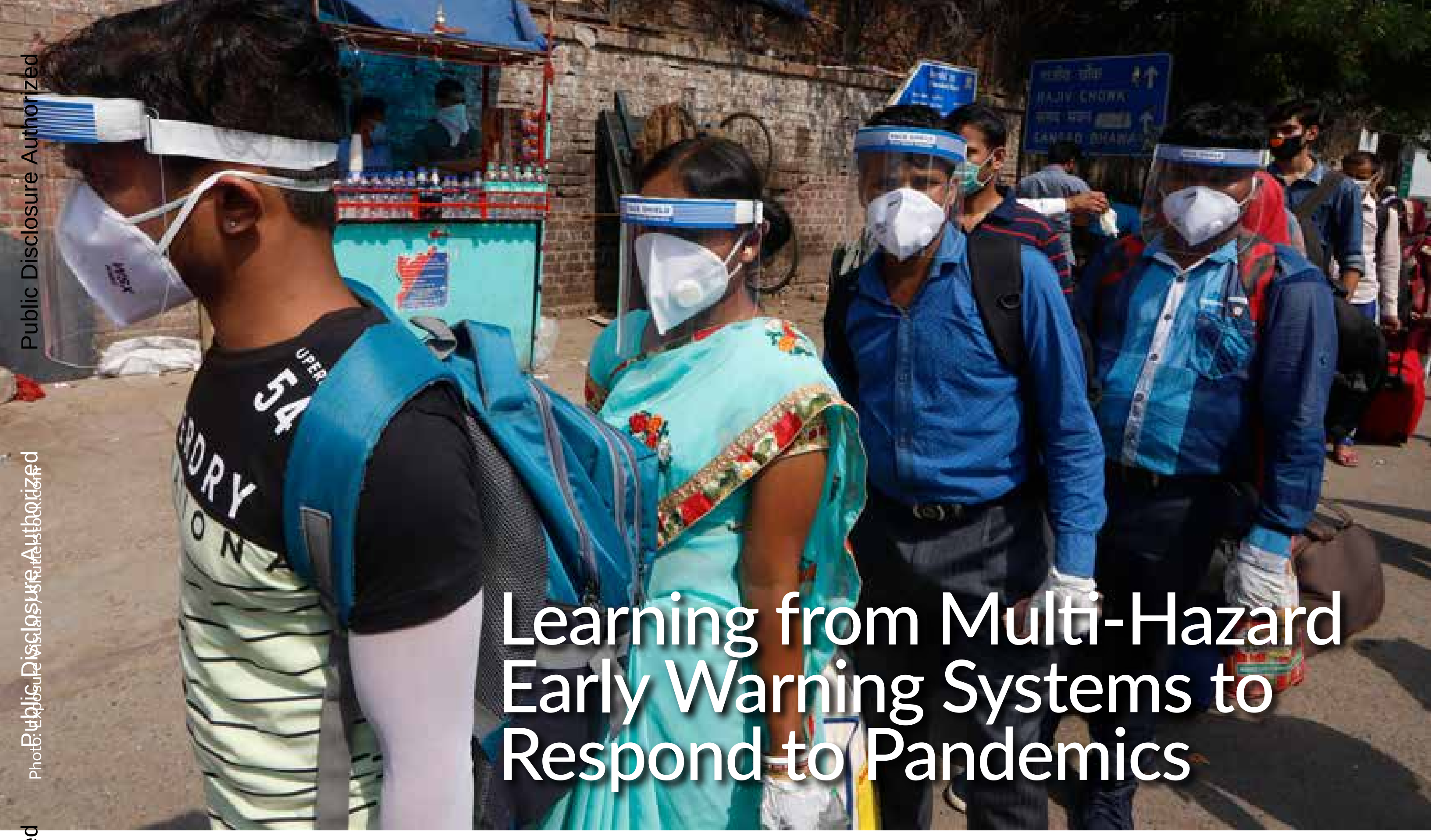

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Learning from Multi-Hazard Early Warning Systems to Respond to Pandemics

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Abstract. Having a common framework for early action to cope with complex disasters can make it easier for authorities and other stakeholders, including populations at risk, to understand the full spectrum of a disaster's secondary and tertiary effects and thus where to focus preparedness efforts, and how best to provide more targeted warnings and response services. Meteorological and hydrological services worldwide have developed and implemented Multi-Hazard Early Warning Systems (MHEWS) for weather- and climate-related hazards; these are now being expanded and transitioned toward Multi-Hazard Impact-Based Early Warning Systems (MHIEWS). While it is still early, it is becoming clear that this approach has useful lessons for the COVID-19 global pandemic, and some valuable insight to be gained in risk communication, risk analysis, and monitoring methodologies and approaches. The ability to understand and respond effectively to warnings through appropriate behaviors and actions is central to resilient societies and communities. By avoiding physical, societal, and economic harm to the greatest extent possible, recovery from a hazard is likely to be faster, less costly, and more complete.

MHIEWS can be a common approach for all hazards and therefore is more likely to become a trusted tool that everyone can understand and use as a basic element of their national disaster risk management system. The interconnectedness of hazards and their impacts is a strong motivator for a common approach. One of the lessons from both the COVID-19 pandemic and extreme weather events is the need to understand the vulnerability of individuals, communities, and societies so as to provide reliable, targeted guidance and warnings and ensure the willingness and capacity to prepare for a reasonable worst-case scenario based on informed long-term planning. Meteorology and hydrology are making good progress in this direction, and the process can be readily applied to health and other sectors.

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1. Introduction

The COVID-19 crisis and extreme weather events each provide important lessons in understanding risk and creating effective Multi-Hazard Impact-Based Forecast and Early Warning Systems (MHIEWS). Over the past decade, meteorology has made significant progress in applying the likelihood of occurrence and impacts to early warning systems. An important tenet of the probability- versus- impact matrix (**Figure 1**), which is a commonly used qualitative assessment method, is to be prepared for a very-low-probability, high-impact event. This leads to the related concept of the "reasonable worst case," for which good risk management requires us to be prepared. Examples of preparedness and anticipatory action would be ensuring that economic safety nets are in place, ensuring the availability of personal protective equipment and access to ventilators to cope with complications of a pandemic; reinforcing shelters to protect vulnerable people from the impact of storm surges or flooding caused by tropical cyclones; and cleaning drainage systems to reduce flood impact on communities.

The probability-versus-impact risk matrix is used in the national risk assessments carried out by many countries and mandated by the European Union for Member States.[1] The Joint Research Council of the European Commission has published recommendations for national risk assessment and disaster risk management in the European Union that incorporates a similar impact/probability matrix approach to mapping risks.[2] What is evident, however, from both publications (and presumably in national risk assessments from many other countries) is that the risks arising from different sources are largely treated independently, with little consideration of the potential societal and economic consequences that ensue as one hazard begets another, or as multiple independent hazards happen at the same time. In the world of meteorology, however, the move toward

Abbreviations

CAP
Common Alerting Protocol

DSS
decision support systems

GMAS
Global Multi-Hazard Alerting System

MHEWS
Multi-Hazard Early Warning Systems

MHIEWS
Multi-Hazard Impact-Based Forecast and Early Warning Systems

PM
particulate matter

UNDRR
United Nations Office for Disaster Risk Reduction

WMO
World Meteorological Organization

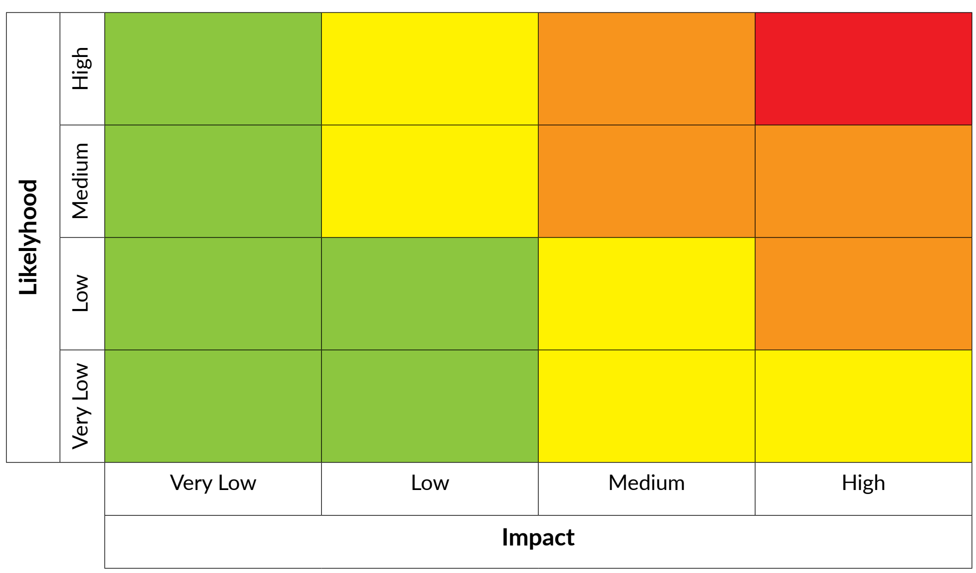

Figure 1.
A probability versus impact matrix for any hazard. The colors are assigned based on an assessment of the risk, which typically has four categories: very low (< 20%, green), low (20–40%, yellow), medium (40–60%, orange), and high (> 60%, red). In practice, only the right half of the matrix is considered—that is, when the impact is medium or above.

[1] See, for example, the National Risk Assessment for Ireland, available at https://www.gov.ie/en/publication/709bf3-a-national-risk-assessment-for-ireland-2017/.

[2] See https://ec.europa.eu/jrc/en/publication/recommendations-national-risk-assessment-disaster-risk-management-eu.

Impact-Based Forecast and Warning Services (WMO 2015) has prompted an explicit examination of the inter-relationships between natural hazards, vulnerability, and risk in thinking through the possible consequences of a severe weather event. Typically, the recovery and rebuilding efforts in many island nations, for example, take three to five years—or even longer if the areas are remote. It is worth noting that some of these events (for example, Hurricane Maria in Puerto Rico, or any drought event) have permanent impacts on those societies that are the least resilient (Rogers et al. 2018). In many countries, similar impacts may be anticipated from COVID-19.

In the case of each potential hazard, a simple theoretical analysis of rational decision-making suggests that proactive action should be taken if the forecast probability of a life-threatening event is greater than the ratio of the costs of protection (for example, infrastructure investment) and the losses when no protective measures are taken and an event occurs (for example, loss of life, damages, economic disruption) (de Perez et al. 2015; Palmer 2019; Murphy 1969). The COVID-19 pandemic reveals in hindsight that the costs of mitigation were very small compared with the losses and therefore more should have and could have been done to mitigate the risk (Harford 2020). However, optimism bias, or our tendency to underestimate the impact of the highly improbable (Kahneman 2011; Taleb 2010), compounds our inability to be prepared. These traits also illustrate the challenges in anticipating the wider societal implications of natural hazards and the complications in estimating the potential impacts and costs, and they throw into sharp focus the value judgments that must be made in balancing protection costs against human and economic impact.

Early detection, early warning, and early action are also important precepts as ex ante mitigative actions cannot completely eliminate risks. Early detection and early warning enable early action, but the latter will occur only if there is a clear understanding, based on rigorous risk assessment, of the potential impact, which must include the range of environmental and societal consequences and a complete understanding and acceptance of the need to act on high-impact events, even if the probability of occurrence is very low. The actions may differ depending on the likelihood of the event, but the impact will be the same if the event occurs. In practice, we should be ready to undertake preparatory actions for all medium- and high-impact events. The definition of high, medium, and low impact is hazard-specific and determined by collecting impact data and through expert opinion and analysis.

Meteorology has developed the capacity, largely through ensemble forecasting methods, to apply probabilistic forecasting techniques to its warning systems, and it has sophisticated tools to ensure the reliability of the system (Palmer 2019).

Meteorology has developed the capacity, largely through ensemble forecasting methods, to apply probabilistic forecasting techniques to its warning systems, and it has sophisticated tools to ensure the reliability of the system (Palmer 2019). Similar approaches are also being applied to epidemic forecasts using multi-model ensemble techniques, which produce broader and more realistic possible trajectories of epidemics (Chowell et al. 2020). Probabilistic forecasting of complex cascading catastrophes remains a challenge, but it is one that must be addressed. We are still vexed with the problem of forecasters not having sufficient confidence to issue guidance or warnings for low-likelihood events, even when its potential impact is high. Some of this is down to the "boy-who-cried-wolf" syndrome, but some is also down to the limited ability of humans (and all forecasters are human!) to imagine an event completely outside their own experience, and thus to warn for that event.

Ironically, many users are much more likely to want and use probabilistic information because most will base their decisions on their understanding of their own costs and potential losses. For example, farmers in Bangladesh, risking the loss of livelihoods, do act on the very low or low probability of a high-impact event to avoid or mitigate losses (Webster et al. 2010). This action could take the form of moving livestock to higher ground or taking out an insurance policy. In the first case, they are responding to the warning, and in the second to the risk analysis. Providing cash to households based on forecasts of extreme events is another approach (Gros et al. 2019). The different responses of countries to the COVID-19 pandemic, especially those having difficulties managing caseloads, suggests that a more rigorous approach to understanding the full spectrum of risk is needed.

This inability to accept low-probability, high-impact situations must be overcome if the benefits of MHIEWS are to be realized and highly adverse impacts avoided or mitigated. Reliably identifying a low-probability, high-impact flood hazard five to seven days ahead, for example, would allow civil protection agencies to prepare resources in this time frame professionally and without stress. If their reaction is based only on high-probability forecasts, making resources available in the necessarily shorter time frame is much more stressful and, in most cases, also costlier. From the public perspective, high-probability forecasts have a greater chance of being accepted and reacted upon, thereby building more trust in the authorities and MHIEWS. Taking COVID-19 as an example, the low-probability time frame in Central Europe concerned politicians as the decision-makers, who could have saved time and money by gathering and improving response capacity. The high-probability scenario started around early March, where the focus should have been on modifying public behavior, accepting hygienic measures, and imposing lockdown and social distancing. The scramble in many countries to acquire personal protective equipment during the high-probability phase of the hazard highlights the failure to act on the low-probability scenario and the dire consequences for frontline workers.

These basic concepts must be kept in mind as we explore MHIEWS in more detail. Decision-making for low-probability, high-impact events is often hindered by the fact that government decision-makers are focused day-to-day on solving high-probability, relatively minor but media-relevant problems that divert attention from the potential catastrophic impact of low likelihood events.

2. Multi-Hazard Impact-Based Forecasting and Early Warning Systems and Services

During the past decade, considerable attention has been focused on developing, implementing, and improving multi-hazard early warnings systems and—especially in the context of meteorological forecasts and warnings—extending this concept to include impact-based forecast and warning services (Tang et al. 2012; WMO 2015) and to specific sectors, including health (Ghebreyesus et al. 2008). A common methodology has evolved, which ultimately aims to provide guidance to people at risk and those responsible for mitigating those risks in a form that is understandable and actionable. MHIEWS are designed to support the early alerting of governmental and nongovernmental decision-makers, thus permitting preparatory steps to be taken before public warnings are issued. This approach requires combining information about specific hazards with the likely impacts of those hazards on people, livelihoods, and property. It is also essential to understand the cascading effect of hazards, where a single natural event may have a multiplying effect resulting in primary, secondary, and tertiary hazards. For example, a meteorological event such as a tropical cyclone produces heavy rainfall, which in turn causes flooding that disrupts transportation networks, energy supplies, and other critical infrastructure, that causes loss of life or physical harm, social isolation, interruption to employment and livelihood activities, and psychological distress. COVID-19 follows the same pattern, bringing about major social and economic hazards and consequential impacts.

Tang et al. (2012) stress the importance and effectiveness of a multi-hazard approach to disaster reduction by understanding how hazards can produce a series of social consequences that are also public hazards themselves. The emphasis on impacts implies that warnings should be related to multiple hazards, since the initial event can cause a series of cascading threats or consequential effects—public health deterioration, accidents, infrastructure damage, civil unrest, food insecurity, and so on. Ideally, each of these should also be considered and the means to predict their likelihood developed, so that a more complete modeling of impacts can be achieved. Unfortunately, despite the demonstrated usefulness of the concept in meteorology and the best efforts to date (IFRC 2012; WMO 2019), multi-hazard impact-based early warning systems have remained primarily focused on hazards of meteorological origin. A renewed effort is needed to make MHIEWS fully multisectoral, inclusive of biological hazards regardless of the cause of the underlying events (Yao et al. 2020b). This is an important part of a more effective and streamlined disaster risk management plan.

In all MHIEWS, the ultimate aim is to provide people with information that they understand, trust, and act on. The pandemic crisis highlights the importance of trusted sources of information (Hua and Shaw 2020). This suggests the benefits that would flow from a common framework for all warning services that emphasizes the impact of the hazard rather than the technical jargon that normally accompanies the description of the hazard itself. In meteorology, the emphasis is shifting from "what the weather will be to what the weather will do"; this can be generalized to any natural, socioeconomic, or technological hazard by focusing on the impact of the hazard. This shift has come about because, despite huge technological advances in forecasting meteorological and hydrological haz-

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ards, we continue to suffer major human and economic losses because of an incomplete awareness and understanding of the potential breadth and depth of the impacts of those hazards. Similarly, although COVID-19 has unique epidemiological aspects, it is a known class of virus and the behavior of a pandemic can be modeled, with advice, guidance, and warnings issued based on detection (observation) or model forecasts (see, for example, Chowell et al. 2020). However, the actions taken by many governments suggest any or all of the following: warnings have not been heeded; the risks have been poorly understood and/or discounted; funding mechanisms to take early action are lacking; capacity is lacking to do the things that need to be done, even if the money is available; and long-term planning to make the best use of the warning is lacking. Unfortunately, this is a common theme for many hazards and a major obstacle in achieving the goals of the Sendai Framework for Disaster Risk Reduction (United Nations 2015). The response to hydrometeorological hazards provides some insight and, through generalizing MHIEWS concepts, we may be able to identify a way forward.

Each year the impacts of severe hydrometeorological events around the world give rise to multiple casualties and significant damages to property and infrastructure, with adverse social and economic consequence for communities that can persist for many years. All this happens in spite of the fact that many of these severe events are recurrent and have been well forecasted, with accurate warning information disseminated in a timely fashion by the responsible authority.

The reasons for this apparent disconnect and the failure of this information to be fully utilized to support effective defensive action and mitigation decisions lie in the gap between forecasts and warnings of the hazardous events on one hand and an understanding of the risk associated with the potential impacts of those events—both by the authorities responsible for civil protection/emergency management and by the population at large—on the other. The forecast and warnings information should be disseminated in a range of formats and styles and across as many communication platforms as are appropriate to the recipient audience. The content and context of the information needs to be believed and trusted as coming from an expert, skilled, and non-biased source and, when it is confirmed with secondary sources, it should be consistent in its message. It is important that the recipient at-risk audience be prepared to accept and enabled to act on this information (Anderson-Berry et al. 2018).

If the gap between forecast and warnings information and effective loss-minimizing actions is to be closed, then an all-encompassing approach is needed to observe, detect, model, and predict severe events and the consequent cascade of hazards through to impacts. Tackling this problem requires a multidisciplinary approach to identify, understand, assess, and address risks. This requires access to the best possible physical, social, and behavioral scientific and humanitarian sector understanding, as well as the optimum services, to manage multi-hazard events. This approach will provide the best possible evidence base on which to make the costly decisions about infrastructure and other preventative investments needed to protect the population in the future.

All countries should provide their citizens and economic sectors with actionable information that, wherever possible, identifies the timing and anticipated impacts of specific hazards. An informed population that fully understands what a hazard will do is more likely to engage in appropriate behavior and take the necessary actions that protect their lives and livelihoods (WMO 2020). Clarity and trust in communication is essential, especially when the likelihood is very low or low, but the potential impact is very high.

In the case of meteorological hazards, the meteorological and hydrological services must work closely with emergency services, disaster reduction, and civil protection agencies to share data and to interpret forecasts in a form that results in early warning and early actions by everyone (Rogers and Tsirkunov 2013; Rogers et al. 2019). It is important that local authorities and agencies with an understanding of community dynamics, physical and societal infrastructure, and social networks are included in this working partnership. They will have extensive knowledge of the vulnerability of individuals and community sectors and of both formal and informal communication networks, and they will have the ability to engage multiple stakeholders. They will also have valuable insight around and the likely behavior of people during an emergency. This is a new area for many meteorological and hydrological forecast and warning services, since it requires extensive knowledge of how meteorology and hydrology affect day-to-day activities. None of this knowledge and awareness may be available to the weather service providers in developing countries, some of which already struggle to produce basic meteorological and hydrological forecasts and services. Coproduction of these new warning services involving all key stakeholders is required (WMO, no date).

The same issues apply to health-related and technological hazards, and therefore all of society would benefit from a common approach to the development of multi-hazard early warning and response systems. Given that pandemics, tropical cyclones, tsunamis, heat and cold waves, and droughts may affect many countries simultaneously, and also that the cascading impacts of a hazard even in a geographically confined area can have global consequences (as was the case with the 2011 flood in Thailand for the global supply chain for hard disk drives), international cooperation at the highest levels of government and industry is an important element of ensuring that tools are available and responses appropriate, as evinced by the COVID-19 pandemic (Kluge 2020). The disaster management laws of many countries cover epidemics or pandemics as disasters; therefore, integrating epidemics and pandemics in MHIEWS is a rational approach to improve coordination, forecasting, warning, and response. Samoa, as an example, did this for the measles outbreak that affected the country in December 2019, which in turn enabled them to take early action as COVID-19 started spreading into the Pacific.

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3. Basic Elements of MHIEWS

Because the goal is to provide guidance to people at risk and to those responsible for mitigating those risks in a form that is understandable and actionable (IFRC 2012), combining information about specific hazards with the likely impact of those hazards on people and on their livelihoods and property is required. Depending both on the knowledge of the hazard and on the vulnerability and exposure of people, the approach may be either qualitative, depending on expert knowledge, or quantitative, depending on measurement.

A MHIEWS has five basic steps: (1) a common framework for visualizing warnings, (2) hazard identification, (3) exposure and vulnerability assessments, (4) risk matrices, and (5) advisories and alerting. These are described in detail below.

3.1. A Common Framework for Visualizing Warnings

Mapping the distribution of hazards and impacts geographically, depicting administrative boundaries as polygons to present the location of the hazard and impact, is the preferred approach. Each of these polygons or grid cells may have its own granular structure portraying a much finer mesh and facilitating more detailed warning information. The advantage of mapping administrative boundaries is the presence of public officials who have a responsibility for public safety in each of the "grid cells." The apps developed in several Asian countries to trace people potentially exposed to COVID-19 lend themselves to this approach, albeit with data privacy issues, which must be resolved (Cho et al. 2020; Hern 2020). A major obstacle that needs to be resolved is to balance privacy and the use of personal data in such systems with the overall public good that can be attained through their deployment. In any case, it is important that individuals receive reliable information that they can trust and act on.

A major obstacle that needs to be resolved is to balance privacy and the use of personal data in such systems with the overall public good that can be attained through their deployment.

Meteoalarm, as an exemplar of a common framework for warning services in the sphere of hydrometeorology, has extended the visualization of such warnings to all of Europe using consistent colors to represent the severity of the hazard, together with a standard set of symbols for each of the meteorological hazards—wind, rain lightning/thunderstorms, heat, and snow/ice (Staudinger 2008)—that are displayed to show the type of hazard (Figure 2).

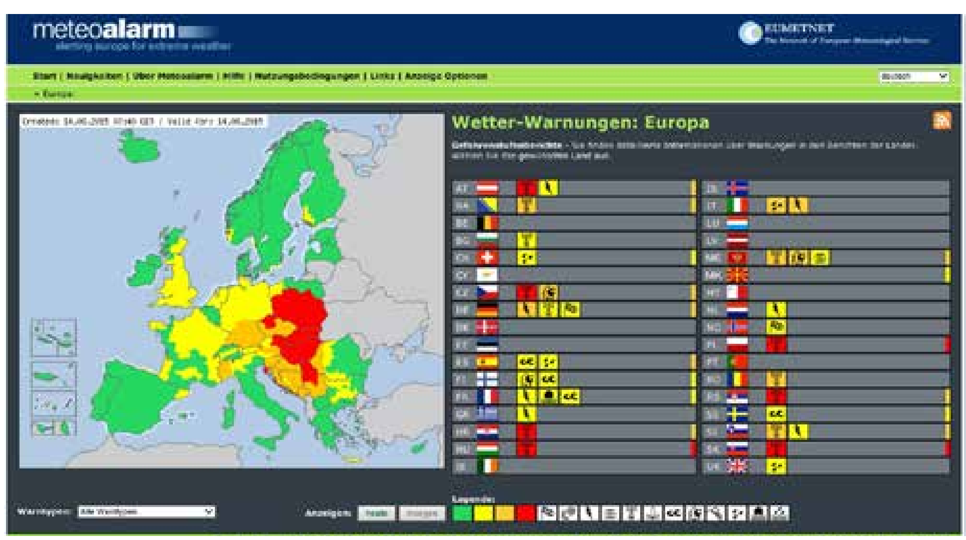

Figure 2.
Example of the graphic output from the Meteoalarm portal. The color coding is consistent across all participating European countries.

This approach could be readily extended to all hazards and could have been of significant benefit in visualizing the dynamic development of the COVID-19 pandemic across Europe. Plans exist to extend the concept of Meteoalarm beyond Europe through the World Meteorological Organization's Global Multi-Hazard Alerting System (GMAS) and through World Bank investment projects aimed at transforming national meteorological and hydrological services, which include the use of the Meteoalarm concept and software.

Figure 3 shows the detailed warning system for Germany, which could be emulated in any country. More effort is needed to include a wider range of hazards and their impacts.

Ultimately the color coding should be related to the impact of the hazard rather than the hazard itself, as depicted in the risk matrix in Figure 1, reflecting the shift in emphasis to actionable information for those at risk. In Wuhan, a color-coded QR code was used to inform the public on safety, with green indicating safe, yellow indicating a need to be cautious, and red indicating "cannot enter" (Hua and Shaw 2020), which largely follows an approach first introduced into China for meteorological warnings in Shanghai (Tang et al 2012).

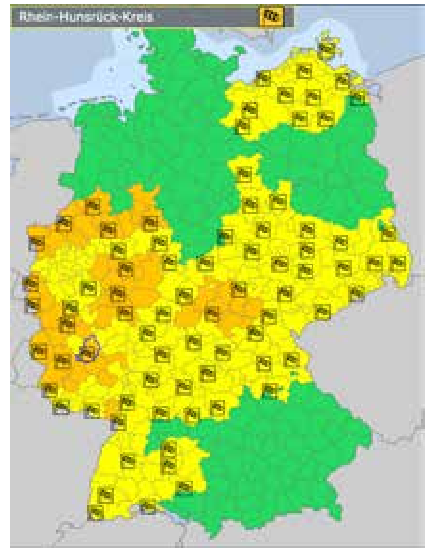

Figure 3.
Example of the German weather service (Deutscher Wetterdienst) warnings displayed using Meteoalarm

3.2. Hazard Identification

The identification of all events and the primary and secondary hazards impacting the territory of a country is ideally required. Primary hazards are directly caused by the event in nature and cannot be mitigated to any significant extent (for example, rain will fall, a virus will exist). Secondary hazards are a consequence or impact of the primary hazard and can often be partially mitigated (for example, structural works can reduce the possibility of a surface flood in an urban area, or hospital equipment can be stockpiled). Tertiary hazards may be caused by the primary and secondary phenomena or may be a consequence of human failure and will have substantial societal impacts. Tertiary hazards may also evolve from efforts to mitigate the primary (natural) and secondary hazards. The societal impacts have the greatest scope for mitigation by either structural or social measures to reduce exposure and vulnerability and build capacity and capability. In the case of secondary and tertiary hazards, the hazard and the impact of the hazard may be closely related and interconnected. Each of the hazards leads to further impacts, but not all impacts are associated with further natural hazards. For example, economic disruption can be caused by social behavior, which spreads disease, and the consequence of the economic disruption can have a significant impact on productivity and public financing, which in turn is a hazard with long-term impacts on poverty and the well-being of society. Table 1 summarizes primary, secondary, and tertiary hazards and associated high impacts for a virus, cyclone, and earthquake. The list of impacts is illustrative and not exhaustive. Impacts are generally place-specific and should be determined based on local knowledge.

Collecting hazard impact data is challenging and the data are often recorded in a very general way—for example, the number of affected people, which not useful for creating impact-based warnings.

Table 1. Example of events with primary, secondary, and tertiary hazards and associated impacts

<table>
<tr><th>Event</th><th>Primary hazards</th><th>Secondary hazards</th><th>Tertiary hazards</th></tr>
<tr><td rowspan="2">Virus</td><td>• Infectious disease</td><td>• Disease spread by human behavior
• Economic disruption</td><td>• Overwhelming of health services
• Loss of productivity
• Public finances overwhelmed
• Loss of education opportunities
• Unemployment
• Civil disobedience
• Psychological problems</td></tr>
<tr><td colspan="3">High impacts:
Excess number of deaths caused directly by virus and indirectly by overwhelmed health services
Civil disobedience resulting in increased rates of disease transmission
Severe disruption to global economy resulting in severe financial losses and economic recession
More people in poverty
Food insecurity, especially in the poorest communities, increasing morbidity
Increased crime related to loss of income and exploitation of crisis
Civil unrest potentially destabilizing societies
Restructuring of social priorities
Increased international tensions resulting in conflict</td></tr>
<tr><td rowspan="2">Cyclone</td><td>• Strong wind
• Lightning
• Heavy rainfall
• Tornado</td><td>• River flood
• Surface water flooding
• Flash flood
• Landslides
• Storm surge
• Water level rise in reservoirs
• Riverbank erosion
• Mudslides</td><td>• Damage to dams and appurtenant structures, embankments, irrigation and drainage facilities, pumping facilities
• Submerged paddy fields
• Migration
• Loss of infrastructure systems and services (shelter, transportation, schools, hospitals, energy supply, communication)
• Waterborne diseases
• Environmental degradation
• Snake bite
• High sediment transport into reservoirs</td></tr>
<tr><td colspan="3">High impacts:
Loss of property and livelihoods, resulting in increased poverty and homelessness
Excess number of deaths and injuries due to the event and subsequent disease outbreaks
Loss of agricultural land and potable water resources
Widespread food and water insecurity, especially in the poorest communities, increasing morbidity
Risk of theft of property results in people not taking shelter
Civil unrest and political instability
Severe disruption to transportation networks
Widespread population displacement</td></tr>
<tr><td rowspan="2">Earthquake</td><td>• Shake
• Shifting geological formation</td><td>• Landslides
• Building collapse
• Road and rail fracture
• Tsunami
• Fire
• Liquefaction</td><td>• Damage to dams and appurtenant structures, embankments, irrigation and drainage facilities, pumping facilities,
• Loss of infrastructure system and services (shelter, transportation, schools, hospitals, energy supply, communication)
• Coastal flooding
• Changes in groundwater formation
• Psychological problems</td></tr>
<tr><td colspan="3">High impacts:
Excess number of deaths and injuries due to collapse of homes, buildings, and other infrastructure
Widespread financial losses
Severe disruption to transportation networks
Widespread population displacement
Decrease in water storage capacity</td></tr>
</table>

3.3. Exposure and Vulnerability Assessments

Understanding who is at risk depends on gathering information on vulnerability and exposure. This involves many different entities, including social and behavioral scientists, disaster managers, nongovernmental organizations, civil and structural engineers, risk finance and risk transfer specialists, and, of course, those at risk. These data are an important layer of information within any decision support system. The responsibility for compiling and updating this information often falls to disaster managers and nongovernmental organizations, which work with mostly disadvantaged communities. However, these data are rarely compiled in a single operational database and are often incomplete and not of very high quality. Social and behavioral scientists are critical to understanding how differently abled people access, comprehend, and use warning and forecast information. Data need to be collected at the level of the individual and updated regularly.

The vulnerability of infrastructure systems and services must also be quantified. For example, the vulnerability of bridges and roads to inundation or destruction due to flooding, or the likely requirements for specialized medical equipment, should be estimated. Understanding sectoral interdependencies is also necessary to determine vulnerabilities and therefore to develop the appropriate impact-based forecasts and warnings. Addressing these vulnerabilities is a way to increase resilience and reduce the risk of disaster stemming from a failure to cope adequately with the primary and secondary hazards (Rogers et al. 2018). Not doing so can result in persistent and sustained loss of economic capacity (Moteff 2012). By understanding the vulnerability of the infrastructure system and services to the primary and secondary hazards, and the decisions that have resulted in mitigating actions—or not—it is possible to provide more accurate and timely impact-related warnings that would protect a population from existing weaknesses in infrastructure, which compound the threat of mortality and morbidity posed by the initial hazards. The collapse of buildings, bridges, and roadways; the loss of information and communications technologies (ICT), electricity, transportation, health services, employment, and sanitation; and the decision and opportunity for people to remove themselves from harm's way frequently contribute to creating, enhancing, or diminishing the circumstances of subsequent disasters. Already available vulnerability and exposure information on hydromet hazards can be used to analyze epidemic risk and its cascading impacts.

The societal impacts have the greatest scope for mitigation by either structural or social measures to reduce exposure and vulnerability and build capacity and capability.

3.4. Risk Matrices

Probability versus impact matrices are required for every hazard and each sector likely to be affected. Their development requires knowledge of the hazard and expert knowledge of the likely impact on a specific sector. This may or may not be informed by a formal vulnerability assessment. At its most basic, it would rely on expert knowledge rather than quantitative data. However, the range of expert knowledge required is broad, and is given not exclusively by those with knowledge of the primary hazard but also by experts in other fields that may be affected by the secondary and tertiary hazards.

The actions to be taken will depend on the likelihood and severity of the scenario, with a color assigned based on an assessment of the risk (**Figure 1**). Consequently, a disease outbreak or flood, which is highly likely to occur with severe impacts, is color-coded red for high risk. The designation of the colors is subjective and depends on a combination of sector-specific knowledge. Historical or climatology-based regional- and/or seasonal-specific thresholds (in the case of meteorology or hydrology) can provide a valuable starting point for discussions in estimating the severity and the impact of an event.

In the case of flood risk, this process may involve water resource managers, irrigation experts, and dam operators as well as disaster managers. The level of risk can be assigned to a specific geographical location—a grid box within the warning map— thereby building a dynamic risk map that highlights the areas that may require specific interventions to mitigate the risk— house-to-house notifications, cell broadcasts, evacuation to shelters, and so on. In particular, this risk map will help civil protection authorities deploy their resources more effectively. Since the system is dynamic, it is a way to progressively express changing expectations of risk as a function of varying exposure, vulnerability, and hydrometeorological likelihood. In the case of a tropical cyclone, for example, the flood risk would be identified based on the trajectory and intensity of the rainfall hazard within the event, among other factors. The risk matrix combines the flood and vulnerability information for each identified geographical section. As the tropical cyclone system evolves, the severity of the risk will change, enabling an adaptive response to the event. Each of the risks associated with the secondary and tertiary hazards would also be estimated.

Understanding sectoral interdependencies is also necessary to determine vulnerabilities and therefore to develop the appropriate impact-based forecasts and warnings.

Unfortunately, risk data management is almost nonexistent in many countries and alternative approaches are needed to acquire the appropriate data.

3.5. Advisories and Alerting

Warning advisories and action matrices are the final stage in the production process. These relate warnings and actions to the probability of an impact based on the impact-risk matrix. Effective standard operating procedures are a critical component of the successful management of risk. Key elements are good communication among all of the relevant stakeholders and timely action. Having a common impact framework is also very useful for complex disasters and can make it easier for authorities to take early preparatory action to focus their resources, and to provide more targeted warning services. For example, the complex consequences of multiple hazards are exemplified by the situation in Vanuatu, the Solomon Islands, and Fiji during April 2020, which faced the simultaneous crises of Tropical Cyclone Harold and the COVID-19 pandemic (Narayan 2020).

It is important that each advisory and message contains the same information and detail across all media—no matter what format is applied. This is fundamental to ensuring community members confidence in the authority, authenticity, and security of the messages they get. The Common Alerting Protocol (CAP) provides a format designed for any and all media to communicate information about any kind of hazard situation. It was developed to standardize the technical format of an alerting message, regardless of content, in a manner such that the alert message is both human-readable and machine-readable. The message can be targeted to the public at large, to certain designated groups such as disaster managers or first responders, or to specific individuals as needed. The African Telecommunications Union has called for harmonized actions by telecommunication regulators by implementing CAP as one element of a strategy to combat COVID-19 (APO Group 2020).

A message formatted with the CAP standard can be carried over or displayed by television, radio, mobile telephone, fax, highway signs, e-mail, the Web, and so on. The message can communicate about weather, fires, earthquakes, volcanoes, landslides, child abductions, disease outbreaks, air quality warnings, transportation problems, power outages, and so on, and can be fully integrated with the Meteoalarm system. While the technical specifications of CAP follow an international standard, CAP messaging can be modified and adapted to suit national requirements.

Without CAP, alerting systems must deal with free text or with different formats that vary across hazard types, and across countries as well. Without a standard alert format, it is practically impossible to implement all-hazard, all-media public alerting (WMO 2013). With the development of the CAP standard, effective and efficient alerting systems promise great benefits for relatively modest investments. Finally, alerting authorities can use fairly simple tools to get critical messages to affected people, wherever they are and whatever they are doing.

A warning and alerting service is successful when recipients receive the warning, via both formal and informal communication networks; understand the information presented; trust and believe the content, context, and message; personalize the information; are enabled to make correct decisions; respond in an adequate and timely manner; and provide feedback and lessons learned. Of these factors, understanding, trusting, believing, and personalizing the information are extremely important and lead to appropriate behavior, correct decision-making, and effective response by recipients (Anderson-Berry et al. 2018). Ineffective prior planning and preparation, haphazard and ad-hoc coordination among authorities to whom the population turns in times of crises, and the inability of authorities to articulate a uniform message can lead to lack of trust, confusion, and an inability or unwillingness to act by the public. This is exacerbated if warning language is too complicated, vague, ambiguous, or threatening, or is contradictory—as can happen if it originates from different sources.

A primary factor that prompts people to trust and act on advice contained in warnings and alerts is the credibility of the issuing authority. People often judge and trust authorities on their expert skill, their past performance, and, on occasion, their freedom from political agendas and interference. This has been demonstrated variously across many nations in the COVID-19 pandemic and the reliance on information directly from health experts and authorities. Without trust and respect for authorities, it becomes difficult to convince a population that the authorities have their best interest at heart and that whatever instructions are being issued are ultimately for their well-being. A MHIEWS, which performs well in the cases of relatively frequent, low-level warnings (as is the case for most meteorological hazards), is perceived by the public as a reliable source of information. Therefore, the system is a trusted and reliable source of warnings for the rare, but extremely damaging events.

4. Decision Support

MHIEWS alone are necessary, but not sufficient, tools in making effective decisions. Disaster management for all types of hazards must cover three broadly overlapping areas: (1) action in real time to an immediate emergency situation, recovery, and rehabilitation planning, and implementation; (2) early action planning and activation, triggered by impact-based warnings of a threat with as much lead time as possible to effectively reduce or eliminate the risk to life, livelihoods, and property, and to prepare for effective response; and (3) long-term planning and action to permanently eliminate or significantly reduce risks and to enhance effective preparedness.

Each of these three areas has a distinct and unique focus. Emergency response requires situational awareness and the tools to make real-time decisions, which reduce the exposure of those at risk through evacuation, sheltering, rescue, self-rescue, or the elimination of the threat if it is technological in origin. Anticipatory action implies advanced notification of a hazard and awareness of its potential impact. Lead-time, understanding, acceptance of the threat, and the ability and willingness to take action are all among the factors that play a role in the effective reaction to a warning where the aim is to reduce the potential for a full-scale emergency situation and need for a disaster response. Long-term emergency planning must have the primary goal of building resilience, capability, and capacity to respond to emergency management authorities and at-risk communities and societies. This planning involves establishing robust protocols between disaster management at all levels and the relevant technical, societal, and community welfare agencies and authorities to enable the reception of warnings related to hazards, facilitate processes to communicate these warnings effectively to at-risk communities, and organize routine exercises to ensure the smooth operation of the warning system. Underlying each of these areas is knowledge of hazards, vulnerability, and exposure, which also contribute to long-term planning to reduce vulnerability and thereby reduce the risk of an adverse impact.

Understanding the differentiated responsibilities of each of the actors involved in all three areas is essential for supporting the safety of lives and promoting the economic security of any country. Decision support systems (DSS) must provide guidance to all three areas. Information exchange and sharing among agencies is critical to the utility of a DSS and clear operating procedures are needed to ensure information flows unimpeded and enabling hazard, vulnerability, and exposure data to be combined with other guidance to promote timely action. The United Nations Office for Disaster Risk Reduction (UNDRR) provides guidance at national and regional levels on how government agencies from different sectors should work together to cover early warning, disaster response and recovery and long-term planning to mitigate the impact of disasters (UNDRR 2020a). A key module of a disaster management DSS is the resources for response at various levels. In many instances, the information on resources required to respond to a health emergency are not collected and included in such databases. While the response to a health emergency could benefit from the available data/information as part of a DSS, during the design and development of DSS, the resources needed to respond to a health emergency must be included.

Knowing who to warn requires knowledge of the hazards; knowing where to focus attention on refining the hazard warnings requires knowledge of the vulnerability and level of impacts. Consequently, all actors need to share data and information and collaborate closely to generate targeted and actionable information. Vulnerable disadvantaged and marginalized groups are often overlooked in the decision-making process. These include people with a range of physical, mental, social, and psychological disabilities who need earlier warnings to take action, tourists with no knowledge of local hazards and risks, minority populations, and migrant workers or refugees with limited access to local information systems or limited knowledge of the local language (UNDRR 2020b). It is extremely important to have an adequate information system that includes information on vulnerable groups, as they are among those most at risk during any kind of hazardous event, and the decision-makers who can activate early actions based on warnings. Decision-making should take into account people who have no access to information or to any mitigation tools, including financial tools, and who are not part of the decision-making process. Strategies should also be devised to minimize the numbers in this cohort through awareness-building campaigns.

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A DSS must encompass, therefore, providing for the internal information requirements of all government actors, as well as generating the guidance needed by nongovernmental decision-makers and the general public. The basic building blocks of a DSS are based on MHIEWS, which includes communication modules and a common data repository that allows multiple users to derive products relevant to their own requirements and to enhance the overall functionality of the DSS. This repository would comprise vulnerability and exposure information and data on primary, secondary, and tertiary hazards and impacts; an alerting module based on impact-based warnings; an external communication module that facilitates the onward promulgation and exchange of information with the public or affected sectors or both; the means to share information with other systems supporting emergency operations (including the media and emergency planning); and clear operating procedures adhered to by all stakeholders.

Essential to the system is consistency and trust. Warning services must be consistent and must engender trust in order for people to take appropriate action (Hua and Shaw 2020). The messages must be understood and actionable. This requires a common understanding of threat level across all hazards and impacts. Increasingly it also means that people need to understand that a low likelihood of medium and high impact events may also require a response from all those potentially affected. This requires a strategy for frequent exercises based on realistic scenarios, which should also be an element of the DSS since it will increase knowledge of vulnerability. In turn, this will help improve the utility of impact-based warnings. It is also particularly important after each event to review the performance of the system and gain feedback from users to further improve the system.

Generally, hazard impacts are localized. The DSS must therefore support decision-making at all levels of government (national, regional, local) and must have clear operating procedures in place to facilitate sound decisions at each level and between all agencies. The structure and flow of information should aim to make emergency response unnecessary by encouraging and guiding appropriate behavior of the people affected. In many circumstances, the notion of self-rescue applies—meaning those impacted will have the capacity to take appropriate actions to reduce adverse risk with minimal or no intervention from authorities. This is an important point. If a warning is issued with sufficient lead time, many people who have options with friends and family will self-evacuate. This will significantly reduce the cost to the government and will allow the government to accommodate the most vulnerable people, who do not have such options, in shelters. Again, consistency and trust of the warning information is critically important in facilitating appropriate individual and community actions, together with an empowerment of citizens through the provision of clear and actionable guidance.

5. Conclusions

The ability to understand and respond effectively to warnings is central to resilient societies and communities. By avoiding physical, societal, and economic harm to the greatest extent possible, recovery from a hazard is likely to be faster, less costly, and more complete (Rogers et al. 2018). Meteorological services have demonstrated that impact-based forecast and warning services based on the fundamental elements of a well-trusted, people-centered warning system can complement traditional warning systems and services by translating technical knowledge into actionable information directly relevant to those affected. The use of probabilistic techniques gives us insight into the likelihood of a hazard, and we can use this knowledge, coupled with information about what and who is likely to be affected, to provide more actionable warnings (Rogers et al. 2019).

The MHIEWS paradigm can become a common approach for all hazards and therefore is more likely to be a tool that everyone can understand and use as a basic element in their national disaster management system. The interconnectedness of hazards is a strong motivator for a common approach, especially where rapidly changing weather patterns increase flood, heat, and epidemic risks (Ghebreyesus et al. 2008; Liu et al. 2014; Liu et al. 2020). One of the lessons from the COVID-19 pandemic is the need to provide reliable warnings and to be willing to prepare for a reasonable worst-case scenario based on informed long-term planning. Meteorology and hydrology are making progress in this direction, and the processes developed in these disciplines can be readily applied to health and other sectors.

Effective MHIEWS are based on authoritative and timely risk information. Creating this information requires systematic and standardized processes to collect, assess, and share data concerning exposure, hazards, and vulnerabilities. Risk must be recognized as being dynamic: vulnerability, the nature of hazards, and the extent of exposure change over time as a result of many factors, including urbanization, rural land-use change, environmental degradation, and climate change. It is extremely important to make sure that vulnerable groups and communities are included in the processes of risk assessment and communication. It is equally important to make decisions that protect vulnerable groups while taking into account the realities that people find themselves in—often without access to information or tools to mitigate the damage, including financial tools.

For the poorest countries, many of which know only too well the extent of the damage natural hazards can lead to, the full danger of COVID-19 is only just coming into view (Pangestu 2020). Similarly, vulnerable communities are challenged by fragile health systems, loss of critical income, and lack of medical supplies or financial support. MHIEWS should be a tool that works in the interest of these groups and that guides governments' decisions that—whether the decisions concern re-locating people or restricting their movements—do not create any counter incentives and provide "shelter" in more than just one sense of the word.

As COVID-19 seems likely to be endemic with no vaccine or other mitigating measures on the immediate horizon (Nabarro and Colombano 2020), a CAP-based warning system is essential if we are to alert people to potential threats as we learn to live with it. In the long term, a comprehensive multi-hazard impact-based early warning system is needed to prepare us for all potential threats from natural and other hazards in a systematic way. As a potential starting point, MHIEWS could focus on heat health, for which there is a growing body of knowledge about the impacts of both high and low temperatures on excess mortality (Liu et al. 2014; Matthies et al. 2008). Air quality and health is another area for cooperation. Recent studies indicate a spatial correlation between ambient particulate matter (PM) pollution and increase COVID-19-related death rates (Andrée 2020; Yao et al. 2020a). This would also link the longer-term consequences of climate change with the immediate needs of society to cope with rising temperatures, extreme cold, and poor air quality, while also generalizing the tools to support the detection and early warning of infectious disease epidemics and pandemics, which may or may not be related to climate (Yao et al. 2020b).

COVID-19 is creating a new reality, beyond its immediate health impacts, by pushing 40–60 million people into extreme poverty (Mahler et al. 2020), thus increasing the vulnerability of people to the impact of other hazards. Reinforcing the use of impact-based forecasting and warning services with a common framework of anticipatory action will help minimize the impact of future disasters.

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