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Exploring Cascading Disaster Risk During Complex Emergencies: Chemical Industry Disaster Risk Assessment in the Aftermath of the Kakhovka Dam Bombing in Ukraine

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Abstract

Objective: This risk assessment aims to investigate the analysis of cascading disaster risks from the perspective of the chemical industry and public health subsequent to the Kakhovka dam bombing in Ukraine.
Method: The study utilized a modified observational cross-sectional risk assessment method to assess disaster risk. The method involved identifying the location of chemical factories, determining flooded or at-risk factories, analyzing the type and frequency of chemical hazards, assessing population exposure, and plotting a disaster risk metric. Data on chemical industries and flood extent were collected from open-source secondary data.
Results: The destruction of the Kakhovka dam in June 2023 led to severe flooding, placing 42 000 individuals at risk. The analysis identified four chemical factories, with 1 affected by flooding and 3 at risk. The overall risk assessment indicated a high likelihood and severe consequences, including loss of life, environmental contamination, and property damage.
Conclusion: The combination of complex emergencies and high-risk chemical facilities in Kherson Oblast poses a significant risk of a chemical industry disaster. The interplay between compound and cascading risks during complex emergencies amid the current war further exacerbates the situation, leading to the devastation and destruction of the environment to the detriment of life, and aligns with the characterization of ecocide.

The invasion of Ukraine by Russia on February 24, 2022, amid the Russo-Ukrainian war, had far-reaching consequences that reverberated throughout Europe.[1] The international armed conflict in Ukraine has led to complex emergencies, humanitarian crises, and other severe public health risks and consequences, such as chemical industry disasters.[2]

On June 6, 2023, the deliberate bombing of the Kakhovska Hydroelectric Power Plant led to its subsequent destruction. As a direct consequence, uncontrolled water discharge ensued from the Kakhovka Reservoir, causing flooding in adjacent riverside areas downstream, specifically toward the Dnipro River delta.[3] Approximately 16 000 individuals residing in 17 settlements on the right bank of the Dnipro River are estimated to be positioned within the inundated zone.[3,4]

The breach of the dam has resulted in the release of approximately 150–450 tons of oil products from the hydropower plant.[5,6] Floods have carried this contamination and waste from industrial sites and fertilizer depots, leading to extensive pollution of water and land resources.[5] The port area in Kherson city, previously serving as a significant storage site for fertilizers and chemical cargo, now poses a considerable pollution threat in its immediate vicinity and downstream into the Black Sea.[7] Additionally, the flooded area encompasses various manufacturing plants that may discharge chemicals into the floodwaters, intensifying the pollution and posing health risks amidst the ongoing complex emergencies related to the current war.[5,7]

Complex emergencies is defined as, “a humanitarian crisis which occurs in a country, region, or society where there is a total or considerable breakdown of authority resulting from civil conflict and/or foreign aggression.”[8] *Cascading disaster* is an extreme event where escalating effects over time lead to severe, unexpected secondary events. These secondary crises, often as impactful as the initial event, prolong the disaster’s overall effects. They are exacerbated by the collapse of physical structures and social functions, allowing for distinct identification of 1 or more secondary events from the original disaster source.[9,10]

This study aims to investigate the analysis of cascading disaster risks from the perspective of the chemical industry and public health subsequent to the bombing of the Kakhovka dam in Ukraine, aiming to shed light on the intricate nature of these challenges. The research question is: What is the cascading risk to the chemical industry in the aftermath of the Kakhovka dam bombing in Ukraine during complex emergencies? We hypothesize that the risk will be high for life and health, the environment, property, and the speed of development.

Methods

In this disaster risk assessment, we adopted an observational cross-sectional approach using a 5-step methodology outlined by Gan et al.[11] *Disaster risk* is characterized by the potential for loss of life, injuries, and damage or destruction of assets within a system, society, or community over a given period. The Awareness and Preparedness for Emergencies at Local Level (APELL) program, initiated by the United Nations Environment Programme (UNEP), is designed to create awareness and prepare for emergencies at the local level, particularly in relation to hazardous materials.[12] One of the key components of APELL is the process of Hazard Identification and Evaluation in a Local Community, which is suitable in the context of the Kakhovka dam bombing in Ukraine.

This disaster risk assessment focuses on 3 fundamental risk assessment frameworks: (1) Hazard, (2) Vulnerability, and (3) Exposure.

Risk Assessment Framework

Disaster risk = Hazard x Vulnerability x Exposure

1. Hazard identification

The assessment considers various hazards, including hazardous chemicals, floods, and the ongoing armed conflict.

2. Vulnerability evaluation

This component addresses the complexities of ongoing emergencies and humanitarian crises, highlighting systemic susceptibilities.

3. Exposure assessment

The focus here is on populations, environments, and chemical factories within conflict and flood zones, susceptible to indiscriminate bombardment.

Methodology

Risk assessment steps are described below:

Step 1: Identify the location of chemical factories in Kherson Oblast. Using Google Maps, we identified the chemical industrial facility in Kherson Oblast. The search strategy utilized keywords such as “chemical factory,” “chemical plant,” and “chemical industry” in “Kherson Oblast.” The presence of industrial structures was verified using Google Earth Pro.

Step 2: Identify the chemical factory flooded or at risk of flooding.

Step 3: Determine the type of chemical factory and the most probable chemical hazard. We then further calculated the relative frequency of GHS hazards. The relative frequency formula is as follows:

$$Relative\ frequency(\%) = \frac{The\ number\ of\ specific\ GHS\ Hazards}{The\ total\ number\ of\ all\ GHS\ Hazards} \times 100$$

Step 4: Determine the number of populations exposed to the potential chemical hazard.

Step 5: Based on information gathered from all previous steps, plot a disaster risk metric utilizing a semi-quantitative method[13] on the likelihood of the chemical factories being damaged and consequences utilizing 4 indicators adapted from the APELL Hazard Identification and Evaluation in a Local Community,[12] namely: (1) Life and health, (2) Environment, (3) Cost of property damage, and (4) Speed of development.

Additionally, step 2 was adapted to encompass all chemical factories susceptible to flooding or at risk thereof, with a focus on individualized analysis rather than the cluster-based approach employed in the original study. In step 3, the quantification of the overall hazard frequency estimation was achieved by calculating the relative frequency of hazards in accordance with the Globally Harmonized System of Classification and Labelling of Chemicals (GHS).

Data collection and analysis

Data on the chemical industries in eastern Ukraine, such as type of chemical factory, address, GPS coordination, and Google Plus code, were extracted from Google Maps and Google Earth on June 7, 2023. Steps 1 through 3 were conducted independently by the first 2 authors, and final findings were compared, and any disharmony was resolved by the last author.

Steps 4 and 5 were done with the input of all authors. The semi-quantitative risk analysis method[13] was utilized by all authors to score and further describe the risk from the perspective of consequences for life and health, the environment, property, and speed of development, using guidelines adapted from the APELL (Awareness and Preparedness for Emergencies at Local Level) Hazard Identification and Evaluation in a Local Community.[12] The average of the final score was tabulated and the disaster risk metric plotted (see Table 3 and Figure 3).

The data on flood extent secondary to the Nova Kakhovka dam bombing, ICEYE satellite image on June 7, 2023, 13:01 UTC, were obtained from OCHA Humanitarian Data Exchange, **UNOSAT code FL20230606UKR**,[14] and projected in Google Earth Pro. The mini map of Ukraine was generated by QGIS 3.28. All data and tools utilized in this risk analysis are from open-sourced secondary data, and all identifiers have been anonymized. Hence, no ethical considerations are needed.

Assumptions

This methodology involved a few inevitable assumptions.

Assumption 1. Pertains to the challenge of ascertaining the operational status of all identified chemical facilities at the time of the incident. It is postulated that notwithstanding the cessation of operations during the war, residual chemicals may persist within storage facilities due to the abrupt onset of hostilities, potentially impeding complete evacuation.

Assumption 2. Revolves around the uncertainty surrounding the existence of undisclosed chemical factories or structures storing chemical substances. Nevertheless, it is presumed that chemical facilities featured on Google Maps, aiming to enhance their commercial appeal both domestically and internationally, would exhibit larger scales and storage capacities compared to those establishments eluding identification via Google Maps. These assumptions, while acknowledged, are deemed indispensable given the absence of alternative data sources due to the ongoing conflict.

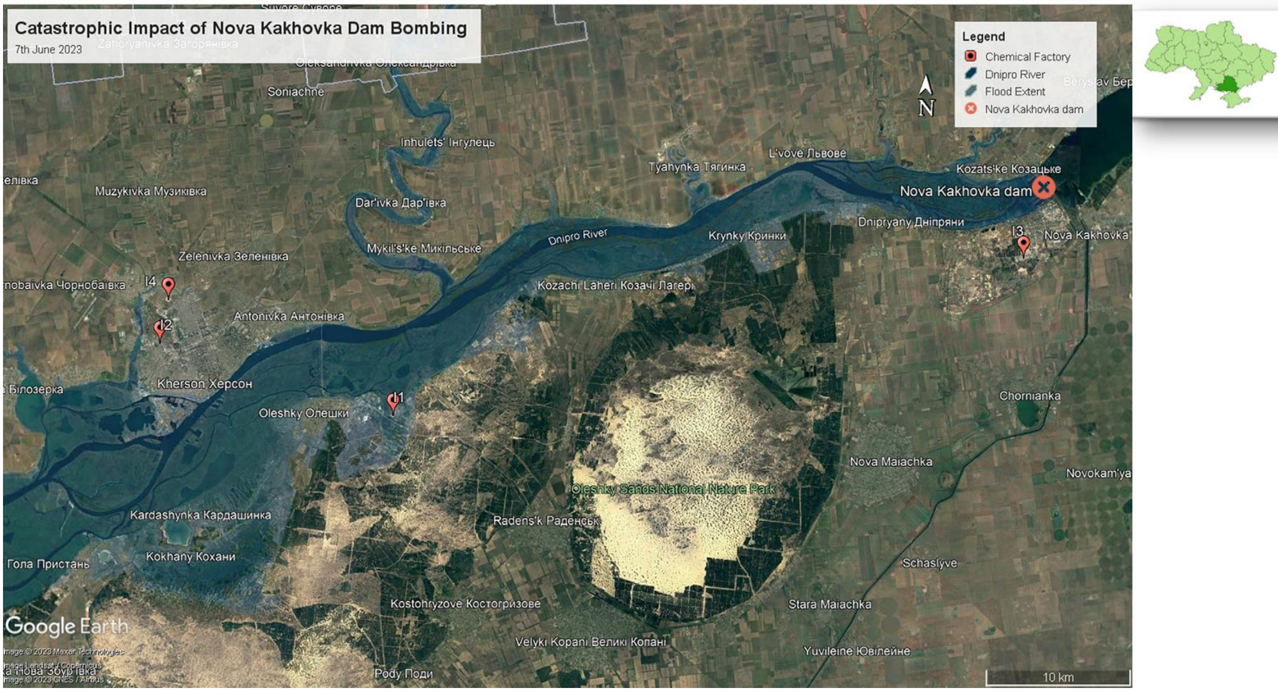

Figure 1. Illustrates satellite-detected flood waters 90km downstream of the Dnipro River between the damaged Nova Kakhovka Dam wall, the Dnipro River mouth, and chemical factories in Kherson Oblast, Ukraine.

Results

The destruction of the Kakhovka dam has resulted in severe flooding covering more than 200 km^2, affecting approximately 70% of Oleshky, a city situated on the left bank of the Dnipro River. Furthermore, on the right bank of the Dnipro River, the capital of Kherson Oblast, Kherson city, the flood affected around 20% of its territory.[15]

As shown in the map, Figure 1, the dark blue polygon represents the Dnipro River before the flood, and the light blue polygon shows the extent of the flood. In addition, Figure 1 also presents the identified 4 chemical factories situated within the Kherson Oblast. Among these, 1 chemical factory located in Oleshky city (I1) has been affected by flooding, while the remaining 2 in Kherson City (I2 and I4), as well as 1 in Nova Khakovka City (I3), were at risk of flooding and its cascading effect. We provided a thorough analysis of each chemical factory, specifying their types and the chemicals they manufactured, as shown in Table 1. The potential hazards associated with these factories have been assessed using the Globally Harmonized System (GHS) and the National Fire Protection Association (NFPA) 704 diamond (Standard System for the Identification of the Hazards of Materials for Emergency Response). It is estimated that approximately 42 000 individuals are at risk as a result of the ongoing flood.[6,16]

Our analysis reveals that among the GHS hazards examined, the 3 with the highest relative frequency were the health hazard, irritant, and flammable, each accounting for 22.2%. Subsequently, environmental hazard and toxic hazard followed closely behind, with both exhibiting a relative frequency of 11.1%. Out of all the hazards, corrosive and compressed gas were the least frequent, with a relative frequency of 5.6% as shown in Table 2.

Regarding the NFPA hazard assessment, it was determined that chemical factory I2 poses the most severe health hazard, assigned a hazard rating of 4, indicating its potential lethality. Additionally, it has a hazard rating of 4 for flammability, indicating that it can vaporize and readily ignite at ambient temperature. Chemical factory I1, on the other hand, exhibits the most severe hazard of 2 for instability, suggesting a propensity for violent chemical changes under high temperature or pressure. Notably, special hazards common to all 4 chemical factories include a tendency to react violently with water (W) at chemical factory I1, corrosive properties at chemical factory I3, and toxicity in chemical factories I2 and I3. The NFPA diamonds, depicting these hazards, are visually presented in Figure 2.

Risk metric score, the likelihood of chemical factory damage is high, consequences, total score. The score is shown in Table 3, and the chemical disaster risk metric is plotted in Figure 3. Our semi-quantitative assessment of the overall disaster risk faced by the chemical industry in Kherson Oblast following the Kakhovka dam bombing in Ukraine reveals a high likelihood of damage to the chemical factories due to both the flooding and indiscriminate civilian bombings.

The interplay between compound and cascading disaster risk will lead to catastrophic consequences in terms of loss of life and severe injuries, with a projected death toll exceeding 20 individuals, hundreds sustaining serious injuries, and more than 500 requiring evacuation. The environmental impact will also be devastating, resulting in extensive contamination and widespread repercussions. Additionally, the property damage will be severe, estimated to range between US $5 and $20 million. Importantly, the development of the chemical industry disaster will occur without warning, as its effects remain hidden until they reach full fruition or manifest suddenly through events such as explosions. The average score of the consequences for all indicators mentioned was tabulated in Table 3, and the overall risk metric was illustrated in Figure 3.

Discussion

The combination of a complex emergency in a wartime setting and the presence of high-risk chemical facilities in Kherson Oblast

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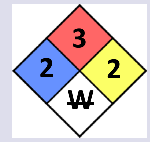
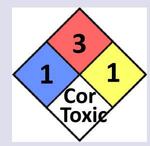
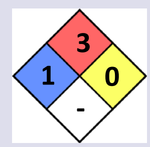
Table 1. Chemical factory hazards analysis

ID	Type of chemical factory	The chemicals involved in manufacturing	Probable classification (GHS)	Potential hazards	NFPA 704 Diamond	Number of people at risk
I1	Foams, sealants, and mounting adhesive	Polystyrene[a] Acrylic[b] Polyvinyl acetate[c]	• Flammable • Irritant • Health hazard	• Health hazard: 2 • Flammability hazard: 3 • Instability hazard: 2 • Special hazard: W̶		42 000 people
I2	Petrochemical	Olefins[d] Benzene[e] Toulene[f] Hydrogen sulphide[g]	• Flammable • Compressed gas • Irritant • Toxic • Health hazard • Environmental hazard	• Health hazard: 4 • Flammability hazard: 4 • Instability hazard: 0 • Special hazard: toxic		
I3	Oil refineries	Benzene[h] Hydrochloric acid[i] Sodium hydroxide[j]	• Flammable • Corrosive • Irritant • Toxic • Health hazard	• Health hazard: 1 • Flammability hazard: 3 • Instability hazard: 1 • Special hazard: corrosive, toxic		
I4	Ceresit, adhesive, and paints	Epoxy[k] Polyurethane[l] Acetone[m] Turpentine[n]	• Flammable • Irritant • Health hazard • Environmental hazard	• Health hazard: 1 • Flammability hazard: 3 • Instability hazard: 0 • Special hazard: -		

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[a]Yasuda N, Uekusa H, Ohashi Y. Styrene. *Acta Crystallographica Section E Structure Reports Online*. 2001;57(12):o1189-o1190;
[b]https://www.acplasticsinc.com/media/documents/MSDS_Acrylic_Acrylite_en.pdf;
[c]https://pubchem.ncbi.nlm.nih.gov/compound/7904;
[d]https://www.marathonpetroleum.com/content/documents/Operations/Western_SDS/olefins.pdf;
[e]https://www.airgas.com/msds/001062.pdf;
[f]https://www.sigmaaldrich.com/US/en/sds/sial/244511;
[g]https://www.airgas.com/msds/001029.pdf;
[h]https://pubchem.ncbi.nlm.nih.gov/compound/241#section=NFPA-Hazard-Classification;
[i]https://pubchem.ncbi.nlm.nih.gov/compound/313#section=Health-Hazards;
[j]https://pubchem.ncbi.nlm.nih.gov/compound/14798#section=Hazard-Classes-and-Categories;
[k]https://charliespaint.com/wp-content/uploads/2018/11/sds-diamondcoatepoxy-countertop-a-resin.pdf;
[l]https://docs.rs-online.com/0b49/0900766b8113a600.pdf;
[m]https://pubchem.ncbi.nlm.nih.gov/compound/180#section=Fire-Hazards;
[n]https://www.hsbuild.com/assets/pdfs/P13304_SDS.pdf

Table 2. GHS chemical hazards relative frequency in Kherson Oblast

GHS specific hazards classification	GHS specific hazard classification in Kherson Oblast	Relative frequency (%)
Explosive	0	0
Compressed gas	1	5.6
Flammable	4	22.2
Oxidizer	0	0
Corrosive	1	5.6
Irritant	4	22.2
Toxic	2	11.1
Health hazard	4	22.2
Environmental hazard	2	11.1

significantly amplifies the potential for a chemical industry disaster. The consequences of such an event can be catastrophic, affecting the health and well-being of the affected population, exacerbating environmental degradation, and impeding the region's recovery. Our disaster risk assessment focuses on understanding the chemical hazards, the release of chemicals associated with the flood, and the interplay between compound and cascading risks of the chemical industry during complex emergencies, as shown in Figure 4.

The mechanism of chemical release can be due to the direct impact of bombing, leading to the chemical release. Instances of chemical releases caused by direct bombing have been documented since the commencement of the conflict. A notable incident took place on April 5, 2022, in Rubizhne, located in the Luhansk Oblast, where leakage of nitric acid was reported in the aftermath of the bombing.[17] The design and construction of chemical factories were not built to withstand such impact and will contribute to the vulnerability and increased risk of chemical release when subjected to bombings.

Furthermore, the inundation resulting from the bombing of the Kakhovka dam can give rise to significant consequences, including the structural impairment of storage tanks and pipelines within chemical factories, consequently leading to the unintended release of hazardous substances. The disruption in power supply due to

Table 3. Score of the chemical factories being damaged and consequences addressing life and health, environment, cost of property damage, and speed of development

Consequences of life and health:	5. Catastrophic – Several deaths (more than 20), hundreds of serious injuries, more than 500 evacuated.
Consequence for the environment:	5. Catastrophic – Very heavy contamination, widespread effects
Consequences for property	4. Very serious – 5–20 (total cost of damage in million USD)
Speed of development	5. No warning – Hidden until the effects are fully developed/immediate effect (explosion)
Average score	4.75

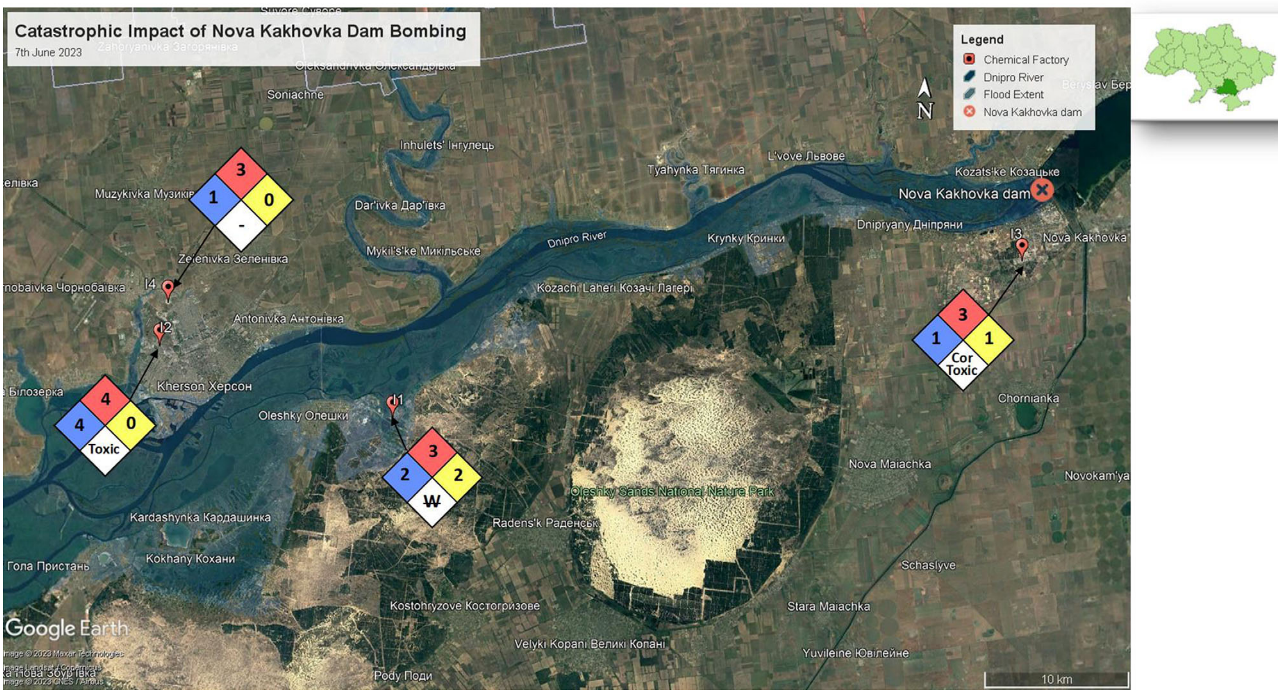

Figure 2. NFPA 704 hazard diamond of chemical factories in Kherson Oblast, Ukraine.

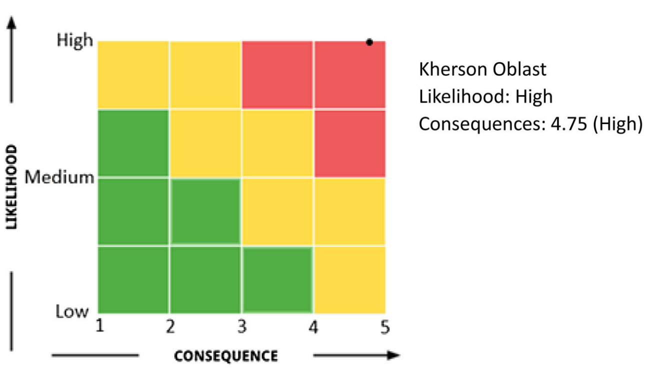

Figure 3. Overall chemical industry risk matric of Kherson Oblast following the Kakhovka Dam bombing.

the flood further exacerbates the situation, causing disturbances in the chemical industrial systems. Specifically, vital safety measures and critical components like temperature monitoring and storage pressure controls become compromised, creating a potential scenario for uncontrolled chemical reactions and subsequent blowdown occurrences.[18–20]

Apart from floods, the bombing of the Kakhovka dam also caused the leak of between 150 and 450 tons of motor oil from the hydropower plant.[5,6] This may cause toxic chemical runoff from the chemical factories' storage, carrying both hydrophilic and hydrophobic chemicals depending on what was stored at the site. Moreover, the released chemicals can have the potential to interact and undergo reactive processes when combined with floodwater, giving rise to toxic reactions or ignitable conditions that may lead to fires or explosions. An example of this risk can be seen with factory I1 which contains special hazards that possess the capacity to react violently or explosively upon contact with water. Consequently, the propagation of buoyant flames carried by the floodwater can pose a significant threat, potentially compromising nearby flammable substances or encroaching upon residential areas.[21,22]

The occurrence of washouts and the presence of floating landmines and unexploded military ordinance (UXO) dislodged by the floods present substantial risks to chemical factories. Numerous reports have documented instances of floating landmines detonating in close proximity to riverbanks and flooded areas, underscoring the potential danger.[23,24] The washout and floating landmines can lead to detonation or explosions transpiring at flooded chemical factories or nearby chemical facilities, thereby causing severe damage and subsequent chemical leakage.

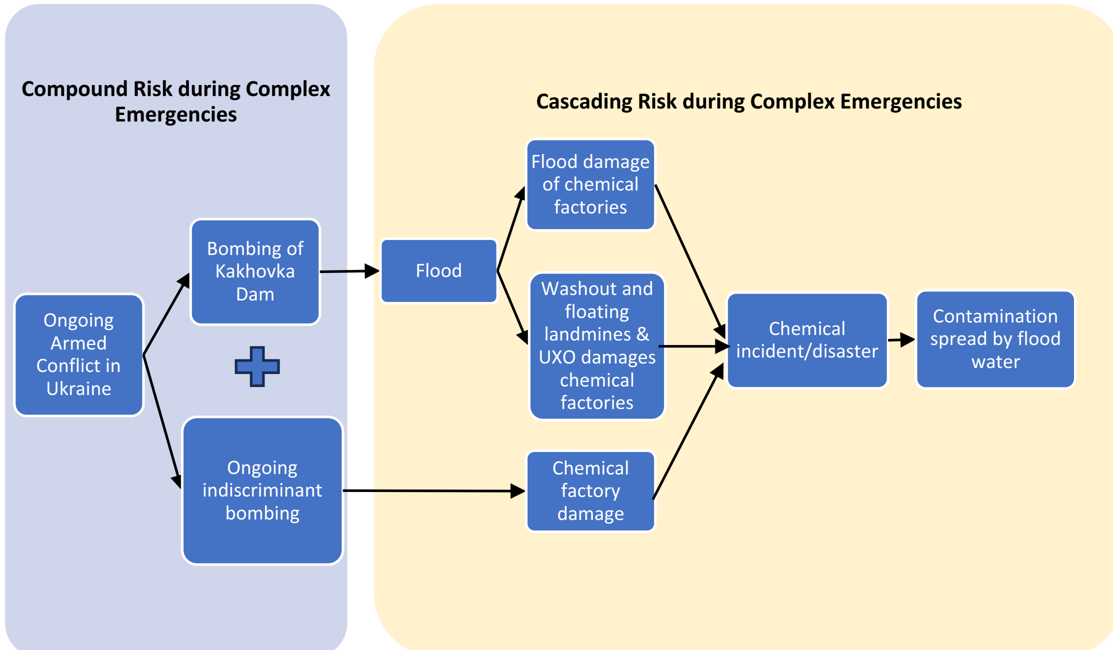

Figure 4. Illustrates the interplay between compound risk and cascading risk during a complex emergency in the Aftermath of the Kakhovka Dam Bombing in Ukraine. UXO: Unexploded Military Ordinance.

The potential impact of a chemical industry disaster during a flood raises concerns for public health, particularly in terms of exposure to the general population and rescuers.[25] Residents and rescuers affected by the disaster are at risk of encountering various health hazards, including exposure to chemical-contaminated water, consumption of contaminated drinking water, and inhalation of volatile chemicals or fumes. These exposures can manifest as symptoms and signs indicative of chemical burns, poisoning, and toxidromes.[26,27] Chemical industry disasters will further complicate the humanitarian response to the flood victim, which is already challenged by insecurity and limited access due to ongoing complex emergencies.

The catastrophic impact of this flood has displaced more than 6500 people.[28,29] In addition to the immediate challenges faced by these displaced individuals, the occurrence of a chemical industry disaster during the flood further complicates the process of their safe return and recovery. This difficulty arises from the lingering presence of hazardous chemicals, which may persist even after the floodwaters have receded.[30]

The bombing of the Kakhovka dam has resulted in clean water scarcity, affecting a considerable population of over 1 million people in Ukraine, as reported.[31,32] The occurrence of a chemical industry disaster during the flood exacerbates this situation by introducing contamination to both rivers and underground water sources. This contamination has far-reaching consequences, severely impacting widespread water supplies, agriculture, and the environmental impact, thereby exacerbating the issue of water availability and worsening food insecurity.[33] These challenges are further compounded by the projected drought conditions, which are expected to reduce agricultural production in Europe.[34] The bombing of the Kakhovka dam has thus fulfilled the term *ecocide*, which is defined as the devastation and destruction of the environment to the detriment of life.[35]

Limitations of This Disaster Risk Assessment

Given the ongoing complex emergencies in Kherson Oblast, it is important to acknowledge that certain crucial components were not included in this risk assessment. These components encompass the collection and analysis of environmental samples, the acquisition of clinical information from individuals affected by the flood, the need for further verification regarding the quantity and quality of chemicals manufactured in each specific chemical factory, and the number of factory employees who would likely be at greater risk of chemical and toxic exposures. Further detailed risk assessment on the type of chemical and their hazards should be conducted once the situation permits. Future research could also take into account the numbers and locations of bombings in relation to the chemical industries.

Conclusion

The combination of complex emergencies and high-risk chemical facilities in Kherson Oblast poses a significant risk of a chemical industry disaster. The interplay between compound and cascading risks during complex emergencies further exacerbates the situation, leading to the devastation and destruction of the environment to the detriment of life, aligns with the characterization of ecocide.

In conclusion, our risk analysis shows that more than 42 000 people in the Kherson Oblast are exposed to potential hazards from the chemical industry in the aftermath of the Kakhovka dam bombing in Ukraine. The overall risk assessment indicates a high level of aggregation risk, characterized by substantial likelihood and severe consequences in terms of life and health, environment, property, and the speed of development.

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Author contributions. All authors contributed substantially to the design, data collection, data analysis, and risk assessment; drafted the article and reviewed the final manuscript; and gave the final approval of the version to be published and agreed to be accountable for all aspects of the work. The first author produced all figures in the manuscript.

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