04-013 – Risk priority number calculation of flood effects on waste management: Valencia's DANA as a case study – Cálculo del número de prioridad de riesgo de los efectos de la DANA de Valencia en la gestión de residuos

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This research addresses the challenge of waste management following natural disasters, such as those occurring after heavy rains and extensive flooding caused by a DANA (Isolated High-Level Depression). Waste management after floods is vital to reduce the damage and environmental pollution resulting from waste accumulation over extended periods due to delays in post-disaster recovery. After visiting the affected areas and consulting the damages declared by the affected municipalities, a list of effects concerning waste management was drawn up. A group of experts in waste, risk, and disaster management estimated the severity (S), probability (P), and temporality (T) of each of these effects. From this evaluation, the Risk Priority Number (RPN=SxPxT) was obtained, which made it possible to rank the impacts and outline a first mitigation plan with the actions to be taken and the resources needed to ensure the proper waste management of the most critical effects resulting from a DANA. The conclusions of this study could serve as a basis for future research and to improve municipal waste management policies, thus increasing urban resilience to natural disasters.

Keywords: *Disaster waste management; Flood; Risk priority number; Action plan; Resilience; IHLD*

Esta investigación aborda el reto de la gestión de residuos tras catástrofes naturales como la ocurrida tras las inundaciones causadas por la DANA (Depresión Aislada en Niveles Altos) en Valencia. La gestión de los residuos tras las inundaciones es muy importante para reducir los daños y la contaminación ambiental derivada de su acumulación durante periodos que pueden extenderse por retrasos en la recuperación tras la catástrofe. Tras visitar las zonas afectadas y consultar los daños declarados por los municipios afectados, se elaboró una lista de consecuencias que afectan a la gestión de residuos. Un grupo de expertos formado por gestores de residuos, especialistas en gestión de riesgos y de catástrofes estimó la severidad (S), probabilidad (P) y Temporalidad (T) de cada uno de esos efectos. Con estos datos se obtuvo el Número de Prioridad de Riesgo (NPR=SxPxT) que permitió jerarquizar los efectos y esbozar un primer plan de mitigación con las acciones a emprender y los recursos necesarios para garantizar la correcta gestión de residuos tras los impactos derivados de una DANA. Las conclusiones de este estudio podrían servir de base para futuras investigaciones y mejorar las políticas municipales de gestión de residuos, aumentando la resiliencia urbana ante catástrofes.

Palabras claves: *Gestión de residuos de catástrofes; Inundaciones; Número de prioridad del riesgo; Plan de acción; Resiliencia; DANA*

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1. Introduction

Natural disasters are becoming more severe and frequent worldwide (Habib et al., 2019). Since the early 2000s, the frequency and duration of floods have increased globally (Najibi and Devineni, 2018). The Intergovernmental Panel on Climate Change (IPCC) stated that more than 20 million people have been displaced annually by extreme weather events such as storms and floods since 2008 (Pörtner et al., 2022). Precipitation extremes are increasing as climate change alters rainfall patterns (e.g., Easterling et al., 2000) and, according to the IPCC, the likelihood of flooding will increase significantly in many regions, including those where it has never occurred before (Cappelli et al., 2021; Pörtner et al., 2022).

The impact of such disasters includes fatalities, multiple damage to homes, schools, businesses, and industry, loss of vehicles and crops, destruction of infrastructure, etc. In the last two decades, 7,348 disasters have been recorded, 1.23 million people lost their lives, 4.2 billion people were affected, and caused a total of U.S. $2.97 trillion in global economic losses (CRED, UNISDR, 2020). Flood damage costs in South Korea in the second decade of the 21st century accounted for 89% of the country's total disaster damage costs (NEMA, 2018). For example, Typhoon Rusa caused damages valued at $4.3 billion. India is another highly vulnerable country; its average annual flood losses are estimated at $7.4 billion (UN, 2015). The economic cost of the floods of Valencia in October 2024 was valued at €18 billion. If the indirect costs derived from this type of catastrophe were to be incorporated, the economic impact would be even more significant.

Behind these catastrophes always appears, despite being often overlooked, an immense volume of debris waste (DW) generation (Habib and Sarkar, 2017). Beyond the fact that the cost associated with DW Management (DWM) can account for up to 27% of the total costs caused by floods (FEMA, 2012), it should be considered that improper DWM has a high environmental impact and can trigger a health and security crisis in the affected areas, both inside and outside the flooding area (e.g., Blight and Fourie, 2005). Furthermore, Crowley (2017) revealed that disaster preparedness and DWM planning had a favorable impact on the effectiveness of recovery processes, leading to significantly reduced costs.

In this scenario, it can be stated that proper disaster Waste Management (WM) is a crucial and underestimated issue in responding to the emergency and facilitating and accelerating the recovery phase (Crowley, 2017; Ho-Park et al., 2020). Research on WM after natural disasters has increased in recent years, and the analyses of risks related to hospitality or hazardous waste are scattered in the literature (e.g., Dadashi et al., 2024; Ho and Cehn, 2018). However, to the best of authors' knowledge, the analysis of the risks and effects of the possible impacts of floods on WM has been the object of lesser study. This work will use the Risk Priority Number (RPN) as a classic indicator for risk assessment to detect and prioritize the main risks that endanger WM after floods. For this purpose, the effects on WM and the associated risk emergence after the DANA (in Spanish; Isolated High-Altitude Depression) suffered in Valencia in October 2024 have been analyzed using Failure Mode and Effects Analysis (FMEA). FMEA determines the effect of a failure mode on a given product, system, or process according to severity (S), occurrence/probability (O/P), and detectability (D). The IEC 60812 standard (UNE-EN IEC, 2018) has assumed a different range of S, O, and D for a system, which is helpful to identify the single Failure Mode (FM) based on RPN. One of the main objectives of the IEC 60812 is to support proactive risk management. Environmental agencies use FMEAs to identify and address potential risks related to environmental management processes, pollution control, and waste disposal.

Valencia is a flooded-prone area that has already been seriously affected by heavy rains in its history, and the possibility of such crises occurrence in the future seems inevitable. However, as specified by the Vice President of the Generalitat Valenciana (GVA) during the presentation of the Diagnostic Report of the Economic and Social Recovery Plan of the Valencian Community on March 21, 2025, the rains of October 2024 were the heaviest and most devastating in its history. The DANA caused 227 fatalities, one missing person, 306.000 people affected, 103 municipalities, 11.242 houses, 64.104 businesses, and 141.000 vehicles. The affected structures were 800 kilometers of roads, more than 550 railways, and 380 bridges and pontoons, more than 350 kilometers of watercourses, two dams, two Drinking Water Treatment Plants (DWTPs), and 123 Wastewater Treatment Plants (WWTPs). This devastation and an estimated volume of debris waste of 800.000 t make it a perfect case study for assessing WM risks that can be repeated in any similar crisis at any time and place.

The remaining sections of the communication will be the material and methods employed, results, discussion of the case study, and conclusions.

2. Material and Methods

Visits to the affected area and meetings with stakeholders were scheduled to get information and clearly define the disaster context, regional characteristics, WM system, and process to be analyzed in Valencia. Then, two focus groups with experts were performed to select the most influential impacts of FMs, calculate their RPN, and prioritize the risk mitigation efforts.

2.1 Ground Zero visit and stakeholders' meetings.

To analyze the impacts caused by the Valencia DANA on WM, the authors visited the principal localities concerned: Paiporta ("Ground Zero"), Picanya, Alfafar, Massanassa, Sedavi, Catarroja, and the Albufera Lagoon on January 8-11, 2025. Experts also visited the treatment and recovery waste plant "Los Hornillos" in Quart de Poblet and several on-site temporary collections centers to store vehicles. During the visits, the experts met the Chief Executive Officer (CEO) of Clean Waste, the Spanish cluster of firms related to WM, EMTRE (Entidad Metropolitana Tratamiento Residuos) employees, camp managers, technical managers of WM companies, citizens, and representatives of associations of affected people. They also participated in a workshop on sustainable WM after DANA, which was organized by Clean Waste and the Project Management, Innovation, and Sustainability Research Centre (PRINS) at Universitat Politècnica de València (UPV).

2.2 Experts focus group to calculate the RPN.

With all the information gathered, the experts worked in one focus group lasting five hours to identify, categorize, and hierarchize the risks faced by the Valencian WM system after suffering severe floods. In the morning, five experts, two on WM, who were responsible for managing all the generated waste in the floodings occurred in Alemania in 2021, two on risk assessment and disaster management, and another on organizational resilience, identified and described effects and FMs. The experts showed their identified FMs, and those on which there was consensus were selected and set aside as an initial selection. The experts then worked in groups with the remaining identified FMs until a final list was defined by consensus. Finally, they classify the identified FMs by grouping them into categories. In the afternoon, three experts, the same two experts on WM who take part in the first focus group, and one in risks and resilience analysis, estimated the severity (S), probability (P), and temporality (T) of each of the identified FMs by ranking between 1 and 10 points. Notice that for the present study, the "detectability" factor typically used in FMEA studies was changed by "temporality", trying to measure the effects of the impacts for the short, medium, and long term. The criteria for rating

Severity were 1 for no danger, 2-3 for minor danger, 4-6 for moderate, 7-8 for high, and 9-10 for very high. For the probability of occurrence, experts assigned 1 for non-documented failures, 2-3 for low-few relatively failure, 4-6 for moderate-occasional failures, 7-8 for high-repeated failures, and 9-10 for very high- when failure is almost certain. Finally, Temporality was rated with 1-3 for effects only in the short term (disaster response stage), 4-7 for impact in the medium term (recovery response), and 8-10 for implications in the long term (reconstruction phase and even later).

The experts worked individually before sharing their ratings and working together to discuss them, as they did in the first focus group. After discussions, the experts could review their ratings and change them if necessary. The RPN (S x P x T) was obtained using the average of the experts' ratings for Severity, Probability, and Temporality.

It is worth noting that the experts only identified FMs related to the response, recovery and reconstruction stages after the flood. Experts omitted the risks of not performing beneficial actions regarding DWM before the advent of the crisis because Valencia lacked a specific pre-disaster plan for DWM.

3. Results

The experts classified and coded the FMs into three categories: Planification and Management (P&M), Infrastructure and Logistics (I&L), and Environmental and Social (E&S).

The selected FMs for each category are shown in Table 1.

Table 1. List of FMs classified into categories.

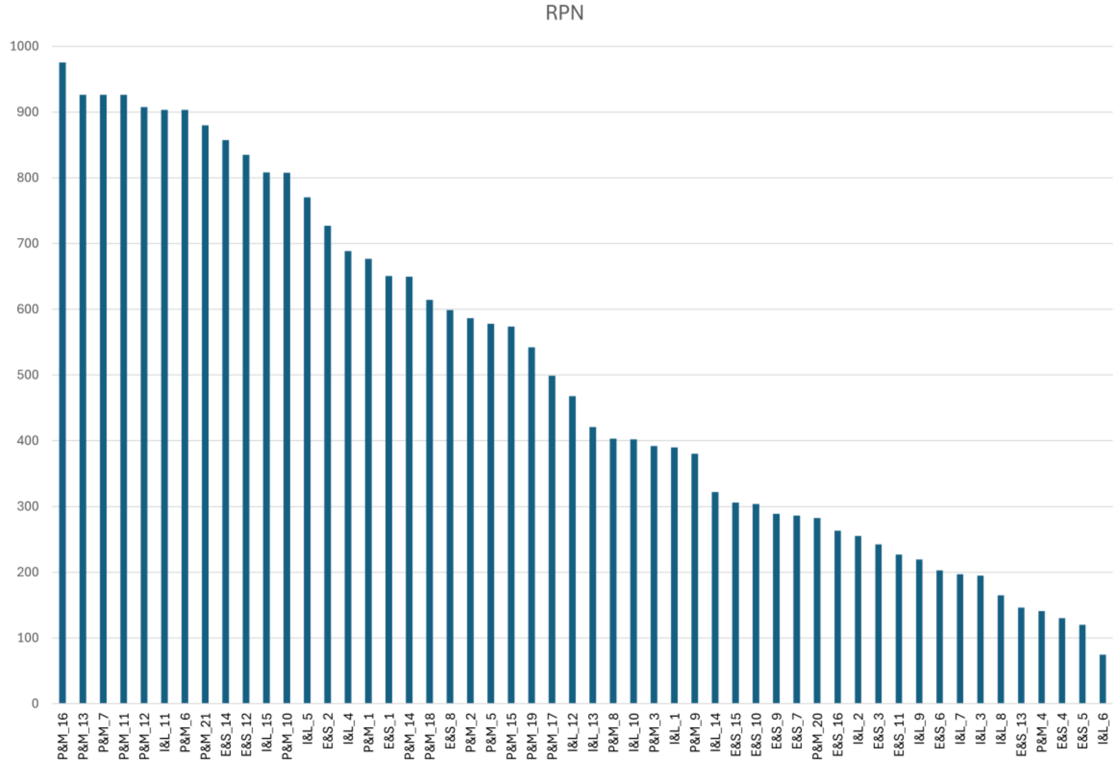
FM code	Description
P&M_1	Choosing inappropriate locations for temporary staging sites
P&M_2	Improper estimation of the total post-flood volume of DW generated
P&M_3	Having and communicating insufficient disaster and debris operations Information
P&M_4	DWM delayed by giving priority of road use to emergency services (affecting WM time and cost)
P&M_5	Poor/lack of coordination and integration among top management
P&M_6	Poor/lack of enforcement by the government of legal instruments
P&M_7	Low accessibility of data and information
P&M_8	Having imposed time constraints on DW removal and disposal
P&M_9	Elements of challenges in handling waste: Insufficient funds and finance allocated
P&M_10	Lack of regulations/ acts and guidelines
P&M_11	Lack of type of waste assessment to be treated
P&M_12	Poor information about the description of the general terrain types, land use, and accessibility for the areas impacted by the incident and how these characteristics may affect DWM operations.

FM code	Description
P&M_13	Lack of coordination with specialized services for disposing of hazardous waste/dangerous substances
P&M_14	Lack of fluid collaboration among all levels of government regarding DWM
P&M_15	Lack of coordination and synergy among all WM agents
P&M_16	Not including disaster waste management with the emergency management
P&M_17	Having difficulties hiring external contractors to provide additional labor and equipment
P&M_18	Ill-defined roles and responsibilities among stakeholders
P&M_19	Performing outside the regulatory framework to speed up DW removal
P&M_20	Ill-defined priorities during both the response and recovery phase operations
P&M_21	Lack of Monitoring Debris Operations
I&L_1	Inability to use the facilities' full capacity
I&L_2	Non-operational waste facilities due to power outages
I&L_3	Non-operational facilities due to flooded access
I&L_4	Lack of enough landfill equipment and machinery to face the high volume of DW
I&L_5	Lack of heavy equipment (dump trucks, bulldozers, shredders, grapplers) and other essential resources
I&L_6	Access routes and roads blocked and/or damaged
I&L_7	Waste collection routing mistakes
I&L_8	Landfills cut off by road and transport routes
I&L_9	Uncollected building and construction waste hindering reconstruction
I&L_10	Technical constraints/ insufficient equipment, machinery, and workforce with the latest technology
I&L_11	Insufficient landfill capacity
I&L_12	Block drain infrastructure
I&L_13	Lack/low consideration of the impact of post-disaster conditions on the transport network
I&L_14	Suffering from a fire in the fields of stacked cars
I&L_15	Poor management of wrecked vehicles: no hazardous waste removal, stacking, lack of sorting, etc.
E&S_1	Hazardous waste enters the soil and groundwater
E&S_2	Having waterways, agricultural areas, and communities contaminated by chemicals and heavy metals

FM code	Description
E&S_3	Transporting hazardous materials that endanger the health of workers and people in the area
E&S_4	Breeding sites for rodents, mosquitos, arbovirus transmission, and contagious disease vectors (Causing viral diseases and potential infection)
E&S_5	Serious health risks to residents, including inhalation of dust, odor, and noise
E&S_6	Mixing hazardous and toxic wastes such as asbestos in damaged buildings and its reuse: health risks associated with inhalation and contact
E&S_7	Disrupting the lives of residents near the temporary debris management sites
E&S_8	Residents and volunteer’s unawareness of safety rules, measures, and procedures to protect themselves from DWM perils
E&S_9	Underestimating Environmental Considerations and other Regulatory Requirements
E&S_10	DW Visual impact
E&S_11	Deficient management of pruning waste, reeds, and logs in the lagoon and beaches
E&S_12	Excessive sludge deposition in the lagoon
E&S_13	Flood-induced microplastic mobilization from WM facilities
E&S_14	Excessive amounts of sludge deposited on crops
E&S_15	Suffering trauma after disaster
E&S_16	Increasing mental health cases

Figure 1 shows the ranking of the FMs, according to their RPN values, obtained after experts’ severity, probability, and temporality ratings.

Figure 1. FMs ranking according to RPN.



4. Discussion

The work has made it possible to identify and prioritize the FMs that appear in waste management because of the floods caused by the DANA in Valencia. The absence of a WM specialist among the members in charge of managing the emergency (P&M_16) is the most significant risk, according to the experts, in line with what is claimed by some authors (e.g., Zawawi et al., 2016). It is followed, with practically the same score, by FMs related to the lack of coordination with the different centers specialized in hazardous waste (P&M_13), the lack of knowledge regarding the composition and type of waste to be managed (P&M_11), the lack of information in general (P&M_7) and the lack of information regarding the terrain types, land use, and accessibility and how all these issues may affect DWM operations (P&M_12). Next comes the risk of a lack of landfill capacity (I&L_11), the first risk in the I&L category. The lack of political agility to enact actions and the inability to monitor the execution of WM tasks also pose considerable risks to making the right decisions or rectifying them quickly and effectively (P&M_6, P&M_21), which is in line with the FEMA assistance guide (FEMA, 2018). Among the top 10 essential FMs are the environmental risks generated by a heterogeneous mixture of debris filled with sludge for crops and protected green areas (E&S_14, E&S_12). Thus, it can be said that in the top 10 positions risks are related to the lack of planning and strategic management to properly face the early stages of response to the crisis, where confusion, misinformation, uncertainty, and lack of coordination to give an agile, flexible, and rapid response to the flood disaster prevail.

Between positions 11 and 25 in the first place is the risk of not correctly managing wrecked vehicles (I&L_15), the lack of clear guidelines and regulations (P&M_10), and poor selection of temporary storage sites, as occurred with vehicles in Valencia, since their storage caused much controversy, lasting many months before it was regulated how to manage them. Also, risks like the lack of heavy and specialized machinery for waste treatment centers and the risks derived from chemical contamination by hazardous waste in aquifers and crops are among the most relevant, as has been argued in previous works (e.g., Dubey et al., 2007). The last FMs in this second quartile are derived from defective operational management of waste, where the lack of knowledge of the amount of waste to be treated, the defective assignment of responsibilities, and the lack of coordination between the different political levels (local, regional, national), the interested parties, the WM agents and among senior management, together with the difficulties in contracting cleaning services appeared. The risks of dumping untreated waste outside the regulations stipulated in everyday situations, as pointed out by Novarlić et al. (2024), together with the risk to the health of neighbors and volunteers who joined the debris removal and cleanup work due to lack of knowledge of the dangers of handling waste are also among the most relevant risks. All these risks could be applicable and play a key role during the first stages of the recovery phase, being essentially more operational than strategic.

In the third quartile, there are failures such as blockage of the sewage system (I&L_12), damage to the logistics network (I&L_13), lack of means, equipment, personnel, or capacity of the facilities (I&L_10, I&L_1) that may lead to accidents such as fires in the car storage areas (I&L_14). Planning and management failures in this quartile could be linked to the beginning of the recovery phase, in which all the work done till then is evaluated. These FMs have to do with being pressured to remove waste quickly and not communicating well what is being done and should be done regarding WM (P&M_8, P&M_3). In addition, the FMs related to the lack of funds to deal with the massive amount of waste generated and the lack of coordination to define priorities during the response and recovery phases appear (P&M_9, P&M_20). Environmental and social risks are more present in this quartile of FMs. The crisis effects are already visible (E&S_10), and feeling surrounded by waste further disrupts the lives of those affected (E&S_7), as Sharifah et al. (2018) stated. After the floods and the response phase, the magnitude of the tragedy becomes apparent, accidents occur, and people fear for their health and the environment's security (E&S_9, E&S_15, E&S_16). Among the WM technicians, there is a phase of evaluation and criticism about the work done, the lack of means (P&M_9), the visible amount of waste, and its impact, which makes it clear to them what lies ahead.

The FMs with the lower RPN values in the fourth quartile appear to be failures linked to I&L and E&S categories. These are risks that, although important, score low in some of the severity, occurrence, and temporality factors. Risks such as power failure in the Waste Treatment Plants, inaccessibility due to flooding, road blockages, temporary isolation of landfills, and mistakes in the design of collection routes are essential but can be amended in a relatively short time, which reduces their RPN values. The risk of infection and serious health effects from hazardous and toxic waste did not occur in Valencia. Finally, the poor management of pruning debris, reeds, and trunks appeared after a few months, when the sea returned all the discharges after the floods, and the release of microplastics into the ocean from the landfills was improbable because the landfills in Valencia have not been flooded.

The classification of risks has indeed been made for the specific case of Valencia, which may be a limitation of the study. Further work should compare the risks from floods on WM in similar crises. The essential problems probably remain common in most cases. However, regulations on WM and government structures always depend on the location, and every flood depends on disaster context and local characteristics (e.g., Park et al., 2020; Lee et al., 2022), so comparing different crises could shed light on shared risks and risk location dependent.

Basic suggestions to address the risks detected would include discouraging urban development in flood-prone areas, implementing early warning systems, diverting excess runoff to natural depressions or ad-hoc constructed facilities, and encouraging water-sensitive urban planning and design (e.g., using permeable pavements and green infrastructure). Drawing a detailed action plan is beyond the scope and objectives of this work. However, the following is a summary of actions to be taken to achieve a more sustainable and resilient WM in the face of floods mentioned by experts taking part on the workshop on sustainable WM after DANA, 1) It seems mandatory to include DWM within the emergency management planning, 2) waste experts along with national, regional and local emergency managers, disaster consulting agencies, volunteer organizations, academics and local residents must design a preventive plan to deal with DW including at least: predicting volume of DW, planning waste collection and transport, designating temporary storage areas, selecting treatments and final disposal methods, 3) finance the DW plan with the annual allocation of a budget including the provision of resources and updated equipment, 4) define roles, participation and responsibilities of the local, regional, and national stakeholders, including affected citizens and volunteers, and 5) personnel training is mandatory to handle proper DWM.

In addition, facing the challenge of identifying innovative strategies to overcome the criticality of WM during these floods requires the involvement of universities and research centers. These organizations must face the problem with an approach that combines technical, economic, environmental, and social dimensions to help decision-making based on the specific characteristics of each location according to the type of tragedy suffered (Amato et al., 2019). To address resource constraints, they must work with national, regional, and local emergency management agencies and industry in writing grant applications. Also, researchers should encourage and guide the inclusion of technologies such as Artificial Intelligence (AI) and Internet of Things (IoT) for real-time waste tracking, as well as blockchain to ensure data security and improve waste management systems when this kind of natural disaster occurs. Finally, academics and experts from waste companies are best suited to provide continuous training and capacity building among technicians and managers to use these technologies.

5. Conclusions

This paper identified risks and possible effects on waste management in the aftermath of a natural disaster such as DANA. National and international experts who already managed DW after the floods in Germany in July 2021 identified 52 possible WM failure modes. The experts classified these risks into three categories: 21 were related to Planning and Management issues, 15 to Infrastructure and Logistics, and 16 to Environmental and Social impacts. Afterward, the risk priority number for all of them was calculated according to the severity, probability of occurrence, and temporality of the DANA suffered in Valencia in October 2024, thus being able to rank these risks. The results show that in the top 10 positions, risks related to the lack of planning and strategic management appeared to be related to the failure to properly face the early stages of response to the crisis, where uncertainty and lack of coordination prevail. The FMs that follow until completing the second quartile represent risks that have to do with the operational tasks performed in the first stages of response to the crisis and that in Valencia are exemplified very well through all the problems involved in the management of the 141,000 wrecked vehicles (e.g., the lack of clear guidelines and regulations, poor selection of temporary storage sites, lack of machinery and resources, presence of hazardous waste, defective operational management of waste; defective assignment of responsibilities, and the lack of coordination). In the third quarter, the failure modes have to do with the beginning of the recovery phase, in which all the work done until then is evaluated. Environmental and social risks are more present in this quartile because the amount of waste is already visible, accidents occur, and people fear for their health and the environment's safety. In the last quarter, failure modes that, despite being important, score low in some of the severity, occurrence, and temporality factors close the ranking. These are failure modes in the I&L category that were solved quickly and others in the E&S category that fortunately did not occur in Valencia.

The actions suggested by the experts participating in the workshop on sustainable WM after DANA were briefly discussed in the paper. They show the need for WM to be considered in decision-making during emergency management and to seek solutions to address the complexity of sustainable and circular WM due to its multi-level, multi-expert, and multi-agent character. Finally, emphasis is placed on the role of universities and research centers in attracting funds and introducing technological advances to improve the conditions for dealing with this type of natural crisis that threatens to become increasingly frequent and devastating.

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Use of Generative Artificial Intelligence

No generative artificial intelligence was used to prepare this communication.

Communication aligned with the Sustainable Development Goals