig. 3).

Effects of sludge clearance operations

Channel processes

In the case of an unmodified fluvial system, the dispersion of waste pyrite sludge would seem to be directly related to the river slope and its water depth, or water stage. Given their high conveyance capacity, sedimentation of the waste sludge is less likely to occur in the middle and upper reaches than in the lower reach where aggradation is probable.

Although natural fluvial dynamics did not lead to important changes in channel morphology over the period 1956 to 1998, the present lack of protection of the river bed and banks following the cleaning operations (Figs. 5 and 6) suggests a high risk of erosion and sedimentation of the river course aimed at restoring natural fluvial forms. Based on well-known geomorphological relationships concerning the concept of equilibrium of the fluvial system (Lane 1955), certain changes in processes operating in the river channel as the result of sludge clearance may

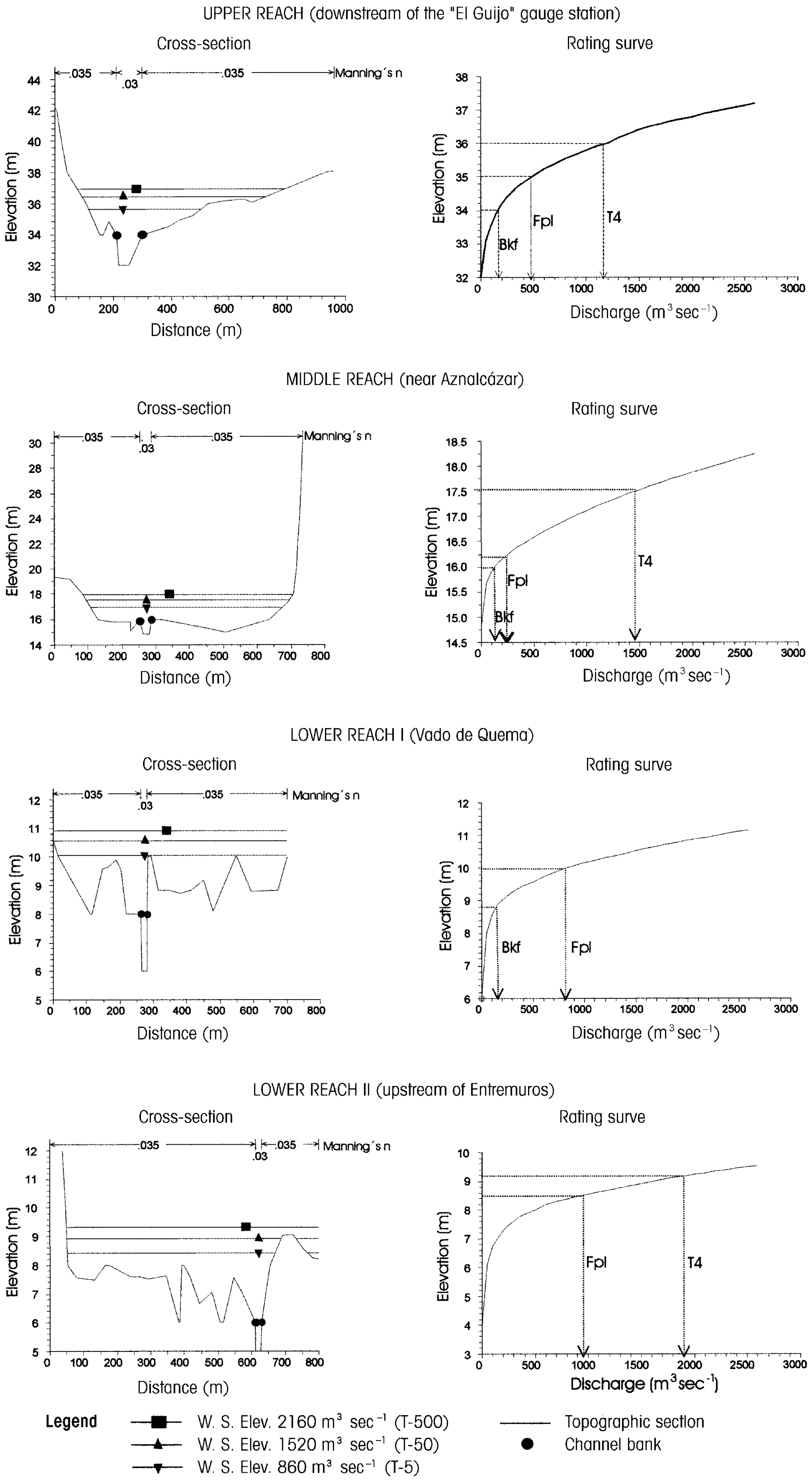

Fig. 4
Hydraulic calculations for defined cross sections of the Guadiamar River at **A** the upper reach, upstream of the El Guijo gauging station, **B** in the middle reach close to Aznalcazar, **C** in the lower reach, near the El Quema ford and **D** in the lower reach just upstream of Entremuros. Cross-sections show water surface elevation (*W.S. Elev.*) for peak discharges of 860 $m^3 s^{-1}$ (5-year return period, T-5), 1,520 $m^3 s^{-1}$ (50-year return period, T-50) and 2,160 $m^3 s^{-1}$ (500-year return period, T-500), and rating curves showing the elevation of characteristic geomorphological elements and their associated discharges required for being overflooded. B_{kf} Bankfull discharge; F_{pl} complete flooding of floodplain; *T4* flood of stream terrace 4 (+4–5 m)

Fig. 5
Upstream view of the Guadiamar River channel after the mine waste removal (23 November 1998). The photograph was taken near the El Guijo gauging station. Note the flat channel bottom and the steep river embankments, as well as the lack of herbs and bushes

Fig. 6
Downstream view of the El Quema ford (Guadimar downstream reach) after the mine waste removal (23 November 1998)

be anticipated. According to such relationships, the river channel, in response to the predictable increase in sediment supply after the cleaning process, would tend towards aggradation, a straighter course and a reduction in bed-load material size. Similarly, it may also be predicted that the clean-up activities involving heavy machinery, in both the channel and floodplain, will accelerate erosion processes in the banks and increase bed-load transport. Consistent with the increase in sediment load, Schumm's equation (1969) suggests an increase in channel width, slope, meander wavelength, and a reduction in depth and sinuosity. In other words, aggradation and fining of bed material may favour the accumulation of the remaining waste sludge and that of natural sediments along the channel, particularly in the middle and lower river reaches. The channel itself should not be considered a permanent trap for pyrite particles because, in the long term, the regrowth of vegetation and armouring of the bed will reduce sediment supply and restore the transport capacity of the channel for such fine particles.

Floodplain processes

Processes associated with the floodplain include cutbank erosion caused by lateral channel migration and suspended load deposition. In the Guadiamar, floodplain sedimentation has been dominated by crevasse splay deposition produced when bankfull discharge is exceeded and is related to convex banks and confluence zones, as well as overbank deposits related to vertical aggradation. The clean-up activities conducted in the floodplain caused partial infilling of flood channels leading to changes in the floodplain's erosion/sedimentation processes. However, highest sedimentation rates of suspended pyrite load are likely to correspond to those of the floodplain because of the low depth of the flood water even during times of peak discharge. Thus, although cleaning activities have, in part, affected the natural conditions of the floodplain, its recovery is critical because one of the floodplain's main roles is to act as a sediment trap. This will possibly avoid the transport and dispersion of contaminated sludge towards the Doñana marshlands and the Guadalquivir estuary.

Flood-prone areas and potential geomorphological changes

Sludge clearance, including heavy machinery levelling operations, may have certain hydrological effects. In the short term, the diminished roughness of the channel and floodplain caused by the removal of vegetation and channel forms (Figs. 5 and 6) may increase the flow velocity and consequently the erosive power of flood events. In the long term, the pyrite sludge remaining will form part of the geomorphic system and be subjected to erosion and transport along with natural sediments.
One of the first steps in the predictive analysis of hydrological behaviour, in terms of both sediment dispersion and channel changes, was to draw up a flood-risk map. Three areas of risk were defined: high, medium and low. Similarly, flood-flow variables were estimated to predict the potential dispersion of sludge by fluvial transport.

Hydrological and geomorphological criteria used to define potential flood areas

The lack of detailed topography of the area affected by the contaminated sludge during the initial stages of this study meant that, for different recurrence intervals, potential flood areas had to be based on geomorphological criteria calibrated through hydraulic calculation for defined sections of the Guadiamar. For some of these floods, the affected area was compared with flooded areas observed in satellite images (Landsat 5 TM) taken during a flood of known discharge. The peak discharge values used here are included in a project conducted by the

Guadalquivir water authorities with regard to the isolation of the Guadalquivir marshlands from the Guadalquivir River (Confederación Hidrográfica del Guadalquivir. Proyecto de control y permeabilización de la marisma de Doñana frente al río Guadalquivir, al Brazo de la Torre y a Entremuros, unpublished report, 1998). More specifically, four stretches of the Guadiamar River were selected: one in the upper reach, upstream from the El Guijo gauging station (Fig. 5), one in the middle reach close to Aznalcázar, and two in the lower reach, near the Quema ford just upstream from Entremuros (Fig. 6). For these sections, calculations were performed assuming uniform flow and using Manning roughness coefficients (n) of 0.030 for the channel and 0.035 for the floodplains. Photographs of floodplain and channel segments where Manning n values have been verified were used as a comparison standard to aid in assigning n values to the study sections. Using rating curves, water levels were estimated for discharges corresponding to return periods of 5 (T-5: 860 $m^3 s^{-1}$), 50 (T-50: 1520 $m^3 s^{-1}$) and 500 years (T-500: 2,160 $m^3 s^{-1}$).

In the upper reach of the Guadiamar, the bankfull channel has the potential capacity to carry peak discharges of up to 175 $m^3 s^{-1}$ (Fig. 4A). The floodplain is completely flooded for a peak discharge of 500 $m^3 s^{-1}$ (Table 1). Thus, both the channel and floodplain would be flooded by events of a 5-year recurrence period. The second morphological step, the low terrace, would be overflooded by events with peak discharges of 1,175 $m^3 s^{-1}$, corresponding to a 50-year return period.

In the middle reach (Fig. 4B), the bankfull discharge is 140 $m^3 s^{-1}$, and the floodplain would be completely flooded by a peak discharge of 200–250 $m^3 s^{-1}$, corresponding to a return period below 5 years (Table 1). The morphological step corresponding to the low terrace is reached by peak discharges of 1,450 $m^3 s^{-1}$ and is thus flooded in the case of events of 50-year return period.

In the lower reach, calculations corresponding to two different sectors gave similar results (Fig. 4B, C, Table 1). Bankfull discharge was 175 $m^3 s^{-1}$, after which flood water flows towards the plain. This peak discharge corresponds to return periods of 1 to 2 years. Total flooding, of both the plain and natural levees, would correspond to peak discharges of 825 to 940 $m^3 s^{-1}$, or those of 5-year return periods. In this reach, the lowest terrace becomes flooded when discharge is 1,940 $m^3 s^{-1}$, corresponding to 50- to 500-year return periods.

Flood-risk zones of the Guadiamar

In this analysis of flood risk, the consistency of peak discharge values generated by the hydraulic estimations for the different geomorphological steps suggests a high degree of reliability of the flood maps based on geomorphological criteria (Figs. 2, 3 and 4). The following areas were identified in the cartographs.

Low flood-risk zone

The area presenting a low risk of flood is inundated by floods of 50-year return periods (T_{50}) and discharges ex-

Table 1
Results of the hydraulic calculations at the selected cross sections and for discharges of 860 $m^3 s^{-1}$ (5-year return period, T-5), 1,520 $m^3 s^{-1}$ (50-year return period, T-50) and 2,160 $m^3 s^{-1}$ (500-year return period, T-500). *LB* Left bank; *RB* right bank

	Water surface elevation (m)	Discharge ($m^3 s^{-1}$)	Maximun depth (m)	Discharge ($m^3 s^{-1}$)			Velocity (ms^{-1})			Water depth (m)			Shear stress (Nm^{-2})			Stream power (watts m^{-2})		
				R.B.	Channel	L.B.	R.B.	Channel	L.B.	R.B.	Channel	L.B.	R.B.	Channel	L.B.	R.B.	Channel	L.B.
Cross section at the upper reach (downstream of the 'El Guijo' gauge station)																		
500-year return period	36.91	2,160	4.9	367.7	1,067.5	725.0	1.43	2.8	1.12	1.8	4.30	1.3	18.9	45.2	13.8	28.6	130.4	15.5
50-year return period	36.43	1,520	4.4	252	873.4	394.4	1.29	2.6	0.93	1.6	3.83	0.9	17	39.8	10.3	21.9	105.6	9.5
5-year return period	35.61	860	3.6	106.80	584.6	168.5	1.00	2.2	0.89	1.1	3.01	0.9	11.5	31.2	9.7	11.4	70.6	8.6
Cross-section at the middle reach (near Aznalcázar)																		
500-year return period	17.98	2,160	3.18	465.5	220.9	1,473.5	1.4	2.2	1.6	1.8	2.9	2.2	20.1	31.5	23.50	28.9	71.4	37.4
50-year return period	17.55	1,520	2.74	315.3	168.5	1,036	1.2	2	1.4	1.5	2.5	1.8	16.4	26.6	19.1	20.6	53.9	26.7
5-year return period	16.99	860	2.19	163.4	110.3	586.1	0.9	1.7	1.1	1.1	1.9	1.3	11.4	20.3	13.8	11.4	34.6	15.6
Cross section at the lower reach I (Vado de Quema)																		
500-year return period	10.93	2,160	4.9	746.5	253.2	1,160.1	1.4	2.9	1.4	1.9	4.7	1.9	20.5	45.8	20.2	29.9	133.2	29.2
50-year return period	10.54	1,520	4.5	512.8	218.1	789	1.2	2.7	1.2	1.5	4.3	1.5	16.3	41.5	15.9	20.5	113.4	19.6
5-year return period	10.04	860	4.0	281.2	175.8	402.9	1	2.4	0.9	1.1	3.8	1	11.5	35.8	10.4	11.5	89.1	9.8
Cross section at the lower reach II (upstream of Entremuros)																		
500-year return period	9.31	2,160	5.3	1,675.8	271.9	212.1	1.4	3	0.9	2	4.9	0.9	21	48.8	10	31.2	148.6	9.1
50-year return period	8.93	1,520	4.9	1,169.2	236.5	114.3	1.2	2.8	0.7	1.6	4.6	0.7	16.8	44.6	7.6	21.6	127.8	6
5-year return period	8.43	860	4.4	628.2	192.4	39.3	0.9	2.6	0.6	1.1	4.1	0.4	11.3	38.5	4.1	11.3	100.7	2.7

ceeding 1,175–1,450 $m^3 s^{-1}$. The morphological level characterising this low risk area corresponds to the lowest Guadiamar terrace (T4: +4–5 m).
The flooding produced by the spill only affected areas where the narrowness of the Agrio-Guadiamar floodplain led to an increase in the water level and to backflooding areas such as occurred just downstream from the Agrio-Guadiamar confluence or in areas were the terrace was degraded. Given the low risk of flood, the main threat of remobilisation of waste sludge would correspond to runoff processes during periods of heavy rain. In areas where clearance procedures have done away with the protection afforded by the vegetation cover, the efficiency of the sheetwash and rill erosion processes will be increased.

Moderate flood risk zone

The area of moderate flood risk, presenting return periods of 5 years (T_5), corresponds to the floodplain of the Agrío-Guadiamar system. Although it is true that the main channel exceeds its capacity for peak discharges of 175 $m^3 s^{-1}$, complete flooding of the plain only occurs in the case of discharges over 500 $m^3 s^{-1}$.
Because of the shallow flood water, even during peak stages, and because of the high roughness provided by vegetation inducing lower flow velocities and laminar flow conditions, floodplains are a natural trap for sediments and thus sedimentary processes predominate. In the sequential comparative study of the geomorphology of the middle-lower reach of the Guadiamar, areas undergoing repeated sedimentary processes were observed, which will foreseeably act as accumulation areas in future floods.
Despite the predominance of sedimentary phenomena in the floodplain, significant erosive processes capable of remobilising the waste sludge also take place. Such erosive processes may be related to lateral migration and cutoffs in the plain, which, although not observed in the natural river dynamics over the period looked at, could occur because of the effects of extreme floods or anthropogenic activities. Erosive processes could be enhanced by diminished roughness because of the removal of natural forms and vegetation, which would lead to an increase in flow velocity during floods and, consequently, in flood power.

High flood-risk zone

The high flood-risk area, where remobilisation of waste sludge is most likely, corresponds to the Agrio-Guadiamar channel and flood channels of high functionality. This area has a corresponding flood return period of 1.5 years ($T_{1.5}$) for bankfull discharges of 140–175 $m^3 s^{-1}$.
Just as the floodplain acts as a natural sediment trap, the river channel is characterised by the constant remobilisation of sediments, which continuously affects their morphology and geometry. During the set of years under study, channel changes in the Guadiamar were minimal although, as mentioned above, exceptionally large floods or modifications induced by human activity could alter such dynamics. Variations within the channel are continuous and mainly affect the morphology of the bed and channel banks. The most significant potential changes affect the upper reach under study, where migration of the multiple channels permits the greatest variation in bed forms including the construction and erosion of gravel and sand bars. In the middle and lower reaches, channel migration could be induced by anthropogenic modifications.

Estimation of potential dispersion of waste sludge by fluvial transport

Sedimentological properties of pyrite sludge particles

Determination of the grain size of the pyrite sludge performed by laser beam scattering indicated that >90% of particles were smaller than 60 μm in diameter, and that their mean diameter was 6–13 μm (Gallart and others 1999). Given that the density of the pyrite particles is much higher than that of common sediments, their water-settling velocity is greater than that of particles of similar grain size. The results show that the diameter of the pyrite particles should be multiplied by a factor of 1.75 in order to be compared with quartz grains and suggest that, even after correcting for density, the pyrite sludge particles show sizes comparable to those of silt. In fluvial systems, silt sediments are transported in suspension and are generally deposited on floodplains where water movement is sufficiently slow to permit the settling of small particles.
The critical shear stress τ_c for the erosion of pyrite sludge was estimated by applying a factor of 0.0001 to the shear strength of samples determined using a vane test device (Torri and others 1987). The values obtained for different sludge concentrations and the water depth threshold required to initiate erosion in the valleys of different gradient (Table 2), confirm the high risk of erosion of the sludge waste remaining on channel beds and banks of the Guadiamar. Indeed, the depth range capable of producing erosion is exceeded on many occasions throughout the year (Tables 1 and 2). In contrast, the risk of erosion of the pyrite sludge on the floodplain is much lower, although erosion is ultimately dependent on that of the natural materials in which they are found.

Hydraulics and transport of sludge particles in the Guadiamar

Because of the lack of detailed topography, which would permit the continuous hydraulic modelling of the Guadiamar River, control areas representative of the different reaches of the Guadiamar were established. Here, the river's sludge transport capacity for floods of different return periods was analysed. These control areas correspond to the segments described in the flood risk section. Manning's equation was used for the calculations and

Table 2
Critical shear stress for erosion and corresponding depth of erosive flow obtained for different water contents of a sample of pyrite muds taken near Don Simón ford (after Gallart and others 1999). The erosive flow depth was obtained for two gradient values characteristic of the Guadiamar valley. Liquid limit of the sample was 28.3%

Water content (%)	Critical shear stress ($N\ m^{-2}$)	Minimum flow depth required for erosion (m)	
		Slope = 0.0015	Slope = 0.0006
25.6	8.2	0.55	1.39
34.6	12.0	0.82	2.05
37.6	4.2	0.28	0.7

thus a uniform regime was assumed. In the lower part of the Guadiamar, and specifically in channel reaches presenting sudden expansions and constrictions such as Entremuros, the prevalence of a two-dimensional pattern of flow required the application of a two-dimensional model based on a finite volume discretisation.

Upper reach

Hydraulic estimations (Table 1) corresponding to the upper reach of the river for the return periods T-5, T-50 and T-500 shows flood stages ranging from 3.6–4.9 m. Seventy percent of discharge occurs in the channel with velocities of 2.2–2.8 $m\ s^{-1}$, and 30% in the floodplains with velocities of 0.8–1.4 $m\ s^{-1}$ reached. The shear stress generated by such flood discharges ranges from 31.2–45.2 $N\ m^{-2}$ for the channel, and from 9.7–19.9 $N\ m^{-2}$ for the floodplain; in each case sufficient for the transport of waste sludge particles (Tables 1 and 2). Only in the floodplain areas of flow depth <0.5 m, where it is possible to attain velocities below 10 $cm\ s^{-1}$, would it be possible for sludge re-sedimentation processes to occur.

Middle reach

Flood water depth for flood events of return periods T-5, T-50 and T-500 ranges from 2.2–3.2 m (Table 1). The main channel carries 10% of the discharge with velocities of 1.7–2.2 $m\ s^{-1}$, whereas 90% of the discharge is found on the floodplain with velocities ranging from 1–1.6 $m\ s^{-1}$. Shear stress presents values lower than those of the previous reach, 20.3–31.5 $N\ m^{-2}$ for the channel and 11.4–23.5 $N\ m^{-2}$ for the floodplain. Both would be sufficient to transport the sludge particles in the channel and floodplain area.

Lower reach

The two sectors of the lower reach examined gave rise to similar hydraulic estimations (Table 1). In the main channel, water depth for events with return periods of T-5, T-50 and T-500 ranged from 4.4–4.9 m. Discharge in the main channel reached a volume of up to 10%, with velocities of 2.5–2.9 $m\ s^{-1}$, whereas, on the floodplain, the volume was 90%, with velocities of 0.9–1.4 $m\ s^{-1}$ recorded. Similarly, shear stress for the channel was 35.8–45.8 $N\ m^{-2}$, and 10.4–20.5 $N\ m^{-2}$ for the floodplain indicating the capacity of the flow to transport contaminated sludge particles downstream.

Two-dimensional modelling of a reach of the Guadiamar upstream from the Puente de Don Simón

Preliminary two-dimensional hydraulic modelling of a reach of the Guadiamar just upstream from the Don Simón bridge was conducted. To this end, a numerical model based on the resolution of the two-dimensional Saint Venant equations was developed to obtain a spatial distribution of water depth and the two horizontal components of the depth averaged velocity vector. Because the hydraulic model is a two-dimensional one, the vertical component of the flow velocity is not obtained.

For this approximation, a simplified topography was employed based on 1:10,000 topographic maps since no more detailed information was available for this reach at the time of the study. A horizontal bottom was assumed for the entire area. The ford formed by the Don Simón bridge was not included in the model because of a lack of geometric data.

Steady state flow modelling was performed for discharges of 1,065 $m^3\ s^{-1}$, which appears to correspond to a return period of 10 years (Confederación Hidrográfica del Guadalquivir, unpublished report, 1998) and of 500 $m^3\ s^{-1}$.

For the boundary condition, a rating curve obtained assuming normal depth and using the geometry and slope of the reach immediately downstream was used. A Manning roughness coefficient of 0.030 was applied to the entire study area.

The areas shown in Fig. 2 (inset contour of the Entremuros area) correspond to those where the velocity is under 0.1 $m\ s^{-1}$, for discharges of 1,065 and 500 $m^3\ s^{-1}$ in which sedimentation is predicted according to the Hjulström (1935) diagram. This analysis demonstrates that the areas susceptible to the deposition and storage of pyrite mud remnants transported by floods are highly reduced in this lower reach of the Guadiamar valley. In fact, under existing conditions, the hazard for dispersion of pyrite particles remaining in the Guadiamar River, together with the natural sediments into the marshlands of the Doñana National Park, is very high. Although these modelling results should be considered an initial approximation to the problem using simplified geometric and roughness data and simple boundary conditions, we must consider that a horizontal topography will always correspond to the scenario of lowest energy conditions and, probably, one of the most favourable settings for sediment deposition and storage.

Discussion and conclusions

The clearance of the sludge spilt in the Aznalcóllar mine disaster has, in large measure, fulfilled its aim of removal of the pyrite sludge. However, this clean-up operation has served to transfer the environmental problem to two new fronts: (1) there are wide areas, especially those of the upper river reach of the affected area, where sludge remains continue to pose a significant environmental threat, and (2), the removal of pyrite sludge has meant the mobilisation of thousands of metric tons of waste together with the upper layer of sediments and soils, changing the river's natural configuration and drastically increasing its susceptibility to erosion.

The present investigation suggests that, given their textural characteristics and the river's capacity for fluvial transport during floods, the sludge remains could easily be transported by floods to the Doñana National Park marshlands, at least for the present conditions. Because of the high risk of dispersion of the remaining toxic sludge towards these marshlands, the construction of sediment traps and settling reservoirs is highly indicated. These areas of induced sedimentation and natural areas of sediment deposition defined in the geomorphological cartography would need to be cleaned after each flood event.

For future scenarios, a dense vegetation may increase the roughness coefficient values, diminishing the flow erosion capacity and favouring deposition because of vegetation filter effect. In channel lining practices, the permissible tractive force that will not cause serious erosion may reach up to 150 N m^{-2} under dense vegetation conditions, and up to a third part for poor vegetation conditions. Consequently, most of the studied reaches would be efficiently protected against erosion using an appropriated vegetation cover, which presently does not exist. Regarding deposition, a dense and long grass cover may favour laminar flow conditions facilitating deposition at some sites despite the calculated high velocities of the studied reaches. Therefore, vegetation cover is pointed out as the main factor to be considered in the technical measures directed to prevent the short- and mid-term diffusion of pollutants into the Guadalquivir marshlands. So far, the river banks and 30-m-wide belt along the Guadimar course have been planted with grass, together with ~170,000 bushes and trees, namely reeds, *Aeneas*, rosebays, ash trees, willows and white poplars. This vegetation has a relatively short regeneration time, and hence may act with a positive feedback in the erosion/sedimentation processes.

Similarly, it may be predicted that the first floods after the catastrophe will cause considerable erosion and deposition of sediments throughout the bed and banks of the river channel. Such instability might lead to changes in the shape and pattern of the channels because channel materials are normally transported short distances and are mainly deposited in channel bars and meanders. Eroded pyrite particles mixed with natural sediments will be transported much further because of their reduced size. Floodplains and channel pools are natural areas for deposition of these waste particles where flow is very slow.

In order to protect downstream areas of high environmental value, in addition to adopting increased erosion control measures, it is proposed that the natural areas of pyrite sludge deposition be improved. Restoration of the Agrio-Guadiamar valley is an urgent requirement as well as a long-term concern, and should be approached in a multidisciplinary manner including hydrological and geomorphological methods. Indeed, the water resource and environmental regeneration projects 'Doñana 2005' and 'Green belt of the Guadiamar' established by regional and national authorities are felt to be a good starting point for the recovery of these natural areas close to the Doñana National Park.

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