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Discrepancies on the Spilled Volume in the Aznalcóllar Mine Disaster

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Abstract

The failure of the pond that stored the tailing of the mining activity of Aznalcóllar (1998) supposed one of the most catastrophic mine disasters ever worldwide. More than 400 scientific publications, including two special issues and two reviews, attempt to clarify the causes and the environmental consequences of the spill. However, some hydraulic aspects were analysed in less detail, and nowadays several uncertainties and inconsistencies still persist. The spilled volume was officially determined to be 4.5 hm^3, and later on increased up to 6 hm^3. Despite that, in the literature this value ranges from 0.45 to 10.32 hm^3, being increased up to 14.4 hm^3 from data inferred from rating curves and the registered hydrograph. Additionally, the volume recovered during the restoration activities is also uncertain, ranging from 4.7 to 10 hm^3. Differences between the spilled and the recovered volume can be due to the natural hydrological processes. To clarify that, this paper firstly conducts a state-of-the-art review of the spilled volume of the mine disaster, and then new data is introduced and analysed aiming to get some light in this essential hydraulic parameter. To that end, photointerpretation and digital terrain analysis techniques were applied to determine the volume that could potentially be spilled, and then unpublished data of the mean discharge registered at EA90 gauge station was analysed to estimate the volume spilled. The most important findings reveal that the spill could have had a volume around 11.5 hm^3, twice the most referenced values in the literature.

Keywords: Aznalcóllar; Mine accident; Spilled volume; Hydraulics; Hydrology

1. INTRODUCTION

The mine complex of Aznalcóllar is located in the southwest of the Iberian Peninsula, 35 km northwest of Seville city. The mining activities of the complex are associated with the western foothills of the Iberian Pyrite belt (Borja et al., 2001), which has been mined since the ancient Roman Empire (CSIC, 2008) to extract minerals, mainly pyrite.

On 25 April 1998, the pond where the mine tailings had been stored since 1978, a waste product of the mining activities, collapsed. Millions of cubic meters of a complex fluid were spilled directly into the Agrio River and then into the Guadiamar River, an affluent of the Guadalquivir River, affecting the area's environment for ever since. The spill reached the northern limit of the Doñana National Park (CMA, 1998), and the catastrophe would have been worse had it not been for the efforts taken to stem the flow (AGE and JA, 1999).

The accident was, and still is, one of the most catastrophic mine disasters of the Iberian Peninsula and Europe (CSIC, 2008). At that time, it was the second in the world by volume (Turner et al., 2002), being nowadays the largest reported in Europe (Nikolic et al., 2011) and it remains the fifth largest spill worldwide (WISE, 2020). Besides the environmental damages, the event probably contributed to a worldwide general deterioration of the image of mining and it also generated a notable social alarm (Ayala-Carcedo, 2004). Nowadays, plans for reopening the mine complex (EFE, 2019; Europapress, 2019) have put the mining activities in Aznalcóllar again in the spotlight (ElDiario, 2018).

The disaster was first reported by official communicates of the regional and national administrations, and then by the press and the media: national and international daily newspapers and radio and television newscasts and special programmes (Elías, 2001). Later soon, after a short time since the catastrophe happened, scientific publications started to appear with the aim of signing light about the causes and the consequences of the event.

According to Madejón et al. (2018), more than 400 scientific publications on the disaster since the pond-failure have been published. The event has motivated two special issues, one in an international journal (Grimalt and MacPherson, 1999) and the other in the Spanish Geological and Mining Bulletin (IGME, 2001). Additionally, two reviews on the incident are present in the literature. On one hand, the work of Ayala-Carcedo (2004) provides an in-depth analysis of the breaking process from a geotechnical point of view, while the spill and fluid propagation were covered in less detail. On the other hand, the investigations of Madejón et al. (2018) are focussed on the soil pollution since the failure and add new information in terms of trace elements.

In the literature there seems to be a general agreement in the amount of the spilled volume, considered to be about 5-6 hm^3. Despite that, there still persist significant uncertainties regarding the spilled volume, among others hydraulic parameters (Sanz-ramos et al., 2022). A prove of that is not only the wide range of values found, but also the scarcity of studies that have attempted to reproduce the flood by using numerical methods. Only a few researchers have questioned if the pond volume was enough to affect the area it did, or if there could have been other water sources that entered into the area the days after the event and, in such case, how they could have interacted with the spill and distorted the volume ultimately recovered.

The main goal of this document is to review, from a hydraulic point of view, the volume potentially stored, subsequently spilled after the pond failure, and finally recovered during the clean-up activities. New data are presented and analysed to clarify one of the most controversial aspects of the hydraulics of the mine disaster of Anzalcóllar, the spilled volume. For that purpose, we compiled information about the post-failure topography, including the pond area, analysed the gauge station data to estimate with confidence the volume of fluid potentially spilled and the water sources that entered into the area the days after the event.

2. FACTS, UNCERTAINTIES AND NEW EVIDENCE

2.1. Spilled volume

The pond was originally projected to store 32.5 hm^3 (stage 20th of the original project), but when the dyke broke, it was far from its final stage (on the 16th). Thus, the volume stored just before the pond failure must have been smaller than the projected one.

Despite that, some authors (Cabrera, 2000; Gómez de las Heras et al., 2001; Grimalt et al., 1999), and even an official source (AGE and JA, 1999), support that the stored fluid volume just before the disaster was the projected one (32.5 hm^3). Another official source (CMA, 1998), indicates that from the 16th stage to the final stage the pond could have increased its capacity by 6 hm^3, from which it can be inferred that the pond volume could have been 26.5 hm^3 just before the break. In this line, other authors support similar values of 26 hm^3 (Arenas et al., 2008, 2001; Borja et al., 2001; CSIC, 2008) and 25 hm^3 (Manzano et al., 2000; Santofimia et al., 2011). In contrast, McDermott and Sibley (2000) indicate that the pond stored 15 hm^3 at the time of the failure, while Ayala-Carcedo (2004) suggests that the volume ranged from 15 to 20 hm^3.

The volume spilled during the event is also very controversial, especially due to the volume registered at 'El Guijo' (EA90), a gauge station placed 7.1 km downstream of the breaking point. Figure 1 compiles the values of the volumes found in the literature, plotted separately as pond capacity (grey bar) and spilled volume (grey dashed-bar). When data is available, the spilled volume has been split into the two kind of fluids identified in the literature: acid water (green bar) and muds (brown bar).

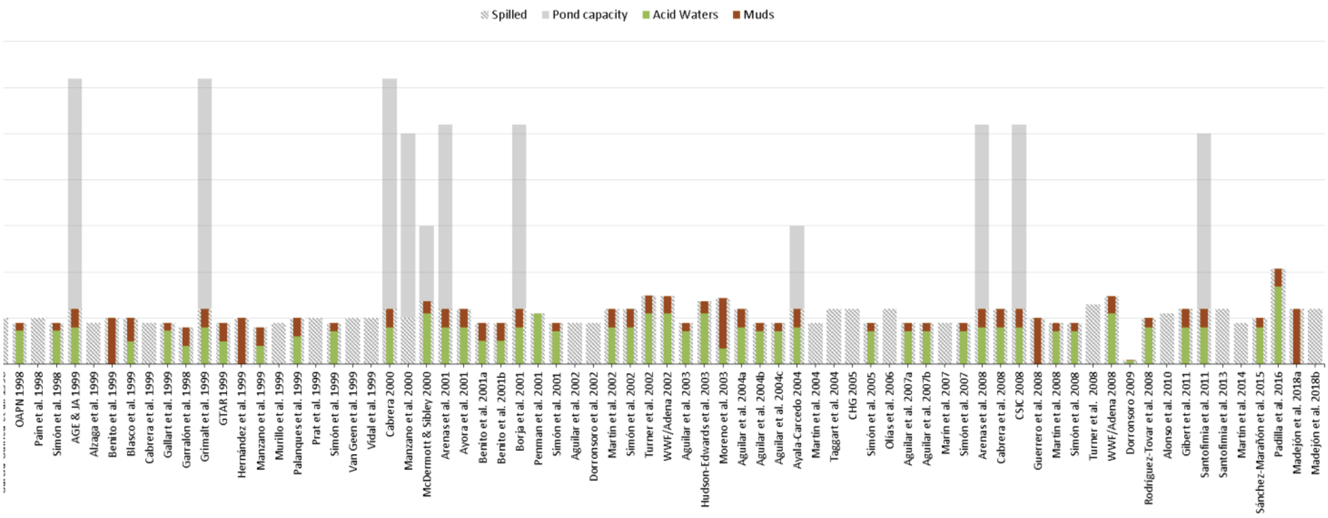

Figure 1. Recompilation of the different volumes found in the literature: pond capacity at the moment of the failure (grey bar), spilled volume during the event (grey dashed-bar), spilled volume of acid waters (green bar), and spilled volume of muds (brown bar).

The spilled volume ranges widely, from 0.45 hm^3 (Dorronsoro, 2009) to 10.32 hm^3 (Padilla et al., 2016). It is worth noticing that Moreno-Millán and Valdés-Morillo (2003) probably confused the type of fluid as the values they present are switched with respect to the values proposed by others authors (Figure 1). Additionally, some discrepancies have been also found in the values published in different publications of the same group of authors (Aguilar et al., 2004b, 2004a, 2004c, 2003, 2002; Dorronsoro et al., 2002; Martín et al., 2008, 2007, 2004; Simón et al., 2007, 2005, 2002, 2001, 1999, 2008). On the other hand, only a handful of authors explicitly referenced the volume of muds (Alastuey et al., 1999; Antón-Pacheco et al., 2001; López-Pamo et al., 1999), some of them being those who considered the whole spill as a mud-like fluid (Benito et al., 1999; Guerrero et al., 2008; Hernández et al., 1999; Madejón et al., 2018b).

The first estimation of 4.5 hm^3 presented by CMA (CMA, 1998) is the most referenced value. Despite that, a general consensus is observed being the value of about 5 hm^3 for the spilled volume. A year later, the value was increased up to 6 hm^3 by the re-evaluation made by AGE and JA (1999). López-Pamo et al. (1999) carried out a detailed cartography of the extension of the deposited muds, calculating their volume as 1.98 hm^3 but omitting the volume of acid waters. One of the most recent value, presented in detail by Padilla et al. (2016), is the highest one with 10.32 hm^3, more than twice that the one initially estimated.

The hydrograph at EA90 (Figure 2a, dotted line) was first presented in the unpublished document of Consultec Ingenieros (1999), with a maximum discharge of 600 m^3/s. Later, using data from Borja et al. (2001), Ayala-Carcedo (2004) showed a similar hydrograph, but as a water-sediment hydrograph (Figure 2a, dashed line). The estimated peak discharge of 811 m^3/s is 35 % more than the previous one, and it was probably overestimated due to the higher viscosity of the fluid (Ayala-Carcedo, 2004).

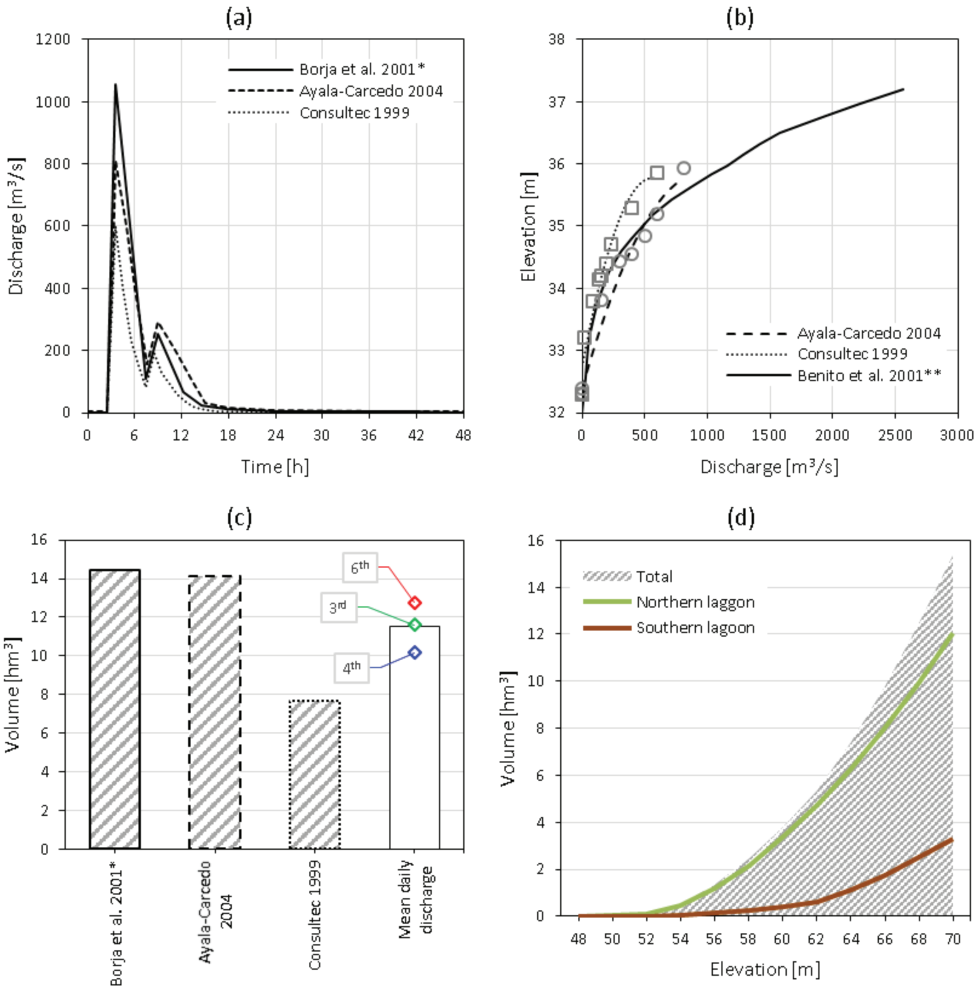

Figure 2. (a) Comparison of the hydrographs presented by Ayala-Carcedo (2004) (dashed line), by Consultec Ingenieros (1999) (dotted line), and calculated from data of Borja et al. (2001) (continuous line) (*)using the rating curve from Benito et al. (2001). (b) Rating curve (**)obtained by numerical modelling (source: adapted from Benito et al. (2001)). (c) Estimated volume that passed through EA90 during the event (25–26 April), the white bar obtained being the mean value of the rating curve extrapolated from polynomial adjustment of the 3rd, 4th and 6th order. (d) Elevation-volume relative curve of the pond inferred from the post-failure topography.

This data can be used to estimate the spilled volume. Using the rating curve of the gauge station, it would be possible to transform water depth/elevation into discharges, and then into volumes. However, the rating curve is currently not available because the gauge station EA90 was re-built after the incident, modifying its geometry (nowadays called A39) and, thus, it differs from that in 1998. Additionally, the gauge station was overtopped during the flood, and high water depths could not be properly obtained (Consultec Ingenieros, 1999). These explain some of the observed discrepancies.

Three rating curves have been inferred from the previous data. Figure 2b shows the best adjustment ($R^2 > 0.95$) of the rating curve calculated here from data of Consultec Ingenieros (1999) (dotted line) and Ayala-Carcedo (2004) (dashed line), and also the rating curve inferred from data of Borja et al. (2001). These rating curves behave similarly for elevations up to 34.5 m, being less conservative the rating curve of Benito et al. (2001) (Figure 2b, continuous line). This last one, taken just downstream of the gauge station, has been used to estimate the hydrograph with data from Benito et al. (2001) (Figure 2a, continuous line). In this case, the peak discharge would be 1,056 m^3/s, almost twice that estimated in Consultec Ingenieros Consultec Ingenieros (1999).

In this regard, data coming from the Confederación Hidrográfica del Guadalquivir (CHG), which related the mean daily water depth and discharges during 1998 at EA90, revealed that mean water depths on 25 and 26 April were 1.41 m and 0.47 m, respectively (these data are detailed in Section 2.3). The rating curve inferred from these data shows a limited application range, up to 1.1 m. Thus, there is no discharge value associated with the water depth of 25 April. For this reason, three different extrapolation methods, which consisted in a polynomial adjustment of the 3rd, 4th and 6th order with a good adjustment ($R^2 > 0.99$), were used to obtain the mean daily discharge corresponding to the water depth on April 25, of 1.41 m.

Figure 2c shows the cumulative volume that passed through EA90 during the event considering the three previously mentioned sources (Ayala-Carcedo, 2004; Borja et al., 2001; Consultec Ingenieros, 1999) and new data presented here. These values were calculated integrating the hydrograph shown in Figure 2a and averaging the mean daily discharge calculated from the extrapolation methods for the CHG data. The volume ranges from 7.6 (Consultec Ingenieros, 1999) to 14.4 hm^3 (Borja et al., 2001), all of them being higher than those usually referenced in the literature (4.5 and 6 hm^3). Considering the uncertainties of the inferred rating curves for the hydrographs, the most reliable spilled volume could be the average value of the mean daily discharge calculated here, of 11.5 hm^3.

The main question is whether the pond had this amount of fluid stored before its failure. The initial and the final volumes retained in the pond are unknown, but ad hoc topographical data carried out few days after the incident by CHG, which consisted in a restitution of a photogrammetric flight, can be useful to assess the volume potentially spilled from the pond. Although the pond geometry was slightly modified by the accident, it is sufficient for our purposes because the modifications were slight.

Figure 2d shows the elevation-volume relative curve obtained from the post-failure topography. Considering the water elevation at the pond crest, the spilled volume could potentially reach 15.4 hm^3, which is slightly higher than the maximum previously estimated volume from Borja et al. (2001), of 14.4 hm^3. Nevertheless, according to Alonso and Gens (2006), the water level was 4.4 m below the crest the day before the failure; with this information, the maximum spilled volume would be 9.3 hm^3. So that, the spilled volume, both presented and calculated here, are within the volume that was potentially stored in the pond.

Finally, it is important to highlight that few authors have attempted to estimate the hydrograph spilled from the pond. As shown in Figure 2a, the registered flood had two peaks. The first one was at around 3:30 AM and the second one around 9:00 AM. Then, approximately 48 h later, the discharges dropped to values similar to those previous to the accident. Despite the fact that the water depth overtopped the maximum calibrated value for the gauge station, the limnograph registers were continuous.

In Consultec Ingenieros (1999), the hydrograph of the spill at the pond was also estimated to be continuous by means of the inverse convolution process (Figure 3a, dotted line), with a peak discharge of 1,050 m^3/s at around 1:25 AM. More recently, Padilla et al. (2016) presented a hypothetical hydrograph, also with two peaks (Figure 3a, continuous line). In contrast to the previous one, the second peak is higher than the first one, being around 1,670 m^3/s (at 1:30 AM) and 2,500 m^3/s (at 7:15 AM), respectively. In addition, these peaks were separated by a no-discharge period of about 3:45 hours, contrary to the observed limnograph. The volumes of these hypothetical spills are 12.3 and 11.1 hm^3, respectively (Figure 3b). Both are within the potential storage capacity estimated here.

In this sense, the volume calculated from data of Consultec Ingenieros (1999) at the pond is 64 % higher than that estimated at EA90 gauge station, suggesting that the rating curve used to transform the limnograph into a hydrograph was probably inadequate. On the other hand, it is unclear whether the spill was released in two time-separately phases as is suggested by Padilla et al. (2016) because the dyke failure was very quick and probably affected both dykes concurrently (Alonso and Gens, 2006b, 2006a; Ayala-Carcedo, 2004).

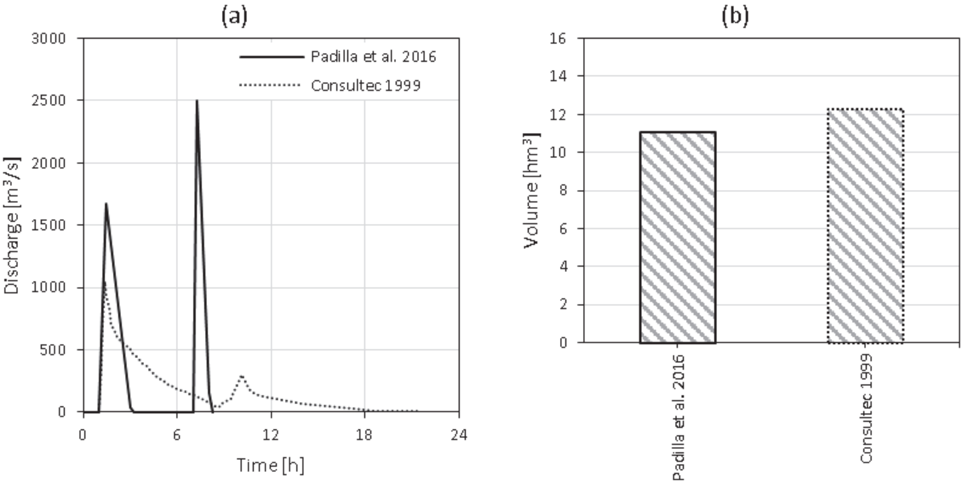

Figure 3. (a) Hypothetical hydrograph of the spill at the failure point estimated by Consultec Ingenieros (1999) (dotted line) and Padilla et al. (2016) (continuous line). (b) Spill volume calculated from the previous data for the first 24 hours.

2.2. Recovered volume

The clean-up activities were split in three areas: from the pond till Sanlúcar la Mayor bridge; from this point to Don Simón ford; and from this point till the end of the affected area of Entremuros. The activities of each area were conducted by the mining company, the CHG and the local administration, respectively (AGE and JA, 1999; Antón-Pacheco et al., 2001; CSIC, 2008). However, the recovery of the muds was not limited to the original topography, and the natural terrain was also dug to ensure a full clean-up.

According to AGE and JA (1999), the extracted natural soil thickness could have varied from few centimetres up to 0.1 m. However, in the area allotted to the mining company, the terrain was dug deeper causing several morphological changes (Antón-Pacheco et al., 2001).

The recovered volume was planned to be kept in the open mine-pit, so-called ‘Aznalcóllar’ (AGE and JA, 1999). In the literature, a total volume of muds and terrain of 7 hm^3 is said to have been recovered and then deposited into that mine-pit (Antón-Pacheco et al., 2001; Arenas et al., 2001; Cabrera et al., 2008; CSIC, 2008; Santofimia et al., 2013, 2011; WWF/Adena, 2002). Arenas et al. (2001) and Cabrera et al. (2008) raised this value by 0.8 hm^3, corresponding to a second phase of the clean-up activities. However, other values are found in the literature, such as the 4.7 hm^3 of Hudson-Edwards et al. (2003) and Turner et al. (2002), the 10 hm^3 of Turner et al. (2008), or recently the 8 hm^3 reported by Madejón et al. (2018a).

According to Santofimia et al. (2011), who analysed in deep the different liquid dumps tipped into the mine-pit during the period 1995–2006, around 2.9 hm^3 were added there from the accident to the end of the mining activities in 2001. Although the volume recovered during the summer of 2000 at the Entremuros area is not detailed, it probably did not reach 1 hm^3, which is in accordance with the 0.8 hm^3 described by Arenas et al. (2001) and Cabrera et al. (2008). In any case, the recovered volume would be larger than 1.98 hm^3, described by (López-Pamo et al., 1999), and probably less than 9.9 hm^3

2.3. Basin inputs and outputs

A spill over a natural basin is always susceptible of interaction with the hydro-meteorological processes, such as rainfall and losses (infiltration, evaporation, etc.). Thus, considering that the spill of the waste tails of Aznalcóllar was not cleaned immediately, some interactions with the environment were bound to happen.

Hydrological aspects have been generally treated with poor detail in the existing bibliography. In this subsection discrepancies found from a hydrological point of view are pointed out, but the focus is mainly put on the analysis of the unpublished data related with the hydraulics of the event. Data from the CHG, and additional meteorological data from the Spanish Meteorological Service (AEMET), is presented and analysed.

At the time of the incident, the Guadiamar basin was monitored by seven hydro-meteorological facilities. There are two water-level gauges (the EA56 located at Gerena village, upstream of the study area, and the EA90) and the rainfall gauge E67; and from the AEMET, four rainfall gauges coded as 5783 (Sevilla), 5860E (Moger-El Arenisillo), 5960 (Jerez de la Frontera) and 5910 (Rota) (AEMET, 2020).

Daily cumulative rainfall data collected from the aforementioned facilities reveal three different patterns during the 1998 April–September period (Figure 4). From April to May, the weather was quite wet with more than 30 % rainy days. From May to mid-September, the rainfall was scarce or null. From mid- to end-September, rainfall events were registered again on around 50 % of rainy days.

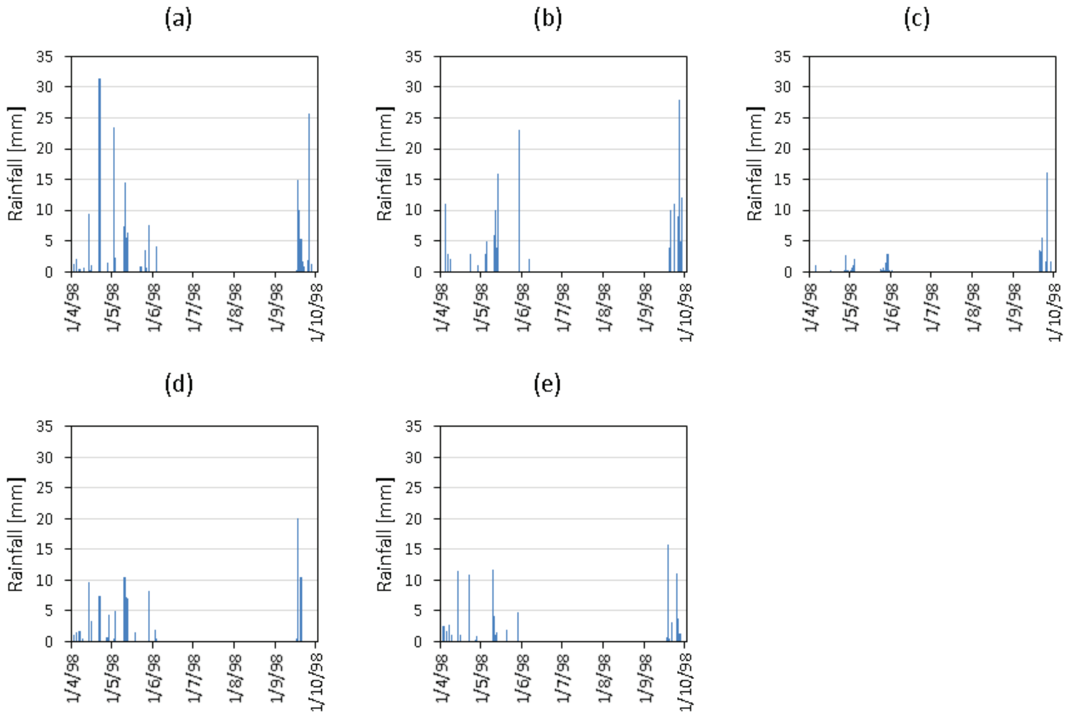

Figure 4. (a) Daily cumulative rainfall registered at the gauge stations 5783 (a), E67 (b), 5860E (c), 5960 (d) and 5910 (e).

According to CSIC (2008), there were rainy days previous to the accident, and after that no-rain was recorded. In contrast, other publications indicate that the days after the pond-failure registered 12 mm of rainfall in May (Alastuey et al., 1999; Martín-Peinado, 2002). However, these statements are not in agreement with the registered data presented here, where the rainfall reached 67 mm in some parts of the basin (e.g. E67).

On the other hand, collected data of the water-level gauges have been grouped by days, and the mean values of the height and the registered discharge have been represented. Figure 5 shows the water level evolution for 24 weeks at each gauge station, starting a week before the failure. From the upper part of the Guadiamar River, gauge station EA56 shows a mean daily discharge of around 0.191 m^3/s, or 0.016 hm^3/day, with an important increment during the rainfall event of the last week of May (Figure 5a). During this period, the upper Guadiamar inlet mean discharge stood around 2.76 hm^3. Additionally, a sharper increment on the cumulated volume was registered during the last week of May (Figure 5b) to a lesser extent due to inputs coming from upper Guadiamar River, and to a greater extent probably due to discharges from the Agrio Reservoir located upstream of the pond, in the Agrio River.

One of the restoration activities organised out during 1998 was the construction of a sewage treatment plant. First, a mobile emergency plant was installed on 1st July (Ayala-Carcedo, 2004), but it did not start working till 24th July (Arenas et al., 2008, 2001). This plant worked till 21th August and treated 1.64 hm^3 (Arenas et al., 2001). Later on, a new facility was built and began to work till 29 September and treated 1.15 hm^3. Thus, the minimum amount of acid waters retained in Entremuros, inferred from the treated ones, was 2.79 hm^3.

During those days of 1998 (25/4–29/9), the natural runoff flowed into the affected area, probably passed over the deposited muds without infiltrating, and thus converted the runoff of clean water into polluted waters. Until 29 September, according to the CHG data, the area affected by the spill accumulated at least 5.4 hm^3 of additional acid waters (no-data of other inputs in the subbasin are available). This value agrees well with the 5 hm^3 of acid waters retained at Entremuros (Arenas et al., 2001; CHG, 2005; Grimalt et al., 1999) and with the retained potential capacity of fluid of the Entremuros area (AGE and JA, 1999; OAPN, 1998; Sanz-ramos et al., 2022).

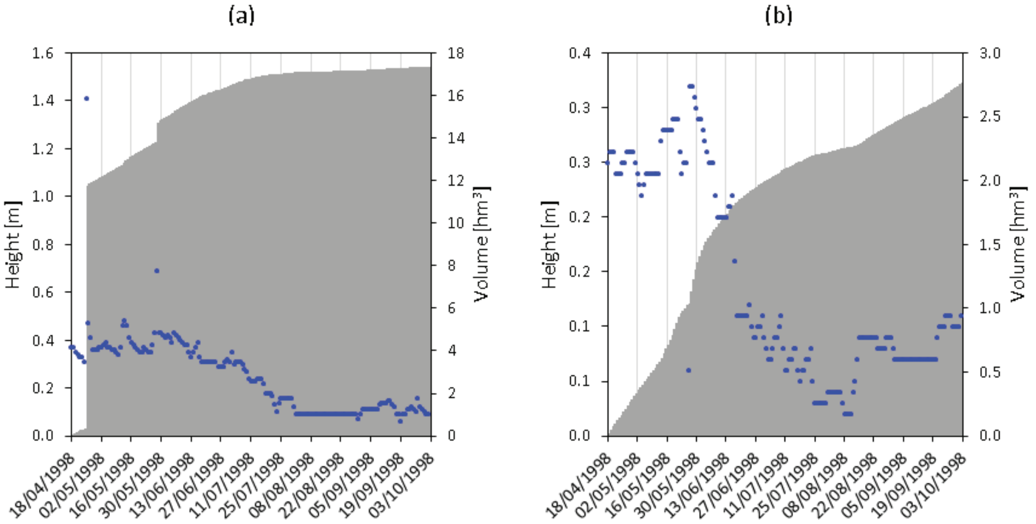

Figure 5. Evolution of the mean daily height (blue dots) and the cumulated volume (grey bars) at the gauge station EA56 (a) and EA90 (b).

Thus, approximately less than a half of the runoff was not treated. However, considering that 1.53 hm^3 of clean water was directly spilled into the Guadalquivir River from 23 July to 2 September (AGE and JA, 1999), the non-treated volume is reduced to 1,08 hm^3. This extra volume was probably infiltrated or evaporated. In this sense, the intermediate period from May to mid-September probably favoured the desiccation of the muds. Some authors (Arenas et al., 2008; Cabrera et al., 2008; CSIC, 2008) present pictures that illustrate the desiccation process of the muds, but neither the date nor the location is indicated.

3. CONCLUSIONS

This paper compiles, discusses, and points out facts and uncertainties about the volume potentially stored, subsequently spilled, and finally recovered during the restoration activities of the Aznalcóllar mine disaster occurred in 1998. Aiming to clarify the most controversial data, new evidence was presented, analysed, and discussed from a hydraulic and hydrological point of view.

The new evidence show that the spill could have had a volume of about 11.5 hm^3, twice the most referenced values. In addition, hydrological evidence indicates additional inputs of water from the drainage basin, increasing the spill volume to more than 5 hm^3 during the period from the disaster to the end of September 1998. This values contrast with the ultimate recovered and treated volume, which rises up to 9.9 hm^3. Thus, this not treated and recovered extra volume probably infiltrated and evaporated.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

AEMET, 2020. OpenData [WWW Document]. URL https://opendata.aemet.es/centrodedescargas (accessed 8.13.21).

AGE, JA, 1999. Comisión de coordinación para la recuperación de la Cuenca del Guadiamar. Memoria de actuaciones - Abril 1999. Administración General del Estado (AGE) y Junta de Andalucía (JA). Sevilla, Spain.

Aguilar, J., Bouza, P., Dorronsoro, C., Fernández, E., Fernández, J., García, I., Martín, F., Ortiz, I., Simón, M., 2003. Contaminación de los suelos afectados por el vertido de Aznalcóllar y su evolución en el tiempo (1998-2001). Edafología 10, 65–73.

Aguilar, J., Bouza, P., Dorronsoro, C., Fernández, E., Fernández, J., García, I., Martín, F., Simón, M., 2004a. Application of remediation techniques for immobilization of metals in soils contaminated by a pyrite tailing spill in Spain. Soil Use Manag. 20, 451–453. doi:10.1079/SUM2004276

Aguilar, J., Dorronsoro, C., Fernández, E., Fernández, J., García, I., Martín, F., Simón, M., 2004b. Soil pollution by a pyrite mine spill in Spain: Evolution in time. Environ. Pollut. 132, 395–401. doi:10.1016/j.envpol.2004.05.028

Aguilar, J., Dorronsoro, C., Fernández, E., Fernández, J., García, I., Martín, F., Simón, M., 2004c. Remediation of Pb-contaminated soils in the Guadiamar river basin (SW, Spain). Water. Air. Soil Pollut. 151, 323–333. doi:10.1007/s11270-006-9254-3

Aguilar, J., Fernández Ondoño, E., Ortiz, I., Dorronsoro, C., Simón, M., 2002. Infiltración de contaminantes en suelos carbonatados afectados por un vertido de lodos Piríticos, in: Ramos Castellanos, P., Márquez Moreno, M.C. (Eds.), Avances En Calidad Ambiental. Ediciones Universidad de Salamanca. Junta de Castilla y León, Salamanca (España), pp. 611–618.

Alastuey, A., García-Sánchez, A., López, F., Querol, X., 1999. Evolution of pyrite mud weathering and mobility of heavy metals in the Guadiamar valley after the Aznalcollar spill, south-west Spain. Sci. Total Environ. 242, 41–55. doi:10.1016/S0048-9697(99)00375-7

Alonso, E.E., Gens, A., 2006a. Aznalcóllar dam failure. Part 1: Field observations and material properties. Géotechnique 56, 165–183. doi:10.1680/geot.2006.56.3.165

Alonso, E.E., Gens, A., 2006b. Aznalcóllar dam failure. Part 3: Dynamics of the motion. Géotechnique 56, 203–210. doi:10.1680/geot.2006.56.3.203

Antón-Pacheco, C., Arranz, J.C., Barettino, D., Carrero, G., Giménez, M., Gómez, J.A., Gumiel, J.C., López-Pamo, E., Martín Rubí, J.A., Martínez-Pledel, B., de Miguel, E., Moreno, J., Ortiz, G., Rejas, J.G., Silgado, A., Vázquez, E.M., 2001. Actuaciones para el reconocimiento y retirada de los lodos depositados sobre el terreno, y su restauración edáfica y morfológica. Boletín Geológico y Min. V.Especial, 93–122.

Arenas, J.. M., Carrascal, F., Gil, A., Montes, C., 2008. Breve historia de la construcción del Corredor Verde del Guadiamar, in: La Restauración Ecológica Del Río Guadiamar y El Proyecto Del Corredor Verde. La Historia de Un Paisaje Emergente. Consejería de Medio Ambiente, Junta de Andalucía. Sevilla, España., pp. 29–64.

Arenas, J.M., Carrero, G., Galache, J., Mediavilla, C., Silgado, A., Vázquez, E.M., 2001. Actuaciones realizadas tras el accidente de Aznalcóllar. Boletín Geológico y Min. V.Especial, 35–56.

Ayala-Carcedo, J., 2004. La rotura de la balsa de residuos mineros de Aznalcóllar (España) de 1998 y el desastre ecológico consecuente del río Guadiamar: causas, efectos y lecciones. Bol. Geol. y Min. 115, 711–738.

Benito, G., Benito-Calvo, A., Gallart, F., Martín-Vide, J.P., Regües, D., Bladé, E., 2001. Hydrological and geomorphological criteria to evaluate the dispersion risk of waste sludge generated by the Aznalcollar mine spill (SW Spain). Environ. Geol. 40, 417–428. doi:10.1007/s002540000230

Benito, V., Devesa, V., Muñoz, O., Suñer, M.A., Montoro, R., Baos, R., Hiraldo, F., Ferrer, M., Fernández, M., González, M.J., 1999. Trace elements in blood collected from birds feeding in the area around Donana National Park affected by the toxic spill from the Aznalcollar mine. Sci. Total Environ. 242, 309–323. doi:10.1016/S0048-9697(99)00398-8

Borja, F., López-Geta, J.A., Martín-Machuca, M., Mantecón, R., Mediavilla, C., del Olmo, P., Palancar, M., Vives, R., 2001. Marco geográfico, geológico e hidrológico regional de la cuenca del Guadiamar. Boletín geológico y Min. V.Especial, 13–34.

Cabrera, F., 2000. La contaminación por metales pesados en el Valle del Guadiamar tras el vertido de Aznalcóllar. Retema 37–48.

Cabrera, F., Murillo, J.M., Madejón, P., Domínguez, M.T., Burgos, P., Madejón, E., Marañón, T., Pérez de Mora, A., Cordón, R., Moreno-Lucas, F., Girón-Moreno, I.F., 2008. Los suelos del Guadiamar: contaminación por elementos traza tras el accidente minero de Aznalcóllar, in: La Restauración Ecológica Del Río Guadiamar y El Proyecto Del Corredor Verde. La Historia de Un Paisaje Emergente. Consejería de Medio Ambiente, Junta de Andalucía. Sevilla, España., pp. 145–164.

CHG, 2005. Doñana. Aguas y Biosfera. Doñana 2005, Confederación Hidrográfica del Guadalquivir, Ministerio de Medio Ambiente. Madrid, España.

CMA, 1998. Informe al Parlamento de Andalucía sobre Las consecuencias de las rotura de la balsa de estériles de las minas de Aznalcóllar.

Consultec Ingenieros, S.L., 1999. Calibración de las tres estaciones de aforo del río Guadiamar (EA n^{o}56, EA n^{o}90 y EA n^{o}76) por métodos informáticos hidráulicos. Estudio de la Riada Tóxica.

CSIC, 2008. Guadiamar. Ciencia, técnicia y restauración - El accidente minero diez años después. Consejo Superior de Investigaciones Científicas (CSIC). Ministerio de Ciencia e Innovación. Madrid, España.

Dorronsoro, C., 2009. Aznalcóllar, hoy. La contaminación de los suelos a los once años del vertido. Macla 8, 11–13.

Dorronsoro, C., Martin, F., Ortiz, I., García, I., Simón, M., Fernández, E., Aguilar, J., Fernández, J., 2002. Migration of trace elements from pyrite tailings in carbonate soils. J. Environ. Qual. 31, 829–835. doi:10.2134/jeq2002.8290

EFE, 2019. La CHG trabaja en la reapertura de la mina de Aznalcóllar, que dice depende de la Junta.

www.efe.com.

ElDiario, 2018. 20 años de Aznalcóllar: los ecologistas advierten de que “otro vertido puede ocurrir.” www.eldiario.es.

Elías, D.C., 2001. Periodismo especializado en medio ambiente: el caso Doñana como paradigma de manipulación informativa. Ámbitos. Rev. Int. Comun. 279–303. doi:10.12795/ambitos.2001.i06.16

Europapress, 2019. La Junta defiende reabrir la mina de Aznalcóllar (Sevilla) con “todas las garantías ambientales y de seguridad.” www.europapress.es.

Gómez de las Heras, J., Gumiel Martínez, P., Custodio Gimena, E., Grima Olmedo, J., 2001. Contribuciones al estudio de la rotura de la balsa de lodos de Aznalcóllar. Boletín geológico y Min. V.Especial, 283–294.

Grimalt, J.O., Ferrer, M., MacPherson, E., 1999. The mine tailing accident in Aznalcollar. Sci. Total Environ. 242, 3–11. doi:10.1016/S0048-9697(99)00372-1

Grimalt, J.O., MacPherson, E., 1999. The environmental impact of the mine tailing accident in Aznalcóllar. Sci. Total Environ. 242, 1–337.

Guerrero, F.M.A., Lozano, M., Rueda-Cantuche, J.M., 2008. Spain’s greatest and most recent mine disaster. Disasters 32, 19–40. doi:10.1111/j.1467-7717.2007.01025.x

Hernández, L.M., Gómara, B., Fernández, M., Jiménez, B., González, M.J., Baos, R., Hiraldo, F., Ferrer, M., Benito, V., Suñer, M.A., Devesa, V., Muñoz, O., Montoro, R., 1999. Accumulation of heavy metals and As in wetland birds in the area around Donana National Park affected by the Aznalcollar toxic spill. Sci. Total Environ. 242, 293–308. doi:10.1016/S0048-9697(99)00397-6

Hudson-Edwards, K.A., Macklin, M.G., Jamieson, H.E., Brewer, P.A., Coulthard, T.J., Howard, A.J., Turner, J.N., 2003. The impact of tailings dam spills and clean-up operations on sediment and water quality in river systems: Rios Agrio–Guadiamar, Aznalcollar, Spain. Appl. Geochemistry 18, 221–239.

IGME, 2001. Las aguas y los suelos tras el accidente de Aznalcóllar. Instituto Geológico y Minero de España, IGME. Boletín Geológico y Minero, Vol. Especial. Madrid (Spain).

López-Pamo, E., Barettino, D., Antón-Pacheco, C., Ortiz, G., Arránz, J.C., Gumiel, J.C., Martínez-Pledel, B., Aparicio, M., Montouto, O., 1999. The extent of the Aznalcollar pyritic sludge spill and its effects on soils. Sci. Total Environ. 242, 57–88. doi:10.1016/S0048-9697(99)00376-9

Madejón, P., Domínguez, M., Madejón, E., Cabrera, F., Marañón, T., Murillo, J., 2018a. Soil-plant relationships and contamination by trace elements: A review of twenty years of experimentation and monitoring after the Aznalcóllar (SW Spain) mine accident. Sci. Total Environ. 625, 50–63. doi:10.1016/j.scitotenv.2017.12.277

Madejón, P., Domínguez, M.T., Gil-Martínez, M., Navarro-Fernández, C.M., Montiel-Rozas, M.M., Madejón, E., Murillo, J.M., Cabrera, F., Marañón, T., 2018b. Evaluation of amendment addition and tree planting as measures to remediate contaminated soils: The Guadiamar case study (SW Spain). CATENA 166, 34–43. doi:10.1016/j.catena.2018.03.016

Manzano, M., Cusotdio, E., Navarrete, P., 2000. Contamination of the Guadiamar river aquifer after the Aznalcóllar mine accident, SW Spain. Boletín Geológico y Min. 111, 93–106.

Martín-Peinado, F.J., 2002. Contaminacion de suelos por el vertido de una mina de pirita (Aznalcollar, España). Universidad de Granada.

Martín, F., Diez, M., García, I., Simón, M., Dorronsoro, C., Iriarte, Á., Aguilar, J., 2007. Weathering of primary minerals and mobility of major elements in soils affected by an accidental spill of pyrite tailing. Sci. Total Environ. 378, 49–52. doi:10.1016/j.scitotenv.2007.01.031

Martín, F., García, I., Dorronsoro, C., Simón, M., Aguilar, J., Ortíz, I., Fernández, E., Fernández, J., 2004. Thallium Behavior in Soils Polluted by Pyrite Tailings (Aznalcóllar, Spain). Soil Sediment Contam. 13, 25–36. doi:10.1080/10588330490269769

Martín, F., Simón, M., Arco, E., Romero, A., Dorronsoro, C., 2008. Arsenic behaviour in polluted soils after remediation activities, in: Soil Health and Land Use Management. InTech, Croatia, pp. 201–216.

McDermott, R.K., Sibley, J.M., 2000. The Aznalcóllar tailings dam accident - A case study. Miner. Resour. Eng. 9, 101–118.

Moreno-Millán, E., Valdés-Morillo, F., 2003. Intervenciones de emergencia en Salud Pública tras el vertido tóxico por el accidente minero de Aznalcóllar (Sevilla). Emergencias 15, 157–164.

Nikolic, N., Kostic, L., Djordjevic, A., Nikolic, M., 2011. Phosphorus deficiency is the major limiting factor for wheat on alluvium polluted by the copper mine pyrite tailings: a black box approach. Plant Soil 339, 485–498. doi:10.1007/s11104-010-0605-x

OAPN, 1998. La catástrofe del río Guadiamar: La rotura de las balsas de lodos de la explotación minera de piritas de Aznalcóllar arrasa los cultivos de la vega del río y amenaza al Parque Nacional de Doñana. Montes, Rev. ámbito For. 53.

Padilla, F., Hernández, J.H., Juncosa, R., Vellando, P.R., 2016. Modelling integrated extreme hydrology. Int. J. Saf. Secur. Eng. 6, 685–696. doi:10.2495/SAFE-V6-N3-685-696

Santofimia, E., López-Pamo, E., González, M., 2011. La corta inundada de aznalcóllar y su uso como vertedero de residuos mineros (Sevilla, España). Bol. Geol. y Min. 122, 235–246.

Santofimia, E., López-Pamo, E., Montero, E., 2013. Environmental Management of Aznalcóllar Mine and Its Influence in the Hydrogeochemical of the Pit lake. Water Environ. Res. 85, 706–714. doi:10.2175/106143013x13698672323263

Sanz-ramos, M., Bladé, E., Dolz, J., Sánchez-Juny, M., 2022. Revisiting the Hydraulics of the Aznalcóllar Mine Disaster. Mine Water Environ.

Simón, M., Dorronsoro, C., Ortiz, I., Martín, F., Aguilar, J., 2002. Pollution of carbonate soils in a Mediterranean climate due to a tailings spill. Eur. J. Soil Sci. 53, 321–330. doi:10.1046/j.1365-2389.2002.00435.x

Simón, M., García, I., Martín, F., Díez, M., del Moral, F., Sánchez, J.A., 2008. Remediation measures and displacement of pollutants in soils affected by the spill of a pyrite mine. Sci. Total Environ. 407, 23–39. doi:10.1016/j.scitotenv.2008.07.040

Simón, M., Iriarte, Á., García, I., Martín, F., Aguilar, J., Dorronsoro, C., 2005. Mobility of heavy metals in pyrite mine spill from an accident in Aznalcollar, SW Spain. Adv. GeoEcology 467–476.

Simón, M., Martín, F., García, I., Dorronsoro, C., Aguilar, J., 2007. Steps in the pollution of soils after a pyrite mine accident in a Mediterranian enviroment, in: Plattenberg, R.H. (Ed.), Environmental Pollution: New Research. Nova Science Publishers, Inc., New York, USA, pp. 185–225.

Simón, M., Martín, F., Ortiz, I., García, I., Fernández, J., Fernández, E., Dorronsoro, C., Aguilar, J., 2001. Soil pollution by oxidation of tailings from toxic spill of a pyrite mine. Sci. Total Environ. 279, 63–74. doi:10.1016/S0048-9697(01)00726-4

Simón, M., Ortiz, I., García, I., Fernández, E., Fernández, J., Dorronsoro, C., Aguilar, J., 1999. Pollution of soils by the toxic spill of a pyrite mine (Aznalcollar, Spain). Sci. Total Environ. 242, 105–115. doi:10.1016/S0048-9697(99)00378-2

Turner, J.N., Brewer, P.A., Macklin, M.G., 2008. Fluvial-controlled metal and As mobilisation, dispersal and storage in the Río Guadiamar, SW Spain and its implications for long-term contaminant fluxes to the Doñana wetlands. Sci. Total Environ. 394, 144–161. doi:10.1016/j.scitotenv.2007.12.021

Turner, J.N., Brewer, P.A., Macklin, M.G., Hudson-Edwards, K.A., Coulthard, T.J., Howard, A.J., Jamieson, H.E., 2002. Heavy metals and As transport under low and high flows in the River Guadiamar three years after the Aznalcóllar tailings dam failure : implications for river recovery and management. Cuad. Investig. Geográfica 28, 31–47. doi:10.18172/cig.1126

WISE, 2020. Chronology of major tailings dam failures. WISE Uranium Proj. World Inf. Serv. Energy.

WWF/Adena, 2002. Minería en Doñana. Lecciones aprendidas.