International Journal of Disaster Risk Reduction 66 (2021) 102634

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Technological accidents caused by floods: The case of the Saga prefecture oil spill, Japan 2019

Alessio Misuri [a,b], Ana Maria Cruz [b,*], Hyejeong Park [b], Emmanuel Garnier [c], Nobuhito Ohtsu [d], Akihiko Hokugo [e], Isamu Fujita [f], Shin-ichi Aoki [g], Valerio Cozzani [a]

[a] Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Italy
[b] Disaster Prevention Research Institute, Kyoto University, Japan
[c] CNRS Chrono-Environment Laboratory, University of Bourgogne Franche-Comté, France
[d] National Research Institute of Fire and Disaster, Fire and Disaster Management Agency, Government of Japan, Japan
[e] Research Center for Urban Safety and Security, Kobe University, Japan
[f] Port and Airport Research Institute, National Research and Development Agency, Japan
[g] Department of Civil Engineering, Osaka University, Japan

ARTICLE INFO

Keywords:
Oil spill
Ironworks factory
Natech
Emergency response
Climate change
Environmental pollution

ABSTRACT

This study investigates an oil spill which involved an ironworks factory in Saga prefecture, during the severe flooding that hit southwestern Japan in late August 2019. The aim of the study is to provide an overview of the accident, highlighting the causes and the consequences of this compound disaster. Furthermore, the study analyses the emergency response and clean-up activities in order to identify lessons learned, and propose recommendations for future flood triggered oil spills. The work presented is based on the integration of information available in newspaper articles, government documents and reports, and data and interviews collected during two field trips in the affected area. The permanence of oil and the strong oil odour in adjacent crops as well as on irrigation canals and citizens' houses was revealed during the first field trip, about one month after the accident. The analysis of the documentation on metal working oil revealed that it might have long-lasting impact in terms of environmental pollution. The presence of oil impacted also the implemented emergency response actions, since vertical evacuation, practiced by many residents during the disaster, actually put many of them in more danger as they ended up trapped in oil-covered floodwaters with strong vapours that were reported to cause nausea and skin irritation. Remarkably, it was also found that a previous oil spill had already occurred at the same site following a severe flooding event, highlighting the need to improve preparedness and develop more effective strategies for accident prevention. Disaster preparedness that specifically considers both the natural hazard and the potential for related technological scenarios should be enhanced, in particular regarding chemical accidents triggered by floods. Japan, as well as other parts of the World, is experiencing stronger rainfall events due to a changing climate leading to unprecedented flooding. Therefore, industry, government and citizens should consider the possibility of an increase of weather-related compound disasters in planning and implementation of climate change adaptation strategies.

1. Introduction

The aim of this study is to investigate a technological accident, an oil spill from an ironworks plant in Saga Prefecture, Japan, during the severe flooding that hit southwestern part of the country in late August 2019. These so-called technological accidents triggered by natural hazards are known as Natechs [1]. This study contributes to the body of knowledge concerning the causes, direct and indirect consequences, and long-term impacts of these types of accidents. Furthermore, the study analyses the available information on the emergency response and clean-up activities in order to identify lessons learned, and propose recommendations to prevent, prepare for, respond and recover from future technological accidents triggered by floods. The importance of the study lies in the fact that there is still relatively little work published concerning case studies of flood-related technological accidents and their overall impacts, while recent hydro-meteorological related

* Corresponding author.
E-mail address: cruznaranjo.anamaria.2u@kyoto-u.ac.jp (A.M. Cruz).

https://doi.org/10.1016/j.ijdrr.2021.102634
Received 28 December 2020; Received in revised form 1 September 2021; Accepted 11 October 2021
Available online 14 October 2021

chemical accidents have demonstrated the complexity and the severity of these cascading events [2–4].

According to a study based on the analysis of the National Response Centre database, in the United States in the period 1990–2008, hydro-meteorological related chemical accidents represent over 70% of all identified Natech events (26% rain induced, 20% hurricane induced, and 25% attributable to storms, winds, and other unspecified types of weather) [5]. Another study focused on Natech events listed in the ARIA (Analysis, Research and Information on Accidents) database, one of the most relevant sources of information on major industrial accidents run by the French Ministry of Environment, and found that flood and storm related Natechs represent about 46% of the reported Natech accidents between 1992 and 2012 [6]. Due to climate change, it is expected that some regions may experience stronger heavy rainfall events, as well as stronger tropical storms both of which can result in flooding. The heavy precipitation that hit southern Japan in late August 2019, caused unprecedented downpours and massive flooding over vast areas. Saga Prefecture, in Kyushu Island, was particularly affected and authorities registered precipitation levels about double the normal level for the time [7]. Thousands people were instructed to evacuate, main train stations were flooded and two people died [7–9].

Extreme rainfall events of this kind are likely to flourish both in terms of frequency and severity in the future. Indeed, the number of climate and weather-related disasters are growing in many areas worldwide along with their costs [10,11]. According to the recent World Economic Forum, extreme weather events and climate change became priority risks for the economy at the global level [12]. Considering the case of Japan, the overall losses due to weather and hydrological disasters from 1980 to 2018 have been estimated at 129 billion US$ [11]. Moreover, according to IPCC, the risk related to extreme weather events is going to further increase in the foreseeable future due to climate change [13]. Recent research pointed out that the intensity of severe precipitations may increase in Japan as consequence of the changing atmosphere air temperature during the current century [14]. In addition to extreme rainfall events, previous research highlighted statistically significant increases in severe tropical cyclones (i.e., categories 3 and 4 of Saffir-Simpson scale [15,16]) hitting southern Japan [17].

It is not surprising then, that the oil spill investigated in this study is not a one-time event. In fact, as it will be shown, another oil spill at the same ironworks plant had occurred in the past, and structural mitigation measures had been taken, considering updated hazard maps at the time. Nonetheless, the intense floods of August 2019 again led to the release of oil outside the premises of the factory and emergency management operations were complicated by the presence of the chemical, indicating that more needs to be done to be better prepared for these types of compound disasters. Therefore, this study hopes to provide some insights and recommendations based on lessons learned from the accident. Firstly, a concise literature review on the topic of Natech accidents caused by flooding and weather-related phenomena and a brief description of the methodology applied in this study will be provided respectively in Section 2 and Section 3. Then, the downpour of August 2019, the resultant flooding and the triggered oil spill will be extensively described in Section 4 together with relevant information on geological and historical data of the impacted region. The main findings obtained during the field inspections and from the open literature will be discussed together with possible recommendations, study limitations and future directions in Section 5. Finally, the conclusions will be summarized in Section 6.

2. Background

The oil spill of August 28th, 2019 in Saga prefecture is an example of a Natech event [1]. The interest of both industry, academia and international organizations in these particular types of technological accidents is relatively new and dedicated literature is growing in recent years [18–20]. The earliest works on the topic are dated back to the nineties, mainly investigating the release of hazardous substances caused by earthquakes in the United States [21–23]. At that time, it was pointed out that Natech events constituted up to 5% of technological accidents reported in the United States and European major accidents databases [24]. These figures have been substantially confirmed in more recent research [25], although nowadays the numbers are probably higher due to the increase in frequency and severity of some categories of natural hazards (e.g., weather-related disasters), and may further grow in the future due to the effect of climate change [26–28].

The significance of Natech accidents in exacerbating the already possibly severe consequences of natural disasters was also remarked by recent severe events. For instance, hurricanes Katrina and Rita, which made landfall in 2005, caused massive damage to oil and gas infrastructures and offshore installations in the Gulf of Mexico leading to more than 600 hazardous material releases [29,30] and environmental pollution which continued for over a year due to start-up/shutdown operations [31]. Research on damage brought by Hurricane Harvey in 2017 again showed the severe impact of hurricanes on facilities handling hazardous substances [32,33]. Earthquakes and tsunamis have also caused severe examples of Natech events as is the case of the Fukushima nuclear disaster and explosions of LPG tanks in Chiba prefecture during Great East Japan Earthquake and Tsunami in 2011 [34].

Besides these examples which are related to high magnitude disasters that had worldwide visibility, also heavy rainfall and the related flooding may constitute potential triggers for hazardous material releases. For instance, it was pointed out that more than a fourth out of the totality of hazardous material releases triggered by natural hazard events in the United States were caused by rain between 1990 and 2008 [5]. Between 2000 and 2001, about 44% of chemical releases related to adverse weather conditions in United States (including weather disasters as hurricanes) was caused by rainfall [35]. In July 2018, an explosion was caused by flooding brought by heavy downpours in an aluminium factory in Soja city, Okayama Prefecture, Japan [2,4]. Despite these alarming examples, there is still little empirical data concerning past flood-related Natech accidents, remarking the importance of studies like this one aimed at expanding the body of knowledge available in the literature on these complex cascading disasters with the final aim of fostering better disaster prevention and preparedness.

3. Methodology

In order to understand the impact of the Natech event of August 2019, two field trips to the affected areas in Omachi town were carried out in September 2019 and February 2020.

The objectives of the field trips were manifold. Indeed, the first field trip was aimed at spotting evidences of the oil impact on the area, collecting qualitative first-hand data on how the chemical sheen damaged dwellings and agricultural fields, and obtaining information from local residents on the evacuation procedures performed, and on the emergency management actions implemented by authorities at local level. An additional point of interest of the first field trip was to do a visual reconnaissance of the factory premises and neighbouring residential areas where the oil spill occurred. We could not interview company officials nor workers, although we were able to observe company workers (wearing the company uniform) carrying out clean-up activities on residential properties near the factory. During the second field trip, officers from the Saga prefecture fire department were interviewed with the aim of having further details on evacuation procedures and post-disaster actions put in place in 2019.

Besides the data collected during the trips, newspapers articles and Japanese government websites were consulted to obtain, on the one hand, information concerning past flooding and oil spills in Omachi town and Saga Prefecture, and on the other hand, the necessary background information on the region and the related flood hazards.

4. Description of the event

The oil spill in Omachi town in Saga Prefecture occurred on 28th August 2019. The area of the accident, Omachi town, is mainly constituted of reclaimed land from the Ariake Sea, which is linked to the high flood proneness of the whole Saga plain. In the next subsection a brief description of the area together with a historical perspective on the recurrent past flooding events will be given, which should help the reader to understand the historical and hazard context of the event. Successively, the flooding event of August 2019 will be described together with the related Natech it caused. The hazardous properties possibly characterizing the released substance and in general the oils employed in ironworks processes will then be presented. Significant information on emergency response activities and post-disaster actions will be reported, along with an attempt of evaluation of the damages of the event.

4.1. Description of the area

Saga Prefecture mainly lies over a low flatland area. As can be seen from Fig. 1, the actual coastline on the Ariake Sea is the result of centuries of soil reclamation activities which began around the 6th century [36]. The Saga plain is deeply characterized by the presence of the Rokkaku river water system, whose basin area is of about 341 km^2 [36]. Given its importance for national economy and for land conservation, the Rokkaku river water system is classified as a first-class river [37]. According to the River Law, the main regulation that covers river management in Japan, first-class rivers (i.e., therein defined as Class A rivers) are directly managed by the central Ministry of Land, Infrastructure, Transportation and Tourism (MLIT) [38].

Clearly, rivers of such importance are critical from a flood control stand point. Japan has a long history of flood control policies, which have been developed and amended since the Meiji Government era [39]. Nowadays, flood control in Japan is supported by several regulations that have been developed in the last century, including the aforementioned River Law itself, the Flood Protection Act and Disaster Countermeasure Basic Act among the others [39–41]. A comprehensive description of these policies is out of the scope of this work, and the interested reader can find further information on this point in Refs. [39–41].

For what concerns the case of Rokkaku river water system, flood risk management is particularly complex due to the morphology of the Saga plain. Indeed, about 60% of the basin is an inland water area, with an elevation of the plain mostly between 0 m and 3 m ASL [36], and since the Ariake Sea tidal range reaches up to 6 m, in case of high tide seawater flows upstream, reaching up to 29 km inland on the Rokkaku river [36]. It is not surprising thus that previous major floods that hit the region caused huge destruction.

To find more information on flood proneness of the region a historical research in the Japan Times (www.japantimes.co.jp) archives was carried out. The area of research was limited to Saga City only in this case, not to bias the historical series. Analysing the newspaper database, 20 floods were identified which hit the capital of the region in the period of 1900–2009, as it is reported in Table 1. As can be noted from the table, the three most severe flood events were registered in 1923, 1953 and 1990. The information retrieved gives also clear indications on the high frequency of floods affecting the region. Indeed, the set of floods identified corresponds to an average return period of 5.45 y (frequency of 1.83e-01 y^{-1}) in the analysed timespan. It should also be noted that an acceleration is highlighted between 1950 and 2009, with 14 floods reported (average return period of 4.2 y), compared to the previous 50 years (6 floods with an average return period of 8.3 y). This higher frequency might be explained considering possible underreporting in past times, but might also be an indication of climate change effects on the area. Thus, considering also the industrialization and urbanization growth in Japan in the second half of XX century (e.g., see Ref. [42]), the exposure to risks related to flooding have clearly increased.

Other sources confirmed that these events had a massive impact in the entire region. Indeed, during the floods of June 1953, more than 14,000 houses in the prefecture were flooded and many landslides were triggered due to soil failure [43]. Again, heavy rain in August 1980 caused high waters to collapse river embankments and about 1700 houses were flooded [43]. During a heavy rainfall event in July 1990, river embankments broke in 10 locations, leading to catastrophic flooding. Indeed, floodwater covered about 8000 ha (8.0e+07 m^2) of farmland and submerged the foundations of more than 5500 houses [43]. Another massive flooding event impacted the region in July 2009 [43].

It should be noted that to prevent flooding, embankments, dams and retarding ponds have been constructed and maintained, and drainage pumps have been installed in the area to allow water discharge into the rivers [36]. Nevertheless, these measures seem to be not effective in case of extreme rainfall events. In the July 2018 rainfall event, which again led to widespread flooding, the river and pumping systems were so overburdened that embankments broke also in one area upstream on the Rokkaku river for the first time after 1990 [43].

The town of Omachi, where the oil spill happened, is located along the main channel of the Rokkaku river. Following the 2007 amendment of the Flood Protection Act, the production of flood hazard maps has become mandatory [39], and inundation maps for the Rokkaku river are

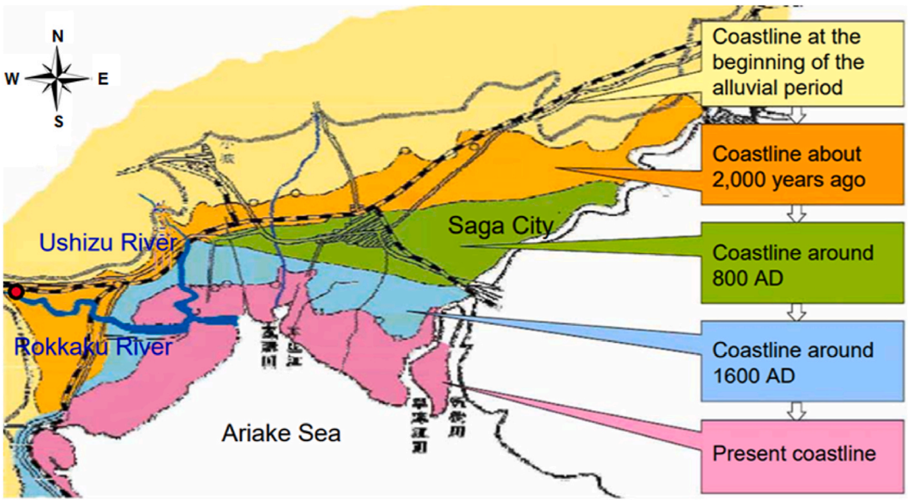

Fig. 1. Coastline of the Saga low flatland area. The source of oil spill is indicated in red. Adapted from Ref. [36].

Table 1
Summary of floods in Saga City between 1900 and 2009, according to the information retrieved from the Japan Times (www.japantimes.co.jp).

ID	Date	Number of flooded houses in Saga City	Flooded fields in hectares	Deaths	Additional information on socio-economic consequences available in Japan Times	Additional information on Meteorological and Hydrological context available in Japan Times
1	1901 Jul.	–	576	–	Crop decreased by 30%.	–
2	1923 Jul. 16	600	–	3	–	–
3	1938 Jun. 14	–	–	–	–	–
4	1941 Jun.	–	–	–	–	–
5	1948 Aug.29	182	134.4	–	–	–
6	1949 Aug.19	–	–	–	–	–
7	1952 Jun. 24	–	–	–	–	–
8	1953 Jun. 28	963	861.6	3	Saga plain turned 'into a sea of mud'. 160,000 people homeless in all Saga Plain, damage to crops estimated at 6.5e+09 JPY. Rivers overflowed their banks and washed away homes, farms and fields. Complete five-day train disruption at Saga and Tosu cities. Authorities said disaster was unprecedented.	Precipitation had reached 41 mm in Saga.
9	1955 Jul. 8	167	–	–	–	Precipitation of 147 mm in Saga.
10	1962 Jul. 9	–	–	71	Ground Self-Defense Force units were mobilized.	Precipitation of 593 mm in Saga.
11	1963 May 11	–	–	–	400 people (85 families) fled their homes and 11,700 people were alerted for possible evacuation in Saga Prefecture.	–
12	1968 Jul. 3	189	–	–	–	–
13	1972 Aug. 9	44	–	–	–	Water level of Ariake Sea near Saga city rose 370 mm above normal.
14	1973 Sept. 4	135	–	–	–	–
15	1975 Sept. 8	–	–	–	–	Heavy rain and abnormal high tide resulted in flooding.
16	1976 Aug. 5	–	–	–	–	Typhoon n°13, 100–200 mm rainfall in Saga plain.
17	1977 Jun. 11	29	–	–	–	Rainfall measured at 81 mm in Saga.
18	1983 Jul. 18	9	–	–	–	Heavy rain.
19	1990 Jul. 2	5500	8000	–	–	Rainfall of 72 mm in Saga city. Rainfall (in 12hr) resulted in 288 mm in Saga.
20	2009 Jul. 21	–	–	–	–	–

now publicly available for consultation [44]. Fig. 2 reports the hazard map created by MLIT considering the worst-case scenario of inundation caused by the Rokkaku river water system. The rainfall scenario considered is of 424 mm in 6-h period [44]. As can be seen, the southern part of the municipality is exposed to relevant flood hazard, and water height might reach up to 5 m [44]. The worst-case scenario approach is included in flood control evaluations since 2015, and the maximum rainfall scenario to be considered in simulations depends on the region in Japan considered and on the extent of the catching area of the river system [45]. It should be noted that the return period for this scenario is not provided, although in case the estimate results in a significantly lower rainfall severity compared to a 0.1% exceedance probability scenario, the severity of the latter is suggested to be assumed. Therefore, the flood hazard map reported in Fig. 2 can be conservatively associated to a return period of 1000 y [45].

4.2. The flooding event of August 2019

From August 27th 2019, a rain front caused strong rainfall over a wide area of the Japanese island of Kyushu. In the morning of August 28th, a special rain warning was issued by the Japan Meteorological Agency (JMA) for Saga, Fukuoka and Nagasaki prefectures [46]. The warning required immediate evacuation to designed sites in case it was possible, while in case that this was not possible, citizens were instructed to move to highest floors of the closest solidly built buildings, away from cliffs and rivers, and in case neither option was feasible, they were required to promptly perform vertical evacuation for imminent catastrophe reaching highest floors of their houses [46]. Consequently, an emergency evacuation order was issued by the Fire Disaster Management Agency (FDMA) to more than 850,000 people in the three prefectures [7,8].

In Saga prefecture, observed rainfall levels exceeded the levels registered during the major flood of 1990 [43] and caused a critical water inflow to Rokkaku river water system. Indeed, the peak level of Rokkaku river reached 4.12 m on August 28th, surpassing the level of 3.1 m height indicating potential imminent flooding [43]. The Ushizu river, belonging to the same water system, surpassed 7.02 m in the same day, while the established flood danger level is 4.4 m [43]. The latter river in particular experienced an unprecedented peak level even higher than the one reached in 1990 of 6.04 m [43]. The unprecedented downpour thus leaded to the collapse of the Rokkaku river water system causing breaches from nine different locations and large-scale flooding involving more than 6900 ha (6.9e+07 m^2) of land and 2936 house units [43]. The main transportation infrastructures were disrupted, landslides were triggered in many locations, many road connections were submerged, and train connections with the region were partially suspended due to flooding of main stations [7,47].

4.3. Description of the oil spill

The factory involved in the oil spill accident is an ironworks plant specialized in production of high-strength bolts for automotive and agricultural applications [48]. The manufacturing site is located less than 100 m far from the Rokkaku river embankment. The site has been running since 1969 and occupies a surface of about 9.9e+04 m^2, while buildings occupy about 4.1e+04 m^2 [49]. The factory operates in continuous mode (i.e., 24 h per day). Some of the key steps for obtaining high performance bolts involve the use of heat treatments for hardening the surface in the final stages of the manufacturing process [50,51]. According to the available information, the plant performs a quenching operation in an oil bath kept in atmospheric storage tanks located 3 m below ground level for safety matters, before the tempering treatment

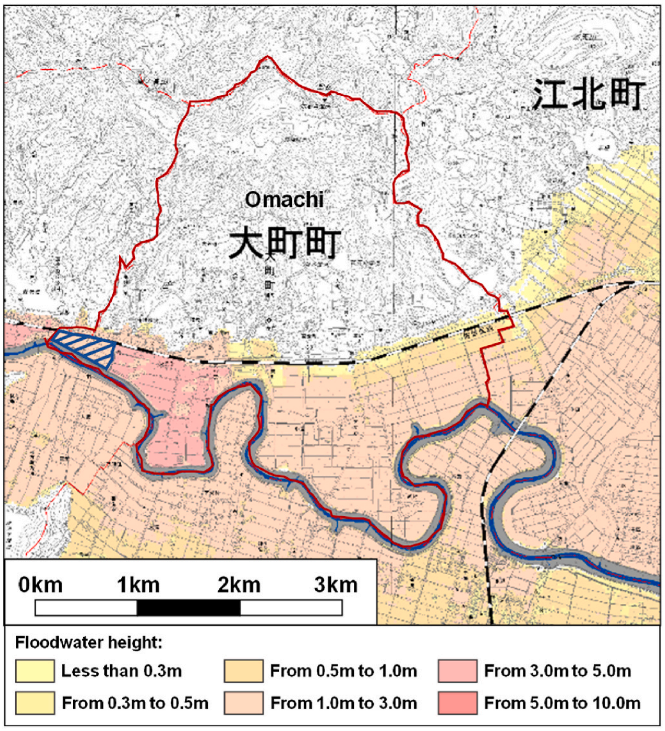

Fig. 2. Flood hazard map for Omachi town area. The blue-dashed area indicates the position of the ironworks factory. Floodwater height is estimated considering the worst-case rainfall scenario of 424 mm (6-h period) [44].

[52]. Quenching is one of the typical processes performed in metalworks to obtain specific mechanical characteristics and consists of the rapid cooling of heated pieces through large volumes of oil, water, or air [50,53,54]. One of the typical equipment design solutions for heat treatment of small parts as bolts is a furnace which is directly connected to quench tanks located below the conveyor level that the parts reach directly through a chute [55,56].

According to a report in the Saga Shimbun, inside the thermal treatment building of the plant there were eight oil tanks with an overall capacity of more than 100,000 l of oil. Because the bolt production is carried out in a continuous regime, the quench tanks are not equipped with lids, making it difficult to seal them [52].

The plant was flooded around 04:00 a.m. on August 28th [57]. The protection measures in place for flood prevention were not effective. At the time of the accident, seven night shift workers were in the plant, and managed to stop operations around 04:30 a.m. [52,57]. A drainage pump was in place as a preventive measure, and there is contradictory information on whether the tanks were sandbagged or not [48,57,58]. Floodwaters reached up to 60 cm in depth inside the plant, flowing into the tanks and lifting the stored oil, as shown in Fig. 3 [52]. Other sources report water inside the building reached 0.4 m, while outside it was about 0.7 m [48]. According to the Saga Shimbun [52] at 5:00 a.m. the oil spill was confirmed by the workers that had to evacuate at 5:30 a.m. due to the danger brought by the severe flooding and the oil spill. Around 6:30 a.m. the oil outflowed from the premises of the factory [48].

The quantity of released oil was not clear at the beginning, and during a preliminary field survey conducted by the authorities on September 3rd estimated that about 110,100 l of quenching oil and about 3000 l of metal working oil were released inside the factory due to the floodwaters [59]. In a later estimation, the company declared that out of 103,000 l which were stored in the quench tanks the day before the accident, 49,000 l were released but kept into the premises of the factory, while the remaining 54,000 l spilled outside the plant [60].

Fig. 4 shows the approximate path of the released oil according to the available information provided by MLIT documentation [43]. As can be seen, the oil sheen moved from the ironworks factory (in blue in Fig. 4) in south-east direction, spreading to residential areas and over flooded agricultural fields, damaging dwellings and finally reaching the hospital (in red in Fig. 4) that was isolated due to the flood.

No patients or staff were injured, but they were stranded in the building due to oil-tainted floodwaters [9]. An aerial view of the path of the oil sheen impacting the hospital is shown in Fig. 5.

During the first field trip, even if it was carried out about a month after the disaster (late September 2019) the smell of oil was still strong in all the area, and there was evidence of the presence of residual oil in the crop fields and in the damaged dwellings. For instance, it was possible to notice that the bricks of the outside pavement near the entrance of the hospital had been substituted and the old ones, piled in flexible bulk containers, were tainted of oil (see Fig. 6-a), while clear oil traces were identified also on dwelling internal walls (see Fig. 6-b) and in inland irrigation channels (see Fig. 6-c).

It should be noted that the same ironworks factory was involved in an analogous oil spill during floods in 1990 [61]. After that accident, the heat treatment building was retrofitted with a series of measures. Heavy shutters had been installed and the floor level of the building where the heat treatment is performed was raised by tens of centimetres to reduce the risk of water entering the oil tanks in case of future severe flooding [52]. According to the available information, the oil spill prevention measures were implemented considering the features of the flood of 1990 [52], and the August 2019 flooding was a far more severe event, whose intensity was not foreseen by company managers and made all these measures ineffective.

4.4. Hazardous properties of ironworks oil

The oil employed in thermal treatment processes needs to satisfy a number of critical properties required by technical application at high temperature. Indeed, quench oil formulations need to have acceptably high flash point and low volatility, so as not to catch fire during operation, need to be stable to avoid sludge formation and must have appropriate thermophysical properties to guarantee an efficient heat removal [50]. The oil employed in the facility is produced by a major Japanese oil company [60]. Considering the atmospheric quenching process employed to achieve high performance parts, and consulting Safety Datasheets (SDS) of main products from major sellers for this kind of treatments [62], these substances are likely classified as “Category 1” chemicals for aspiration toxicity, and according to Globally Harmonized System (GHS) terminology for hazardous properties classification [63]. This means the oil potentially poses an immediate threat to the population residing in the impacted area.

Beside the acute effects to human health related to this class of substances, some high-performance oils employed for thermal treatment and metal working are mixed with small percentages of additives to enhance their thermal stability and reduce sludge formation [51]. Some of these additives are also classified as hazardous substances. For instance, this oil category may contain cresols in low percentage, according to the SDS of commercial products for atmospheric quenching process [64]. These chemicals are associated with H410 hazard statement (according to GHS international standard), meaning these compounds are “Very toxic to aquatic life with long-lasting effects” [63]. Other commercial solutions for metal working may contain additives considered neurotoxic and potentially toxic for reproduction [65]. Typical hazardous properties of commercial oils and additives employed in ironworks processes are reported in Table 2. Given the hazardous properties of oil employed in manufacturing processes, it is clear that the impact on communities and environment may be long lasting.

4.5. Emergency response

Several emergency warnings and evacuation advisories were issued

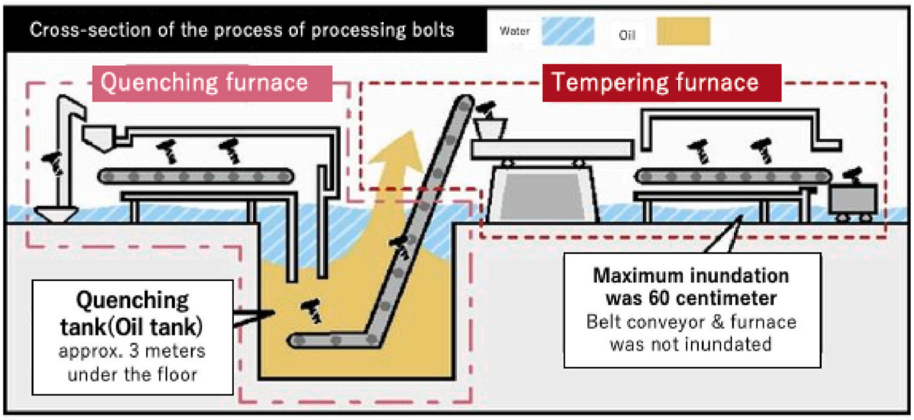

Fig. 3. Simplified scheme explaining the dynamics of oil spill caused by flood. Adapted from Ref. [52].

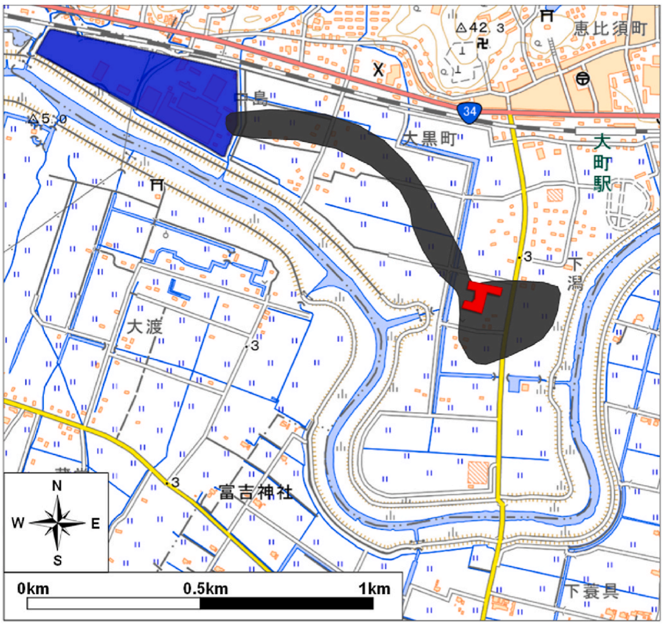

Fig. 4. Approximate path of the released oil. The blue area indicates the ironworks factory, while the hospital impacted is indicated in red. Map adapted from Geospatial Information Authority of Japan website (gsi.go.jp). Oil path realized according to MLIT documentation [43].

from August 27th. These included a call for voluntary evacuation of vulnerable citizens, an evacuation recommendation and an advisory to make residents evacuate to emergency shelters, and if not possible, to move from their homes, to reach the highest floors of the dwellings or the nearest solidly built buildings. According to the interviews conducted during the second field trip in February 2020, first responders from the fire department helped the local government to coordinate evacuation. Following the oil spill, the local fire department initiated the operations to collect the oil exiting from the site using absorbent pads [66,67]. However, since the major task of first responders was to rescue evacuees from the floods, the Self-Defence Forces (SDF) were asked to conduct the main responses to the Natech accident.

As earlier mentioned, a previous oil spill caused by heavy rain and floods had already occurred at the same company in 1990 [61]. According to the interviews conducted during the second field trip, following the previous events, the local government and local fire department in Omachi town had assessed the risk of an oil spill during heavy rain and the related flooding based on the assumption that the drainage pump would work properly ensuring the timely discharge of rain water and thus mitigating any flood hazard. As it turned out during the disaster of 2019, the operational delays in activating the drainage pump and the high-tide level led to the failure of the emergency management strategy in Omachi town. Several residents living within tens of meters from the ironworks plant declared they evacuated to the upper floor of their homes, as they had done in response to previous evacuation advisories, expecting the new water pumps would have been capable of quickly draining the rainwater out of the area and saving the dwellings. Unfortunately, the excessive rainwater, combined with the high-tide, resulted in the flooding of the ironworks plant and the subsequent release of oil, which in turn complicated emergency management actions. The presence of oil delayed emergency response actions, since vertical evacuation, practiced by many residents during the disaster, actually put many of them in more danger as they ended up trapped in

Fig. 5. Aerial view of the area impacted by the oil spill. Adapted from: https://usagi-syufulife.com/2019/08/31/2285.

Fig. 6. Traces of oil identified during the first field trip in Omachi about one month after the oil spill (late September 2019). a) Old bricks tainted of oil removed from the entrance area of the hospital; b) view of the interior walls of a damaged dwelling which absorbed the oil floating over floodwaters; c) oil sheen in an irrigation canal located between the rice fields.

Table 2
Some typical hazardous properties of commercial quenching oil solutions and additives.

GHS Pictogram	H-statement	Description
	H304	May be fatal if swallowed and enters airways.
	H361	Suspected of damage fertility or unborn child.
	H373	May cause damage to organs through prolonged or repeated exposure.
	H400	Very toxic to aquatic life.
	H410	Very toxic to aquatic life with long lasting effects.

oil-covered floodwaters.

The results of the field trips and interviews showed that indeed, the local fire department and local government were both overwhelmed by the disaster, needing assistance from the prefectural government and first responders, who were also not prepared for this type of compound accident despite having previous experiences with oil spills. During the interviews, an officer from the Saga prefecture fire department explained that they had to oversee the response to flood victims in the whole region, not only in Omachi town, with limited human and economic resources. Furthermore, during the interviews they noted that the government policy of rotating staff and personnel every 3–5 years meant that the “memory” of the previous events was lost, despite the fact that records and reports of the past events have been kept. Officers from the Saga prefecture fire department explained that they had updated their disaster risk management plans and strategies considering environmental changes and various disaster scenarios. However, chemical accident risks that could be caused by natural hazards had not been given sufficient consideration, in part also because the responsibility of chemical accident risk management lies with the local government.

4.6. Clean up and post-disaster actions

The water depth in the area where the oil spilled peaked at 3 m in the aftermath of the accident [68]. In order to limit oil spreading and prevent it from reaching the Rokkaku river, five oil booms were set up from the morning of August 28th and personnel from SDF and town officials were dispatched in the area to collect the oil [66]. Oil booms are physical floating barriers employed in case of oil spill on water limit the spreading area, with the aim of protecting specific targets, thickening the oil layer to ease cleaning activities and divert the oil to preferential collection points [69–71].

Draining activities started on August 28th afternoon and the overall flooded area of 6900 ha (6.9e+07 m^2) was reduced to 150 ha (1.5e+06 m^2) by noon of August 29th, dispatching 45 drain pump trucks in total [68]. The oil cleaning activities started on August 29th using oil absorption mats [66,67]. However, the area impacted by the spill could not be drained until the necessary measures to prevent the oil from reaching the Ariake Sea were in place. On August 30th morning an area of about 70 ha (7.0e+05 m^2) was still flooded [68]. Later in the afternoon, the water level was reduced employing up to 16 water drain pump trucks and activating drainage gutters once oil barriers were successfully implemented around them [68]. As a result of the water level reduction, the roads leading to the hospital were cleared and the structure was no longer isolated [68].

It should be noted that the area impacted by the oil was significant and required the mobilization of up to 370 people from SDF per day in addition to volunteers and factory personnel [72]. The cleaning activities were declared officially concluded on September 10th, two weeks after the spill, with the participation of more than 640 people in total on that day [72].

Staff at a volunteer centre run by Open Japan, one of the NGOs that helped to clean-up after floods and to remove oil from houses, explained that they had to wait several days until the water level receded but also due to the strong oil vapours. Moreover, during the interview it was remarked that the clean-up procedures of the houses contaminated with the oil were extremely difficult. Indeed, volunteers suffered from skin irritation and respiratory distress caused by the oil and, unlike ordinary cleaning activities to be performed after flood damage, in this case the substance penetrated deeply inside the columns and the interior walls of the dwellings (see Fig. 6-b) and even after thorough cleaning some oil traces remained along with a perceptible oil smell. Despite the evidence of the severe damages to houses caused by the oil, the volunteer centre staff pointed out that due to the fact that many residents or family members living in the contaminated area were employed at the factory, they did not complain or claim compensation from the factory for the damages and losses.

In the months after the event, the company took additional measures to reduce the possibility events of this magnitude can happen. Indeed, an oil fence approximately 0.9 m high have been installed inside the heat treatment plant, surrounding the oil tanks. Moreover, permanent oil booms with a total length of about 600 m have been installed along the east and south sides of plant premises [48], as indicated in Fig. 7 (red dashed lines).

4.7. Damage assessment

This section is aimed at providing a preliminary evaluation of the damages brought by the oil spill. The information used to perform this damage evaluation has been collected in the first months following the accident, and included data on residential damages and on land damages.

The government of Saga prefecture released official documentation on the residential damages experience by the population as consequence of the rainfall event of late August 2019. Damage to buildings are classified according to a qualitative severity scale spanning from the flooding of the basement only (least severe scenario), to the complete destruction of the dwelling (worst case) [73]. Data retrieved from Saga prefecture official website and updated at the last available date (March

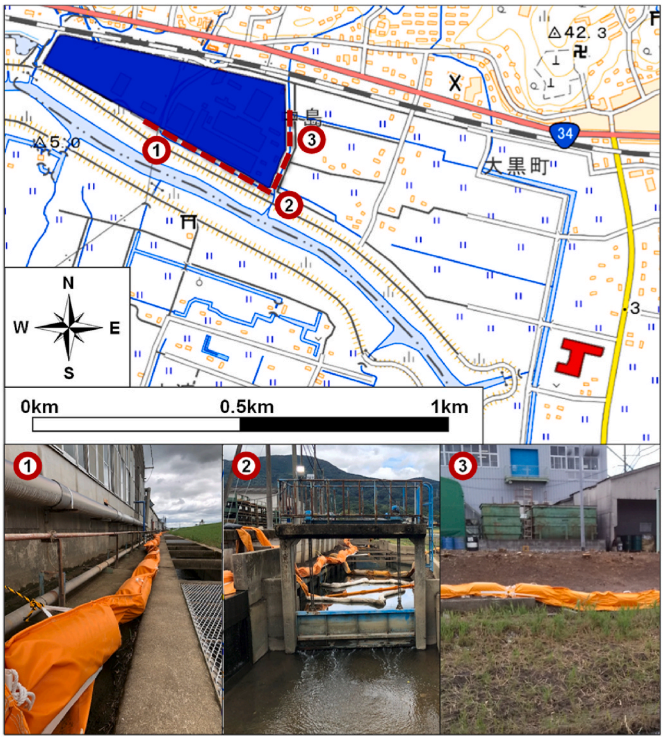

Fig. 7. Permanent oil booms implemented in the east and south sides of ironworks plant premises (in blue), in the closest areas to Rokkaku river embankment (indicated as red dashed lines). Map adapted from Geospatial Information Authority of Japan website (gsi.go.jp). The pictures of the oil booms were taken during the September 2019 field trip.

11th' 2020) are reported in Table 3.

As can be noted, considering the three most severe damage categories, the majority of reported damages have been experienced in Takeo city and Omachi town. In particular, it should be noted that 90% of the total cases of complete destruction (i.e., 79 out of 87) and about 67% of the cases of large-scale destruction (i.e., 71 out of 107) were experienced in Omachi, while about 94% of half-destruction cases involved Takeo (i.e., 712 out of 759).

Nevertheless, the municipalities listed in Table 3 feature different sizes, thus to give an estimate of the relative impact of the event on the residential buildings of each area the size of each of them should be considered. Therefore, the number of households per municipality has been retrieved from multiple sources [74–76]. For the majority of the locations it is has been possible to find data in terms of number of households updated to 2018 [74]. For the two smallest towns (i.e., Omachi-cho and Kouhoku-cho) in Saga prefecture, data from Japan statistics bureau were not available, and the number of households was retrieved from information available in municipality websites [75,76]. The reference number of households considered for each municipality are reported in Table 4.

Results in terms of percentage of households experiencing damages, assuming each household corresponds to a single dwelling are reported in Fig. 8. As can be noted, the highest percentages for the two most severe damage categories (i.e., complete and large-scale destruction) are experienced in Omachi town, where the oil spill happened. This can be possibly attributed to the additional contribution of the Natech event to the already severe impact of floodwaters on dwellings. It should be noted that this information substantially confirms what the NGO local manager declared during the interview, that is, that the oil caused long-lasting damages to houses in addition to the impact of floodwater.

For what concerns land damages instead, Saga prefecture released data on the extent of agricultural land damaged by the flooding event, with a specific focus on the portion of land impacted by the oil spilt from Omachi ironworks factory [77]. An area of 41.8 ha (4.18e+05 m^2) is assessed to be impacted by the oil. The impacted area was mainly dedicated to rice and soy farming.

As a preliminary evaluation of the cost directly connected to agricultural soil remediation activity, an analogous case involving an oil spill happened in Ryuo-cho (Shiga prefecture) in 2018 is considered, as shown in Table 5 [78]. In that case, Japanese authorities implemented two different strategies following a threshold-based approach on the measured oil concentration. On the one side, if the oil concentration for an area is below a previously defined value of 100 mg/kg, the strategy which is followed is lime spreading in the soil without any additional measure. On the other side, that is, if the threshold value is surpassed, the first layer of soil is replaced. In the case of Ryuo-cho, a layer 15 cm thick was removed. The cost per unit area of the two remediation strategies can be estimated directly from the information available in the governmental report on this past accident (see Table 5) [78].

Considering the impacted area, the soil remediation cost may range between 1.2e+06 JPY and 7.82e+08 JPY, depending on to the strategy followed based on the results of the soil sampling. The Omachi area has been sampled by the authorities. The definition of the proper soil remediation strategy and the assessment of its cost are strongly dependent on the oil concentration which is found in the ground samples. As a result of the soil analysis, the main strategy implemented was the lime spraying for the majority of surveyed sites, since the oil concentration in soil samples was deemed generally low except in a limited number of spots where soil replacement was evaluated [79]. Thus, the soil remediation cost is expected to be close to the lower limit reported above.

5. Discussion and limitations

5.1. Main findings

The case study presented throughout the paper offers a series of

Table 3
Residential damages from the rainfall event organized in six categories. From left to right damage decreases in severity (i.e. complete destruction is the most severe). Data updated to March 11th 2020. Adapted from Ref. [73].

Area	Complete destruction	Large-scale destruction	Half-destruction	Partial damage (and flooded floor)	Flooded floor	Flooded foundations (underfloor)	Total
Saga-shi (佐賀市)	3	–	2	4	407	2492	2908
Karatsu-shi (唐津市)	–	1	3	2	–	23	29
Tosu-shi (鳥栖市)	–	–	–	–	1		1
Taku-shi (多久市)	–	1	29	1	41	128	200
Imari-shi (伊万里市)	–	–	–	–	2	24	26
Takeo-shi (武雄市)	2	34	712	14	202	332	1296
Ogi-shi (小城市)	2	–	8	3	70	560	643
Ureshino-shi (嬉野市)	–	–	–	–	2	9	11
Kanzaki-shi (神埼市)	–	–	–	–	–	1	1
Arita-cho (有田町)	–	–	–	–	1	–	1
Omachi-cho (大町町)	**79**	**71**	**4**	–	**18**	**131**	**303**
Kouhoku-cho (江北町)	–	–	1	–	9	167	177
Shiroishi-cho (白石町)	1	–	–	–	20	443	464
Overall	87	107	759	24	773	4310	6060

Table 4
Reference number of households per town/city in Saga prefecture.

Area	Households
Saga-shi (佐賀市)	92,880
Karatsu-shi (唐津市)	42,730
Tosu-shi (鳥栖市)	28,760
Taku-shi (多久市)	6690
Imari-shi (伊万里市)	19,850
Takeo-shi (武雄市)	17,170
Ogi-shi (小城市)	15,170
Ureshino-shi (嬉野市)	8440
Kanzaki-shi (神埼市)	11,050
Arita-cho (有田町)	6950
Omachi-cho (大町町)	**2560**
Kouhoku-cho (江北町)	3460
Shiroishi-cho (白石町)	6750

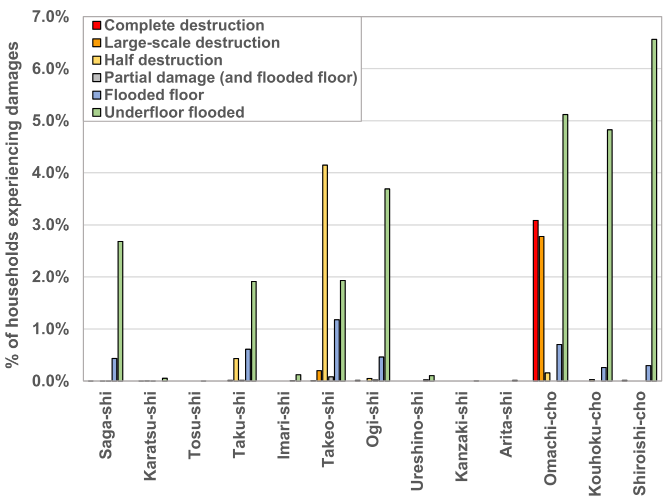

Fig. 8. Percentage of households per city/town experiencing residential damages as consequence of the rainfall event considering the six severity categories reported by Japanese authorities [73].

important lessons on Natech events caused by flood. First of all, it should be noted that the process employed by the facility to perform the thermal treatment is inherently unsafe when applied in areas prone to flood hazard. It is clear that the presence of significant quantities of hazardous substance accessible from ground level is a poor design solution considering the possibility of water entering the tanks. Moreover, since the oil is lighter than floodwater, it may be easily lifted also in case limited quantities of liquid entering the storages. The company declared that the water level reached during the flooding of August 2019 was unexpected, thus they were not properly prepared to deal with this event [48]. Given the possibility that climate change will further exacerbate extreme weather events of this case in Japan [13,14,17], it can be said that the community living in the area might be exposed to growing risks in the foreseeable future. Therefore, the company should evaluate either the implementation of different technology for thermal treatment, or the relocation of the plant in an area where the flood hazard is lower. In general, international organizations are increasingly recognizing the possibility that climate change will lead to an increase in Natech risk, thus requiring the development of proper adaptation strategies to foster industry and community preparedness [80]. With the same objective, the company should consider the implementation of strategies for effective barrier management, assessing whether the implemented safety measures for accident prevention and mitigation are capable of withstanding extreme flood events that may impact the site, retaining their intended functions [81]. Particular care should be taken concerning the evaluation of the expected performance level of safety measures since these might be susceptible to concurrent degradation during floods. Indeed, as recent research performed in the context of industries handling hazardous substances highlighted [82], even engineered and complex systems for accident prevention and mitigation might substantially lose their capabilities during flooding events, possibly leading to an increase in Natech risk [83].

It should also be noted that research on the possibility of Natech accidents involving metal processing industry is lacking. Indeed, this industrial sector was included in one research paper focused on the development of qualitative damage scales due to flooding only [84]. It is worth noting that this category of industries in Japan have been involved in other Natech accidents in 2018 [2,4,78], in addition to the

Table 5
Soil remediation strategies adopted in Ryuo-cho oil spill (2018). Data from Ref. [78].

Remediation strategy	Implementation area [m^2]	Implementation cost [10^6 JPY]	Cost per unit area [(10^6JPY)/m^2]
Lime spreading	4.18e+05	1.20	2.87e-06
Soil replacement	1.0e+03	1.87	1.87e-03

case described in this work. This clearly points out that research effort should be devoted to the development of specific strategies for reducing the risk of Natech accidents involving metal processing industry.

Another key point shown by this accident, is that emergency procedures developed to deal with natural disasters can be substantially affected by the presence of a concurrent technological scenario that might make authorities not prepared to deal with the events. For instance, in this case the oil spill scenario should be considered at municipality level when evaluating both emergency planning operations and damage assessment. Indeed, the area impacted by the substance sheen was the last one to be drained, possibly enhancing the severity of the damages brought by floodwaters (e.g., dwelling foundations submerged for long time) and complicating disaster management operations. The presence of oil required also the implementation of specific measures such as oil booms and absorption mats, that may not be required in case of flooding scenarios not triggering hazardous substance release. Moreover, it is clear the land use planning of the area did not consider the possibility of oil release. As an example, the hospital was located in an area exposed to severe flood hazard (see Fig. 2), and possibly for this reason the elevation of the soil where the structure lays is higher than the surrounding farmland. During the first field inspection on the area, from the flood signs left on the external walls of the building it was clear that the water level reached about 0.3 m in the entrance. Nevertheless, the presence of the oil lead to isolation of the structure, scenario that was apparently not considered. Therefore, the municipality should evaluate relocation of the hospital, since it is a critical infrastructure and there is the possibility that compound disasters like this hamper severely its functionality.

Another point shown by this Natech event is the importance of finding ways to keep disaster history alive for future generations [85]. Indeed, making thorough information on past disasters available might be pivotal in fostering community preparedness and resilience also in cases, as the August 2019 oil spill, when the intensity of the events is beyond the capabilities of available measures. Considering the results from the interview with the firefighters, it is possible that the lost memory of the 1990 oil spill contributed to weaken their ability to deal with the series of events of 2019. As already pointed out, this might be particularly relevant for the case of hydrometeorological events that may be exacerbated by climate change.

5.2. Limitations and future research

Whereas this study provided valuable information on the oil spill triggered by the 2019 flooding of Saga prefecture, it is affected by several limitations. Indeed, data collected during the field trips were mostly qualitative and the availability of information retrieved from open literature was rather limited. For instance, it was not possible to benefit from detailed information on the flooding event that occurred in 1990 in terms of damages experienced, emergency response actions put in place, clean-up activities. This would have enabled a comparative evaluation between the strategies implemented during the 1990 oil spill, the risk-reduction measures developed following that disaster and their actual performance during the flooding of 2019. Still related to this point, formal documentation on the design assumptions considered by the company in defining the protection measures could not be found, and it was not possible to understand the actual skew between the design intent of these measures and their actual implementation. Future works might be dedicated to attempting to retrieve further information on these aspects.

An additional limitation of the study is related to the methodology adopted to perform a preliminary damage estimation. Indeed, only the damage to dwellings and the expected cost related to soil remediation strategies were considered. Other factors which could not be included in this analysis should be considered in attempting a more precise evaluation of the damages, as for instance the quantity of contaminated agricultural products which could not be commercialized, or the possible environmental impact of the oil on the aquifer or the irrigation system of the area. These elements might also help in understanding the long term effect of the event on the community involved.

Related to this latter point, in future research it might be worth trying to assess how the role of institutions and on the responsibilities of the ironworks company following the spill were perceived by the community, and how this influenced the perception of risk. Indeed, despite the several flooding events that affected the region in the past, neither the institutions nor the company were prepared to deal with the possibility of an oil spill. This lack of preparedness might have been perceived by the community as a form of recreancy, that is, a failure of institutions and organizations to accomplish their responsibilities and merit the trust they enjoy [86,87]. This aspect might deserve further attention, since analysing previous technological accidents (e.g., 1989 Exxon Valdez and 2010 BP Deepwater Horizon oil spills) it was demonstrated that the perception of recreancy has a clear role in producing psychological feedbacks as anger, distrust, or frustration, as well on enhancing the awareness of risk [88–90].

6. Conclusions

In this work, a technological accident triggered by a natural (Natech) event is presented. Data obtained from two field trips and from open literature sources were integrated, obtaining relevant information on accident dynamics, emergency management and post-disaster actions. Information collected enabled a preliminary damage evaluation as well as the definition of a series of lessons learnt which can be useful for Natech risk management. The accident involved the release of great quantity of metal working oil as consequence of massive flooding brought by severe downpour that hit southwest Japan in late August 2019. The oil spill slowed down emergency intervention and site cleaning activities, posing an additional burden on emergency teams. The factory involved in the oil spill, had already experienced an analogous event in 1990, and the barriers designed after that event were reportedly not suitable to deal with the extreme rainfall the lead to the latest accident. The projections of climate change impact on Japan pose additional concern on how extreme weather events may increase in severity and frequency in the future, enhancing the risk the communities living in the vicinity of ironworks plants and of facilities handling hazardous materials in general are exposed. The present work is not intended to be conclusive, since due to data scarcity the information presented is mostly qualitative and the attempt of damage assessment is based only on a restricted set of parameters. Nevertheless, the case study presented should help to raise awareness on the severity of possible Natech accidents involving industrial sectors, such as metal working industries, that are usually overlooked in scientific literature on the topic.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors wish to inform that the present work has been partly funded by the Natural Disaster Research Council, Japan; the Japan Society for the Promotion of Science [Kaken Grant 17K01336, April 2017–March 2021]; and the MIUR - Italian Ministry for Scientific Research under the PRIN 2017 program [Grant 2017CEYPS8].

References

[1] E. Krausmann, A.M. Cruz, E. Salzano, Natech Risk Assessment and Management: Reducing the Risk of Natural-Hazard Impact on Hazardous Installations, Elsevier Inc., Amsterdam, The Netherlands, 2017.

[2] M. Kumasaki, M. King, Three cases in Japan occurred by natural hazards and lessons for Natech disaster management, Int. J. Disaster Risk Reduct 51 (2020) 101855, https://doi.org/10.1016/j.ijdrr.2020.101855.

[3] U.S., Chemical Safety and Hazard Investigation Board, Organic Peroxide Decomposition, Release, and Fire at Arkema Crosby Following Hurricane Harvey Flooding, 2018. Crosby, TX, www.csb.gov.

[4] Y. Araki, A. Hokugo, A.T.K. Pinheiro, N. Ohtsu, A.M. Cruz, Explosion at an aluminum factory caused by the July 2018 Japan floods: investigation of damages and evacuation activities, J. Loss Prev. Process. Ind. (2020) 104352, https://doi.org/10.1016/j.jlp.2020.104352.

[5] H. Sengul, N. Santella, L.J. Steinberg, A.M. Cruz, Analysis of hazardous material releases due to natural hazards in the United States, Disasters 36 (4) (2012) 723–743, https://doi.org/10.1111/j.1467-7717.2012.01272.x.

[6] French Ministry of Ecology Sustainable Development, The "NaTech" Risk, or Technological Accidents Triggered by a Natural Event, 2013. http://www.aria.developpement-durable.gouv.fr/wp-content/uploads/2013/08/FT_impel2013_NaTech_risks.pdf.

[7] Mainichi, Heavy Rains in Northern Kyushu - Special Warning for Heavy Rains - Evacuation Orders for 850000 People, 2019. https://mainichi.jp/articles/20190828/k00/00m/040/104000c. (Accessed 28 January 2020).

[8] Floodlist, Japan - Two People Dead, Thousands Evacuated after Floods and Record Rainfall, 2019. http://floodlist.com/asia/japan-floods-saga-nagasaki-fukuoka-record-rainfall-august-2019. (Accessed 28 January 2020).

[9] NHK news, Floods and Landslides in Western Japan, 2019. https://www3.nhk.or.jp/nhkworld/en/news/20190829_04/. (Accessed 20 November 2019).

[10] Noaa, U.S. Billion-Dollar Weather and Climate Disasters, 2018.

[11] Munich Re Group, NatCatSERVICE Relevant Natural Loss Events Worldwide 1980 – 2018, 2018. https://natcatservice.munichre.com/. (Accessed 1 March 2019).

[12] World Economic Forum, The Global Risks Report, Cologny, Switzerland, 2020. http://wef.ch/risks2019.

[13] IPCC, Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in: The Context of Strengthening the Global Response to the Threat of Climate Change, Geneva, Switzerland, 2018.

[14] S. Nayak, K. Dairaku, I. Takayabu, A. Suzuki-Parker, N.N. Ishizaki, Extreme precipitation linked to temperature over Japan: current evaluation and projected changes with multi-model ensemble downscaling, Clim. Dynam. 51 (2018) 4385–4401, https://doi.org/10.1007/s00382-017-3866-8.

[15] H.S. Saffir, Hurricane wind and storm surge, Mil. Eng. 423 (1973) 4–5, https://doi.org/10.2307/44566124.

[16] T. Schott, C.W. Landsea, G. Hafele, J. Lorens, A. Taylor, H. Thurm, B. Ward, M. Willis, W. Zaleski, The saffir-simpson hurricane wind scale, NOAA Tech. Rep. (2012). https://www.nhc.noaa.gov/pdf/sshws_table.pdf. (Accessed 19 December 2018).

[17] K. Yoshida, M. Sugi, H. Murakami, M. Ishii, Future changes in tropical cyclone activity in high-resolution large-ensemble simulations, Geophys. Res. Lett. 44 (2017) 9910–9917.

[18] M.C. Suarez-Paba, M. Perreur, F. Munoz, A.M. Cruz, Systematic literature review and qualitative meta-analysis of Natech research in the past four decades, Saf. Sci. 116 (2019) 58–77, https://doi.org/10.1016/j.ssci.2019.02.033.

[19] S. Girgin, A. Necci, E. Krausmann, Dealing with cascading multi-hazard risks in national risk assessment: the case of Natech accidents, Int. J. Disaster Risk Reduct. 35 (2019), https://doi.org/10.1016/j.ijdrr.2019.101072.

[20] E. Krausmann, S. Girgin, A. Necci, Natural hazard impacts on industry and critical infrastructure: natech risk drivers and risk management performance indicators, Int. J. Disaster Risk Reduct. (2019) 101163, https://doi.org/10.1016/j.ijdrr.2019.101163.

[21] P.S. Showalter, M.F. Myers, Natural disasters in the United States as release agents of oil, chemicals, or radiological materials between 1980-1989: analysis and recommendations, Risk Anal. 14 (1994) 169–182, https://doi.org/10.1111/j.1539-6924.1994.tb00042.x.

[22] M.K. Lindell, R.W. Perry, Hazardous materials releases in the Northridge earthquake: implications for seismic risk assessment, Risk Anal. 17 (1997) 147–156, https://doi.org/10.1111/j.1539-6924.1997.tb00854.x.

[23] M.K. Lindell, R.W. Perry, Identifying and managing conjoint threats: earthquake-induced hazardous materials releases in the US, J. Hazard Mater. 50 (1996) 31–46, https://doi.org/10.1016/0304-3894(96)01764-5.

[24] K. Rasmussen, Natural events and accidents with hazardous materials, J. Hazard Mater. 40 (1995) 43–54, https://doi.org/10.1016/0304-3894(94)00079-V.

[25] E. Krausmann, E. Renni, M. Campedel, V. Cozzani, Industrial accidents triggered by earthquakes, floods and lightning: lessons learned from a database analysis, Nat. Hazards 59 (2011) 285–300, https://doi.org/10.1007/s11069-011-9754-3.

[26] A.M. Cruz, L.J. Steinberg, A.L. Vetere-Arellano, Emerging issues for natech disaster risk management in Europe, J. Risk Res. 9 (2006) 483–501, https://doi.org/10.1080/13669870600717657.

[27] A.M. Cruz, E. Krausmann, Vulnerability of the Oil and Gas Sector to Climate Change and Extreme Weather Events, 2013, pp. 41–53, https://doi.org/10.1007/s10584-013-0891-4.

[28] X. Luo, A.M. Cruz, D. Tzioutzios, Extracting natech reports from large databases: development of a semi-intelligent natech identification framework, Int. J. Disaster Risk Sci. (2020), https://doi.org/10.1007/s13753-020-00314-6.

[29] A.M. Cruz, E. Krausmann, Damage to offshore oil and gas facilities following hurricanes Katrina and Rita: an overview, J. Loss Prev. Process. Ind. 21 (2008) 620–626, https://doi.org/10.1016/j.jlp.2008.04.008.

[30] A.M. Cruz, E. Krausmann, Hazardous-materials releases from offshore oil and gas facilities and emergency response following Hurricanes Katrina and Rita, J. Loss Prev. Process. Ind. 22 (2009) 59–65, https://doi.org/10.1016/j.jlp.2008.08.007.

[31] P.Z. Ruckart, M.F. Orr, K. Lanier, A. Koehler, Hazardous substances releases associated with Hurricanes Katrina and Rita in industrial settings, Louisiana and Texas, J. Hazard Mater. 159 (2008) 53–57, https://doi.org/10.1016/j.jhazmat.2007.07.124.

[32] A. Misuri, V. Casson Moreno, N. Quddus, V. Cozzani, Lessons learnt from the impact of hurricane Harvey on the chemical and process industry, Reliab. Eng. Syst. Saf. 190 (2019) 106521, https://doi.org/10.1016/j.ress.2019.106521.

[33] R. Qin, N. Khakzad, J. Zhu, An overview of the impact of Hurricane Harvey on chemical and process facilities in Texas, Int. J. Disaster Risk Reduct. 45 (2020) 101453, https://doi.org/10.1016/j.ijdrr.2019.101453.

[34] E. Krausmann, A.M. Cruz, Impact of the 11 March 2011, Great East Japan earthquake and tsunami on the chemical industry, Nat. Hazards 67 (2013) 811–828, https://doi.org/10.1007/s11069-013-0607-0.

[35] P.Z. Ruckart, J. Borders, J. Villanacci, R. Harris, M. Samples-Ruiz, The role of adverse weather conditions in acute releases of hazardous substances, Texas, 2000-2001, J. Hazard Mater. 115 (2004) 27–31, https://doi.org/10.1016/j.jhazmat.2004.05.004.

[36] MLIT, New Contingency Plan - Takeo Office, Takeo, JP, 2011. http://www.qsr.mlit.go.jp/takeo/site_files/file/english/eng_03/2_8-1-1New_Contingency_Plan.pdf.

[37] MLIT, The Rokkaku River, 2021. https://www.mlit.go.jp/river/toukei_chousa/kasen/jiten/nihon_kawa/0918_rokkaku/0918_rokkaku_00.html. (Accessed 30 June 2021).

[38] Infrastructure Development Institute - Japan, The River Law with Commentary by Article, Legal Framework for River and Water Management in Japan, Development, 1999.

[39] M. Takezawa, H. Gotoh, Measures for Mitigation of Flood Hazards in Japan, 2011, pp. 73–103, https://doi.org/10.2495/978-1-84564-560-1/04.

[40] OECD, Japan Floods, 2006. http://www.oecd.org/dataoecd/36/16/36100106.pdf.

[41] A. Toshiyuki, Flood damage mitigation efforts in Japan, in: Fifth US-Japan Conf. Flood Control Water Resour. Manag., 2009. https://www.mlit.go.jp/river/basic_info/english/pdf/conf_09-0.pdf. (Accessed 30 August 2021).

[42] H. Yamawaki, The evolution and structure of industrial clusters in Japan, Small Bus. Econ. 18 (2002) 121–140, https://doi.org/10.1023/A:1015134028335.

[43] MLIT, Rokkaku River Emergency Flood Control Project, 2019. http://www.qsr.mlit.go.jp/takeo/prepare_bousai/gensaitaisakukyougikai/gensaikyougikai4.html.

[44] MLIT, Expected Flood Inundation Area Map for the Rokkaku River Water System, 2016. http://www.qsr.mlit.go.jp/takeo/site_files/file/prepare_bousai/kouzuisinsuisouteikuiki/01-1_rokkakusuikeisouteisaidai.pdf.

[45] MLIT, Notification 896 (2015 July 17th) - Maximum Rainfall Scenario, 2015. https://www.mlit.go.jp/river/suibou/pdf/kizyun_saidaikouu.pdf.

[46] JMA, Special Warning Due to Heavy Rain Issued in Saga, Fukuoka and Nagasaki Prefectures, 2019. https://www.jma.go.jp/jma/press/1908/28c/kaisetsu201908280700.pdf.

[47] Japan Times, Heavy Rains in Western Japan Triggered Evacuation Orders for Around 847000 Residents, 2019. https://www.japantimes.co.jp/news/2019/08/28/national/special-landslide-flood-warnings-issued-downpours-hit-western-japan/#.XjKYiGhKiUl. (Accessed 30 January 2020).

[48] Nishinippon Shimbun, Oil Spill, Measures of 30 Years Ago Were Unsuccessful - Ironworks Omachi Factory Discussion with the Government, 2019. https://www.nishinippon.co.jp/item/n/545136/. (Accessed 1 December 2020).

[49] Saga Tekkosho Co. Ltd., Omachi Factory Datasheet, 2019. https://www.dextech.co.jp/modules/pico/index.php?content_id=15. (Accessed 1 December 2020).

[50] G.E. Totten, C.E. Bates, N.A. Clinton, Handbook of Quenchants and Quenching Technology, ASM International, Materials Park, OH, 1993.

[51] D.S. MacKenzie, The chemistry of oil quenchants, Heat. Treat. Prog. 9 (2009) 28–32.

[52] Saga Shimbun, Oil Spills Out of the Iron Factory "Exceeded" - Residents Say "Same as 30 Years Ago, 2019. https://www.saga-s.co.jp/articles/-/422825. (Accessed 1 December 2020).

[53] G.E. Totten, G.M. Webster, C.E. Bates, 20 - quenching, in: G.E. Totten, D. S. MacKenzie (Eds.), Handb. Alum., Taylor & Francis, 2003, pp. 971–1062.

[54] R. Abbaschian, L. Abbaschian, R.E. Reed-Hill, Physical Metallurgy Principles, fourth ed., Cengage Learning, Stamford, CT, 2009.

[55] G.E. Totten, Steel Heat Treatment - Equipment and Process Design, second ed., CRC Press, Boca Raton, FL, 2007.

[56] B. Edenhofer, D. Joritz, M. Rink, K. Voges, Carburizing of Steels, Woodhead Publishing Limited, 2015, https://doi.org/10.1533/9780857096524.3.485.

[57] Tellerreport, Saga Oil Spill Company Executives Apologize Insufficient Measures, 2019. http://www.tellerreport.com/post/2019-08-30—saga-oil-spill-company-executives-apologize-insufficient-measures-%22sorry%22-%7C-nhk-news-.BkZ4Nbv8HH.html. (Accessed 15 November 2019).

[58] Japan Times, Oil Leak at Ironworks Complicates Disastrous Flooding in Saga, 2019. https://www.japantimes.co.jp/news/2019/09/01/national/oil-leak-ironworks-complicates-disastrous-flooding-saga-prefecture/#.XXnaBSgzY2w. (Accessed 1 December 2020).

[59] Saga Shimbun, Oil Spill at the Ironworks, 110000 Liters Spilled - Volume outside the Factory Is Unknown, 2019. https://www.saga-s.co.jp/articles/-/426676. (Accessed 1 December 2020).

[60] Saga Shimbun, Saga Ironworks Findings: 54000 Liters of Oil Spilled, 2019. https://www.saga-s.co.jp/articles/-/437962. (Accessed 1 December 2020).

[61] Omachi newspaper, Record Heavy Rain Caused Damages in Many Areas!, City Omachi, 1990, p. 2. http://www.town.omachi.saga.jp/kouhou/1980/pdf/h0207.pdf.
[62] Idemitsu, Safety Data Sheet - Daphne Master Quench A, 2015.
[63] United Nations, Globally Harmonized System of Classification and Labelling of Chemicals (GHS), eighth ed., 2019. Geneva, Switzerland.
[64] Idemitsu, Safety Data Sheet - Daphne Bright, Quench M, 2015.
[65] Idemitsu, Safety Data Sheet - Daphne Hermetic Oil, 2014.
[66] Tellerreport, Recovery of Spilled Oil Due to Heavy Rain - Difficult to Reach Omachi-Cho, Saga, 2019. https://www.tellerreport.com/post/2019-08-29—heavy-rain-spilled-oil-recovery-work-difficult-to-reach-saga-omachi-cho-%7C-nhk-news-.HyedR0ESr.html. (Accessed 1 December 2020).
[67] Umitonagisa.org, Correct Knowledge of Oil Sorbents, 2019. http://www.umitonagisa.or.jp/pdf/kyutyakuzai.pdf. (Accessed 1 December 2020).
[68] M. Tsukasa, Water Disaster Countermeasures Based on Large-Scale Wide-Area Torrential Rain, 2019. http://www.zenken.com/kensyuu/kousyuukai/H31/657/657_morikubo.pdf.
[69] ITOPF, Use of Booms in Oil Pollution Response - Technical Information Paper Number 3, 2011. http://www.itopf.org/. (Accessed 25 January 2020).
[70] A.E. Ghaly, D. Dave, Remediation technologies for marine oil spills: a critical review and comparative analysis, Am. J. Environ. Sci. 7 (2011) 423–440.
[71] Nuka, Spill Tactics for Alaska Responders, Seldovia, Alaska, 2014. http://www.dec.state.ak.us/spar/perp/star/index.htm.
[72] Saga Shimbun, Oil Recovery Proceeds Steadily with Human Tactics, 2019. https://www.saga-s.co.jp/articles/-/425657. (Accessed 1 December 2020).
[73] Saga Prefecture, Damage Caused by the Heavy Rain in Saga (Heavy Rain since August 27th), 2020. https://www.pref.saga.lg.jp/bousai/kiji00370893/index.html. (Accessed 1 December 2020).
[74] National Statistics Center, E-Stat - Portal Site of Official Statistics of Japan, 2019. https://www.e-stat.go.jp/en. (Accessed 20 December 2019).
[75] Kouhoku Town, Kouhoku Town Website, 2019. https://www.town.kouhoku.saga.jp/default.html%0D. (Accessed 19 December 2019).
[76] O. Town, Omachi Website, 2019. http://www.town.omachi.saga.jp/. (Accessed 20 December 2019).
[77] Saga Prefecture, Damage Related to Agriculture, Forestry and Fisheries Related to the Saga Heavy Rain Disaster (R1.9.10, 2019. http://www.pref.saga.lg.jp/bousai/kiji00370822/3_70822_147023_up_o44pp75c.pdf. (Accessed 16 December 2019).
[78] Environmental Agriculture Administration Standing Committee, The Oil Spill Accident in Ryuo-Cho Arch, 2018.
[79] Economie FGG, Oil Spill in Farmland in Omachi - Lime Spraying Will Be Implemented from Next Month, 2020. https://economifgg.blogspot.com/2020/01/blog-post_75.html. (Accessed 29 January 2020). accessed.
[80] UNDRR-APSTAAG, Asia-Pacific Regional Framework for NATECH (Natural Hazards Triggering Technological Disasters, Risk Management, Geneva, Switzerland, 2020, https://doi.org/10.13140/RG.2.2.17353.77922.
[81] MAHB, Natech Risk Management, Ispra, Italy., 2020.
[82] A. Misuri, G. Landucci, V. Cozzani, Assessment of safety barrier performance in Natech scenarios, Reliab. Eng. Syst. Saf. 193 (2020) 106597, https://doi.org/10.1016/j.ress.2019.106597.
[83] A. Misuri, G. Landucci, V. Cozzani, Assessment of risk modification due to safety barrier performance degradation in Natech events, Reliab. Eng. Syst. Saf. 212 (2021) 107634, https://doi.org/10.1016/j.ress.2021.107634.
[84] E. Krausmann, F. Mushtaq, A qualitative Natech damage scale for the impact of floods on selected industrial facilities, Nat. Hazards 46 (2008) 179–197, https://doi.org/10.1007/s11069-007-9203-5.
[85] E. Garnier, Lessons learned from the past for a better resilience to contemporary risks, Disaster Prev. Manag. An Int. J. 28 (2019) 786–803, https://doi.org/10.1108/DPM-09-2019-0303.
[86] W.R. Freudenburg, Risk and recreancy: weber, the division of labor, and the rationality of risk perceptions, Soc. Forces 71 (1993) 909–932, https://doi.org/10.1093/sf/71.4.909.
[87] W.R. Freudenburg, The 'risk society' reconsidered: recreancy, the division of labor, and risks to the social fabric, in: Risk Mod. Age, Palgrave Macmillan UK, London, 2000, pp. 107–120, https://doi.org/10.1007/978-1-349-62201-6_5.
[88] M.R. Cope, T. Slack, J.E. Jackson, V. Parks, Community sentiment following the Deepwater Horizon oil spill disaster: a test of time, systemic community, and corrosive community models, J. Rural Stud. 74 (2020) 124–132, https://doi.org/10.1016/j.jrurstud.2019.12.019.
[89] L.A. Ritchie, D.A. Gill, C.N. Farnham, Recreancy revisited: beliefs about institutional failure following the Exxon Valdez oil spill, Soc. Nat. Resour. 26 (2013) 655–671, https://doi.org/10.1080/08941920.2012.690066.
[90] D.A. Gill, L.A. Ritchie, J.S. Picou, J. Langhinrichsen-Rohling, M.A. Long, J. W. Shenesey, The Exxon and BP oil spills: a comparison of psychosocial impacts, Nat. Hazards 74 (2014) 1911–1932, https://doi.org/10.1007/s11069-014-1280-7.