[DA-018] GIS&T and Disaster Management

Abstract

Geographic Information Science and Technology (GIS&T) has a long-running tradition of using spatially-oriented methodologies and representational techniques such as cartography and mapping to address hazards and disasters. This tradition remains important as ever as global society faces newer and more complex challenges resulting from climate change and new challenges such as the COVID-19 pandemic. GIS&T has become an invisible technology within the disaster management cycle of planning and preparedness, response, recovery, and mitigation. Spatial technologies such as geographic information systems (GIS), remote sensing techniques, spatial data science, artificial intelligence, and machine learning are now widespread and pervasive. Despite these advancements, there is more that can be done to incorporate GIS&T perspectives into disaster management. In this article, we outline important conceptual ideas to consider on the use of GIS&T for disaster management, disaster management organizations that use GIS&T, and practical information to orient newcomers to this exciting and important interdisciplinary combination.

Keywords: disaster organizations, disaster policies, disaster response, disasters, mitigation, planning, recovery, response

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Explanation

1. Introduction

The discipline of Geographic Information Science and Technology (GIS&T) has a long-running tradition of using spatially-oriented methodologies and representational techniques such as cartography and mapping to address hazards and disasters (Coppock, 1995; S. L. Cutter, 2003). In many ways, disaster management and hazards research has liberated GIS&T from the halls of academia to the frontlines of Homeland Security and Emergency Management. This tradition remains important as ever as global Society faces newer and more complex challenges resulting from climate change and new challenges such as the COVID-19 pandemic. GIS&T has become an invisible technology within disaster management practice (Tomaszewski, 2021). Spatial technologies such as geographic information systems (GIS), remote sensing techniques, spatial data science, artificial intelligence, and machine learning are now widespread and pervasive. Despite these advancements, there is more that can be done to incorporate GIS&T perspectives into disaster management. In this article, we outline important conceptual ideas to consider on the use of GIS&T for disaster management as well as practical information to orient newcomers to this exciting and important interdisciplinary combination.

1.1 Scale and Terms

Before discussing specific technical details about GIS&T for disaster management, it is first important to clarify terminology used in this particular application domain. These terms can be framed in terms of geographic and temporal scale. An **emergency** is often (but not always) considered a smaller type of event that occurs quickly and can generally be resolved within a relatively short amount of time such as hours or days and can be handled by local authorities. For example, calling the local fire department to deal with a house fire or a car accident. However, sometimes an emergency can be framed in terms of scale like a 'national emergency'. A **crisis** is when a set of conditions occurs that could lead to some type of negative impact. The geographic scale of a crisis can vary. Given that a crisis can happen at different geographic scales, the response mechanism can vary. The COVID-19 pandemic could be considered a type of crisis as some aspects of society may not be directly impacted by the crisis but the crisis has potential for negative impact. A **disaster** is generally considered to be a larger event that sometimes but not always, has a sudden onset and the geographic scale and scope of the disaster could potentially be beyond the capacities of local authorities to respond. One example of a disaster could be flooding that occurs from the effects of a hurricane. A **catastrophe** is an event of massive scale and scope that completely overwhelms multiple levels of organizational capacity to respond to the event. The Indian Ocean Tsunami of 2004 is an example of a catastrophe as this event required multiple government levels and even international levels of cooperation to respond (Kelmelis et al,. 2006).

It is important to consider the different terms and their specific meaning in connotation when considering the use of GIS&T for disaster management. A small-scale emergency will have different data, and technology requirements as opposed to a large-scale international catastrophe. For sake of clarity, and the remainder of this article we will refer to events as 'disasters' although in some cases we use this term loosely as per the previous discussion about geographic scale and scope of events.

Clarifying what is meant by an "**event**" is also helpful. Although it is commonly assumed that a situation like a disaster is based on a naturally occurring phenomena such as a hurricane or earthquake, threats and hazards come in multiple forms such as a human-made event like terrorism, a nuclear meltdown like the Fukushima disaster in Japan of 2017, a biological event like the COVID-19 pandemic or compounded events such as climate-induced forced displacement that causes mass migrations of people. Although the specifics of an event vary, often the outcomes of the events will have similar characteristics such addressing survivor needs and long-term recovery.

The **disaster management cycle** is a general cyclical process that can be a helpful conceptual framework for understanding the use of GIS&T for disaster management. In this article, we are framing the use of GIS&T for disaster management in terms of four well-known phases of the disaster management cycle as a means for achieving resilience:

1. Preparedness/Planning: preparation of resources that would be used when an event

occurs to make a response more effective;
2. Response: actions taken when an event occurs to stabilize a situation to return to some state the situation was in before the event occurred;
3. Recovery: the rebuilding and realignment of a situation after the response has stabilized negative outcomes occurring from the event;
4. Mitigation: removing or alleviating the potential negative impacts of an event before they occur in the first place.

Given the inherent spatial nature of disasters, GIS&T for disaster management is applicable to every phase. Later in this article we will give specific examples of how GIS&T can be used within the context of each disaster management cycle phase.

1.2 Geographical Context and Disasters

Finally, before proceeding into technical discussion about GIS&T for disaster management, it is important to always keep in mind the relationship between geographical context and disasters. By ‘geographical context’, we mean the setting in which people live. This can be direct items such as the physical materials of the structures people live and work in, transportation infrastructure, existing capacities they may have such as access to emergency services, medical facilities or financial resources. However, in the case of disasters specifically, geographical context also must consider the lived experiences people have had with prior events. For example, people that live on the gulf coast of the United States that have experienced multiple hurricanes in their lifetime and how those past experiences shape their ability to cope and respond to future disasters. Additionally, geographical context could also include longer generational memories of how societies have responded to and adapted to events such as famines, recurring forced displacement or natural hazards. These aspects of geographical context do not necessarily lend themselves to discrete representation in tools like GIS but are important to keep in mind when considering the broader use of GIS&T for disaster management.

2. Brief Survey of GIS&T and Disaster Organizations and Policy Frameworks

In the following section, we provide a brief survey of organizations and policy frameworks from around the world that utilize GIS&T for disaster management in some form in order to provide insight into the multidisciplinary ways that GIS&T is used for disaster management organizations. By no means is this brief survey an exhaustive collection of all of the organizations and policy frameworks around the world that use GIS&T for disaster management. However, we tried to highlight some of the most notable organizations that use GIS&T for disaster management as well as examples from specific countries, continents, and International organization and policy frameworks that are important to be aware of when beginning to learn about this topic.

2.1 International

The United Nations Office for Disaster Risk Reduction (UNDRR, https://www.undrr.org/), as the name implies, is the primary United Nations (UN) office focused on disaster mitigation and overall reduction of disaster risk. UNDRR accomplishes this mission through country partnerships and implementation of policy frameworks, most notably the Sendai framework that we discuss later. With a focus on disaster risk reduction, UNDRR primarily works on events with longer time spans such as sea-level rise and climate change. Their GIS & Mapping theme (https://www.undrr.org/theme/gis-mapping) lists their GIS&T activities supported by UNDRR.

By contrast, The United Nations Disaster Assessment and Coordination team (UNDAC, https://www.unocha.org/our-work/coordination/un-disaster-assessment-and-coordination-undac) is the UN mechanism used for sudden onset emergencies at the international scale. Like many UN mechanisms, UNDAC is invited into a country that has been impacted by a disaster to assist with response and relief operations. The UNDAC Field Manual is an excellent source for seeing how maps are operationalized in international disaster response activity. GIS is explicitly a part of UNDAC activities as per the UNDAC Field Handbook that offers practical advice on GIS: “J.2.1 Geospatial Information Services (GIS) - Mapped information is very important for creating a shared operational picture of a disaster situation and for coordinating the response. Humanitarian responders may arrive with no geographical knowledge of the affected area. Effective mapping of assessments and aid delivery is needed to avoid gaps or overlaps in response efforts.(Office for the Coordination of Humanitarian Affairs (OCHA), 2018, pp. Section J-7)”.

2.2 United States

The Federal Emergency Management Agency (FEMA) is the primary organization in the United States at the federal level tasked with all aspects of disaster management. In particular, FEMA plays an important role when a federal disaster declaration is made meaning that the federal government of the United States is requested to assist when an event is beyond the scope of local or state capacities. The applications of GIS&T in FEMA (https://gis.fema.gov/) are now well-established and widespread.

The US Department of Homeland Security (DHS) is the broader US Federal government umbrella organization that oversees organizations such as FEMA, US Coast Guard, Office of Countering Weapons of Mass Destruction, and the US Border Patrol. With this broad mandate, DHS is an excellent example of the use of GIS&T for all types of event as per the previous discussion. Over the past 15 years, GIS&T has become essential to DHS missions, operations, and key stakeholders as well as development of geospatial information and technology policies in the US federal government, state, local, and tribal agencies. To learn more about the Homeland Security Enterprise (HSE) Geospatial Concept of Operations (GeoCONOPS), see https://communities.geoplatform.gov/geoconops/.

2.3 Europe

The Copernicus Emergency Management Service (https://emergency.copernicus.eu/) is funded by the European Union with a mandate to be “Europe’s eyes on the Earth“ during major disasters in Europe and internationally. More specifically, Copernicus provides rapid mapping services, disaster risk mapping services and access to satellite imagery from European Union member states. Many of the geospatial data products created through Copernicus are available for free download.

2.4 Asia

The Asian Disaster Preparedness Center (ADPC) is an autonomous organization with a focus on disaster resilience in the Asia-pacific region of the world, and maintains a substantial Geospatial Information Department (https://www.adpc.net/igo/contents/adpcpage.asp?pid=1271&dep=GEO).

2.5 Africa

To the best of our knowledge there is not a single pan-continent organization focused on disaster management for the continent of Africa. However, the use of GIS&T for disaster activities in Africa Is broad and extensive. One particularly notable effort is the World Bank's Global Facility for Disaster Risk Reduction (GFDRR) that leverages investments in specific African countries for disaster risk reduction such as resilient infrastructure.

Some country-level organizations even have dual mandates for disaster management activities and forced displacement. In this regard, the Ministry in Charge of Emergency Management (MINEMA, https://www.minema.gov.rw/) in Rwanda has a dual mission of disaster management risk reduction and refugee management where GIS&T is prevalent through all of these activities.

2.6 Latin America

Coordination Center for the Prevention of Natural Disasters in Central America (CEPREDENAC, http://www.cepredenac.org) is a cooperation of seven countries in Central America designed to pool resources to deal with pan Caribbean events ranging from hurricanes, volcanoes end more recent challenges such as the Covid-19 pandemic.

2.7 Non-Governmental Organizations (NGOs)

NGOs have become invaluable players in GIS&T for disaster management. The following are two of the most prominent organizations in this regard.

- **Humanitarian OpenStreetMap Team (HOT).** Deriving from the broader OpenStreetMap initiative that is designed to provide free and open-source geographic data for the entire world, the Humanitarian OpenStreetMap team (https://www.hotosm.org/) has evolved over the past 10 years to provide community development services rapid reference data collection for areas of the world that are missing important base map data that is often the basis for emergency response activity. In fact, HOT has even been focusing on the Missing Maps Project (https://www.missingmaps.org/) where they are working on filling data gaps for parts of the world where digital reference data does not currently exist.
- **Map Action**. One of the longest-running and successful rapid mapping projects, the UK-based non-profit Map Action (https://mapaction.org/) is focused on rapid deployment to disaster response situations where local mapping capacities may not exist. A review of their deployment catalog shows the depth and geographic scope of Map Action's field activities to bring GIS&T capacities to disaster response situations.

2.8 Policy Frameworks

The Sendai Framework for Disaster Risk Reduction (https://www.undrr.org/implementing-sendai-framework) is the primary disaster risk reduction framework followed by the international community. GIS&T for disaster management (and disaster risk reduction specifically) has several explicit references in the Sendai Framework, thus making GIS&T key to global disaster risk reduction in terms of policy and mandates.

For example, Priority 1: Understanding disaster risk at the National and local levels states: "(c) To develop, periodically update and disseminate, as appropriate, **location-based disaster risk information, including risk maps**, to decision makers, the general public and communities at risk of exposure to disaster in an appropriate **format by using, as applicable, geospatial information technology**; (f) To promote real time access to reliable data, make use **of space and in situ information, including geographic information systems (GIS),** and use information and communications technology innovations to enhance measurement tools and the collection, analysis and dissemination of data (United Nations International Strategy for Disaster Reduction, 2015:15) (bold words added by authors).

Furthermore, priority 1: Understanding disaster risk at the Global and regional levels states: "To enhance the development and dissemination of science-based methodologies and tools to record and share disaster losses and relevant disaggregated data and statistics, as well as to **strengthen disaster risk modelling, assessment, mapping**, monitoring and multihazard early warning systems; (b) To promote the conduct of comprehensive surveys on multi-hazard disaster risks and the **development of regional disaster risk assessments and maps**, including climate change scenarios; (c) To promote and enhance, through international cooperation, including technology transfer, access to and the **sharing and use of non-sensitive data and information, as appropriate, communications and geospatial and space-based technologies and related services**; (g) **disseminate risk information with the best use of geospatial information technology** (United Nations International Strategy for Disaster Reduction, 2015:16) (bold words added by authors).

3. GIS&T and Disaster Management Phases

With some context in mind now as to the broader world of GIS&T for disaster management, we will now discuss some ideas for the use of GIS&T in each disaster management phase. The topics we list are some of the most well-known uses of GIS&T in particular disaster phases. However this is by no means an exhaustive list and is only representative of a starting point for further research and ideas.

3.1 Planning and Preparedness

Much like preparing with medical supplies and food, a specific goal of GIS&T in the planning and preparedness phase is to ensure that all aspects of GIS&T (software, data, training, policies) are prepared and in place before disaster occurs. Examples include activities such as development and maintenance of essential disaster management map layers like transportation, locations of infrastructure, hospitals, and any other contextually relevant reference data that may need to be drawn upon when a disaster occurs. As one example from the United States, the Homeland Security Foundation layers (HFLID, https://hifld-geoplatform.opendata.arcgis.com/) are an excellent source of contextual, reference data that can be drawn upon during an event. Examples of remote sensing data that can be used for planning and preparedness include the US Geological Survey's EarthExplorer (https://earthexplorer.usgs.gov/). HFLID and EarthExplorer are excellent examples of new developments in open data, or where data sets are provided for free by authoritative sources, like governments. Specific GIS&T technical skills related to planning and preparedness could range from development of geospatial metadata, geodatabase management, and developing data-sharing memorandums of understanding (MoUs) between governments organizations and the private sector.

Development of evacuation routes is also inherently spatial and generally conducted during planning and preparation so that evacuation routes can be used when an actual event occurs. For instance, Li (2020) and Rahman et al. (2021) are examples of the development of evacuation routes based on the use of spatial networking algorithms. Additionally, identifying evacuation “trigger points” or when exactly to inform the public about when to evacuate can draw upon spatial variables such as in the case of wildfires wind speed, topography, and ease of evacuation (Cova et al. 2005).

Public outreach and citizen participation for planning and preparation involves the use of spatial methodologies for communicating about potential hazards and risks, disaster response plans, and disaster survivors can begin to rebuild their lives after an event. This is arguably becoming an even more important topic as people become suspicious of science and untrustworthy of government communications that in the case of disasters, often comes in the forms of maps. It is also an excellent way to utilize public participation GIS (PPGIS) methods where community members can communicate about potential hazards they see in their neighborhoods and how the community can plan and prepare for an eventual event (e.g., Lugeri et al. 2021).

Another very common activity in disaster planning and preparedness is the use of simulations and exercises to train disaster management personnel and others on what to do in the event of a given type of scenario. In this regard, the FEMA has published several examples of table-top exercises that can be used for a variety of event types such as floods, earthquakes and terrorist attacks (e.g., https://www.fema.gov/emergency-managers/national-preparedness/exercises/tools). HAZUS (https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/about) is a well-established GIS-based analysis tool for calculating hazard risk and loss. To model and map the dispersion of hazardous chemicals over geographic space, CAMEO (Computer-Aided Management of Emergency Operations, https://www.epa.gov/cameo) and its related programs Areal Locations of Hazardous Atmospheres (ALOHA) and Mapping Application for Response, Planning, and Local Operational Tasks (MARPLOT), are well-established and free tools from the US Environmental Protection Agency (EPA). CAMEO is often used for tabletop exercises, or the use of a simulation to test and assess the ability of a group to respond to the given scenario (US Department of Homeland Security, n.d.). For a specific example of the role of CAMEO in a tabletop exercise from the US, see https://www.hazmat.org/epa-region-9-tabletop-exercise-pdfs/.

There has also been a growing body of research on combining game development techniques with real-world geographic data for realistic simulation and modeling of disaster events (e.g., Tomaszewski et al., 2020).

Finally, it is important to include disaster warnings as part of planning and preparedness in terms using GIS&T for activities that include but are not limited to communicating oncoming risk to communities, predicating risk impacts (i.e., hurricane tracking on a map), or consolidating inputs from sensor-based warning systems (i.e., tsunami or flood warning systems) (de León et al., 2006; Yekeen et al., 2020).

3.2 Responses

The Response phase is perhaps the most well-known of the entire disaster management cycle due to its public visibility via the news and social media. Disaster response is often very time-sensitive. Accordingly, the primary goal of disaster response is to “save lives, reduce health impacts, ensure public safety and meet the basic subsistence needs of the people affected” (United Nations Office for Disaster Risk Reduction (UNDRR), 2022c).

Disaster response requires high levels of situation awareness, or the basic idea of knowing what's going on through the use of maps. One classic example of the use of maps during a disaster response is that of an Emergency Operation Center (EOC) where large screens will display maps and other visual artifacts that help inform people responding within the overall situation.

The increasingly widespread use of social media generates a spatial data deluge following disaster events, with people often reporting their experiences. Often, these social media artifacts have a spatial component that requires machine learning, natural language processing and other artificial intelligence techniques to interpret and decipher the data. As starting points for research on this aspect of GIS&T and disaster response, see Athanasis et al. (2018) and Wang & Ye (2018).

Disaster damage assessment is an excellent use of mobile mapping technology such as using smartphones for inventorying building damage or the use of tablet computers for conducting field surveys. Specific tools such Esri’s Survey123 (https://survey123.arcgis.com/), ArcGIS Field Maps (https://www.esri.com/en-us/arcgis/products/arcgis-field-maps/overview), or open source tools like ODK Collect (https://getodk.org/) have become robust disaster response toolkits for damage assessment.

In the United States, the Civil Air Patrol (CAP, https://www.gocivilairpatrol.com/) leads emergency response and disaster relief operations in partnership with the Federal Emergency Management Agency, the US Air Force, and local emergency management entities. CAP maintains its own Geospatial Program (https://gis.cap.gov).

3.3 Recovery

When the immediate aftermath of an event subsides, also inherently spatial, recovery process, defined as: “the restoring or improving of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development and “build back better”, to avoid or reduce future disaster risk” begins (United Nations Office for Disaster Risk Reduction (UNDRR), 2022a).

Recovery provides numerous opportunities for the use of GIS&T. For example, spatial activities such as the use of networking algorithms can be used for defining service areas and routing for debris cleanup and removal (Dymon & Winter, 2012; United States Environmental Protection Agency (US EPA), 2019). GIS&T can also play in pivotal role in cost recovery, resource allocation and recovery decision making (c.f. Meyer, 2021; Yang & Jahan, 2018). Additionally, humanitarian uses of GIS&T for recovery such as story mapping techniques can be used to develop a sense of community, and restoration of place and rebuilding, especially in cases where an event has caused long lasting physical, social, psychological or other types of damage. For a case study on using Esri's Story Maps for helping Syrian refugees rebuild their lives, see Tomaszewski (2019).

3.4 Mitigation

The goal of disaster mitigation is "the lessening or minimizing of the adverse impacts of a hazardous event." (United Nations Office for Disaster Risk Reduction (UNDRR), 2022b), a goal that engenders several GIS&T workflows. For example, the predictive and modeling aspects of GIS&T are particularly well suited for disaster mitigation. More specifically, the development of spatial models of risk, vulnerability, and resilience have seen widespread attention in the literature over the past 20 years. Most notably in this regard are indexes such as the social vulnerability index or SoVi which makes a particular focus on the human impacts (and preventing those impacts) from disasters. The SoVi is calculated within geographic administrative units such as US counties or Census tracts using Census population indicator variables (such as age, gender, and economic status) to develop an index or score related to a particular level of vulnerability. However, indicators like the SoVi are calculated at somewhat coarse spatial resolutions (i.e, US Census tracts) and do not incorporate any modeling of physical risk. To better understand GIS&T-based vulnerability and resilience research using indicators, good starting points are Cutter et al. 2003 and Cutter et al. 2010.

Remote sensing approaches such as LiDAR are commonly used for modeling physical risks such as floods (Mihu-Pintilie et al. 2019; Muhad et al. 2020, Smith & Alexander, 2018). Remote sensing approaches have also become ubiquitous to catastrophic modeling in support of the larger disaster resilience, insurance and risk management sectors to better assess damages to expedite payouts, model current and future risks for insurance ratings, and quantify the relationship between earth and human systems to improve adaptation planning and mitigation effectiveness (Alexander et al. 2019; Botzen et al. 2020; and Franzke et al. 2022).

4. Future Trends

4.1 New Technologies and Developments

Artificial intelligence and machine learning have already become well-established and prevalent in both the broader computing world and disaster management practice. Such achievements now allow even further advances, such as the use of **digital twins**, where virtual models are designed to reflect real-world objects at levels such as temperature, energy outputs and more. From a disaster management perspective, a digital twin could serve as a complete virtual copy of a city to simulate the effects of a disaster, going far beyond the existing practices of table top exercises or traditional 3D digital models (Ford & Wolf, 2020).

As discussed previously, foundational and open data like HFLID has the potential to revolutionize how the access to geographic information will transpire in the future disaster management practice. Beyond simply providing data sets to those who need it, foundational data can address long-running challenges of data standardization and data interoperability for large-scale events that cross jurisdictional boundaries where multiple organizations will need to communicate and find common ground in order to effectively manage a given event. For example, open data resources have been used to address the COVID-19 pandemic (National Institutes of Health, 2020).

Expanded and novel uses of social media will continue to serve an important role for filling location-based gaps in situation awareness while balancing issues of trust, reliability, and rumor control (c.f. (US National Library of Medicine, 2019).

The integration of GIS&T into cybersecurity practice will also continue to gain further importance for risk management and integrating physical and virtual spaces as threats arise (e.g., Brode, 2021).

4.2 New Problems and Opportunities

Finally, there is a concurrent dual tension of new problems facing global society that are geographic in nature and opportunities that will concurrently exist to address those problems. Drivers that are impacting global society on all levels include climate change, terrorism and extremism, political instability, and changing social demographics. Additionally, rapid acceleration of technology is seeing a convergence between emerging threats/hazards and technology such as misinformation and fragmentation of society created through social media, such as the need to control false rumors spread on social media during a natural disaster (Federal Emergency Management Agency (FEMA), 2017).

Meanwhile, as geo-based observational technologies become more prevalent and invasive, and larger segments of society are impacted by disasters, well-established concerns with privacy, ethical and civil liberty will continue to be raised.

Of course, climate change is producing bigger and more frequent natural disasters. The COVID-19 pandemic revealed how vulnerable global economic and social systems are to disease outbreaks and it is certainly possible that another pandemic could come again in the future. Finally, many of these drivers are leading to increased forced displacement whether because of armed conflicts or climate change, such as seen in 2021 with vast groups of migrants on the southern border of the United States fleeing both violence in Central America and impacts from natural disasters.

With these challenges, however are new opportunities. GIS&T usage is now widespread within governments around the world; it is no longer considered a disruptive technology but rather an invisible, essential technology that drives all aspects of disaster management. More efforts are being made at including geospatial technology education in university practice and practitioner practice. The aforementioned increase of open and foundational data will create additional opportunities for the use of reliable and valid data sets that can be shared among organizations, always important as disaster events do not recognize international or organizational boundaries. Furthermore, GIS&T can support the advancement of diversity, equity and inclusion toward better addressing the needs of low capacity communities and better understanding the vulnerabilities. For example, the Department of Housing and Urban Development (HUD) provides geospatial datasets specifically tailed for community development (https://hudgis-hud.opendata.arcgis.com/), and even children can become involved in participatory mapping for disaster risk reduction (De et al. 2020).

The mobile technology of smartphones, cloud computing, and the ease of developing and using web apps has forced traditional mapping via desktop GIS to become a minority practice. Although many challenges still exist, there are incredible opportunities to bring GIS&T and disaster perspectives to the developing world that ideally will lead to better local capacities to handle events when they occur and ultimately save lives.

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