Chapter 3: Risk

The term "risk" has different meanings: (a) as a synonym for probability of a harmful effect occurring and (b) as a synonym for the mathematical expectation of the magnitude of the undesirable consequence (even as a quasi-synonym of consequence, whereby risk has a similar meaning to undesirable outcome).

Ten years from the publication of this GAR, the world population is projected to exceed 8 billion, and by 2055, more than 10 billion. This growth in population has resulted in an increase in economic losses due to natural hazards from $14 billion annually to more than $140 billion between 1985 and 2014.[1]

In the period since GAR15, the hazard community has shifted away from a focus on individual hazards and broadened its scope to examine more complex, real scenarios that acknowledge the likelihood of one hazard eventually leading to another (cascading hazard), or multiple hazards crossing in either time and/or space creating an even larger disaster. In addition, the Sendai Framework has expanded the range of hazards to be considered.

Most hazard sciences now use open source tools and are part of a larger movement promoting the widespread use of sharing open data. The democratization of risk information empowers individuals, communities and governments to draw conclusions and influence their own exposure and vulnerability. The shift towards open source and open data has provided a foundation for greater collaboration on a global scale within hazard communities and across hazard science.

The march towards openness, collaboration, interchange and cooperation has momentum. While there will be holdouts to this movement, trends in technology and data science suggest they will be increasingly in the minority. Openness solves many challenges, but there are still challenges to producing and communicating good risk information.

This part will outline developments related to understanding of risk since the publication of GAR15. In addition to expanding the scope of hazards under consideration beyond natural hazards, the Sendai Framework has called for recognition of the impact on and role to play for local, regional, national and global actors, and for a richer understanding of exposure and vulnerability. Furthermore, it considers an expanded list of hazards including human-made hazards and natural hazards that have been historically difficult to represent. In investigating the dynamic interconnected nature of risk, it calls for the imperative to develop new ways of thinking, living and working together that recognise the nature of systems.

New challenges call for novel solutions. While the GAR may never again produce individual risk metric figures for countries, this GAR is intended to give as true a picture of risk as possible. Facing that challenge, it must be acknowledged that: (a) the truth can be complicated and (b) some readers will be disappointed that the focus of this section is not on presenting probable maximum loss (PML) and average annual loss (AAL) figures. Furthermore, inasmuch as this GAR seeks to pay due respect to the expanded scope of hazards in the Sendai Framework there are hazards this report has previously covered that are not represented – notably, wind and storm. This GAR does include many hazards that have never been covered before, including biological risk, chemical and industrial, environmental, NATECH and nuclear/radiological. The GAR has never been exhaustive in its coverage of hazard and while GAR19 makes an effort to be comprehensive, there are and always will be sections that stand to be enriched in future iterations.

People and assets around the world are being exposed to a growing mixture of hazards and risks, in places and to an extent previously unrecorded. Heatwaves mixed with drought conditions can trigger intense wildfires that cause high levels of air pollution from burning forests and hazardous chemicals, such as the dioxins from burning plastics, as well as water pollution from the flame retardants used to fight the fires leaking into waterways, drinking water and marine systems. In other words, a perfect storm is created by the complex interlinkages of different natural and anthropogenic events and processes.

This part concludes with an exploration of drought hazard from a multidimensional perspective. Past GARs did not present drought risk partly because it is a highly complicated risk. The drivers are manifold, and the impact is felt more strongly in the secondary effects (lost livelihoods, forced migration, and top soil and nutrient erosion) than in primary effects. The chapter on drought will serve as an introduction to an off-cycle GAR special report on drought to be published in 2020.

3.1

Hazards

The growth of accuracy and sophistication of risk assessment has been propelled by the hazard community. This is reflective of a past paradigm where disaster and hazard were used interchangeably. It also reflects the emphasis on empiricism in risk science. In many ways, that emphasis on scientific methods to understand hazards has led to a state in which disaster research is accorded a certain respect. Hazard research continues to dominate global research related to understanding risk.

The era of the Sendai Framework has opened the door for the inclusion of a broader community of research in understanding the true nature of risk. Social science researchers, economists, public policy specialists, epidemiologists and others who can contribute valuable information about the nature of vulnerability and exposure are finding a welcoming community whose main objective is to give increasingly clear and accurate risk information. There is no doubt that the nature of risk information is and will continue to be quantitative, but the focus on probabilistic modelling and homogeneous data sets is giving way to a future that is less definitive and more accurately representative of the world as it is.

In this section, there is still a focus on hazards first, but the interconnection among hazards and the connections of the hazard research community to other risk research is validation of the Sendai Framework.

1 (UN DESA 2019)

3.1.1

Seismic

This peril has been responsible for an average direct death toll of over 20,000 people per year in the last several decades and economic losses that can reach a significant fraction of a country's wealth. On average, earthquakes constitute 20% of annual economic losses due to disasters, but in some years, this proportion has been as high as 60% (e.g. in 2010 and 2011).[2] In Central America and the Caribbean, the earthquakes of Guatemala (1976), Nicaragua (1972), El Salvador (1986) and Haiti (2010) caused direct economic losses of approximately 98%, 82%, 40% and 120% of the nominal GDP of each country, respectively.[3]

While global earthquake models have not changed dramatically, many of the inputs have changed, as has the way in which earthquakes are being studied and understood. GAR15 focused on earthquakes as ground shaking and the impact of earthquakes as related to structural damage to buildings due to shaking. Nearly five years on, knowledge of earthquakes is being informed by new models, and by a better understanding of faults and thus movement within time and space. This has been facilitated by greater collaboration enabling local-level data to help inform the global level.

In general, earthquake models are heavily based on data from past earthquakes: magnitude, frequency, ground shaking and damage. Thus, models at the global level have been created mainly through statistical analyses of past events and empirical data on damage and mortality. Models are improving in several ways: increased understanding of how active faults accumulate seismic energy; greater availability of ground shaking recordings from damaging earthquakes; better understanding of the vulnerability of structures from field observations as well as computer simulations; and better descriptions of the human and built environment from a wide range of sources, including satellite imagery and crowdsourcing.

Global models now integrate local information about faults and microfaults as well as to reflect verified plate movement measurements. There is a growing emphasis on the use of geodesy (the branch of mathematics dealing with the shape and area of the Earth). Each factor affects ground shaking differently, thus the greater the level of detail, the more accurate forecasting can be.

Box 3.1. Volcano Risk

A particularly interesting development is the use of information about the drivers of seismic risk from one location to inform risk scenarios and planning in other locations with similar dynamics. This enables experts to understand models by learning from the results of those run elsewhere. This technique is also in use by the volcanic research community. During volcanic crises, the most challenging task is to interpret the monitoring data to better anticipate the evolution of the unrest and react.[4] In other words, volcanologists need to make an informed decision about what is likely to happen next. Aside from real-time monitoring data, volcanologists will rely on historical unrest and past episodes of the same volcano. Such analysis requires a standardized and organized database of past events of the same volcano. Moreover, if the volcano has not erupted frequently or is not well studied, the only recourse of the volcanologist is to consult what has happened at other volcanoes, for which the need of a robust monitoring database is even more acute.

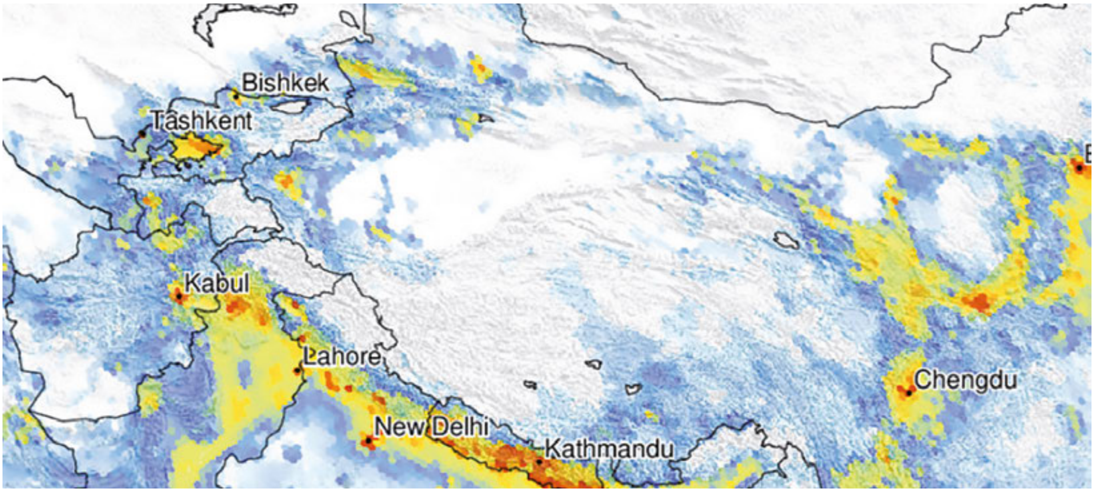
(Source: (Costa et al. 2019); (Newhall et al. 2017)

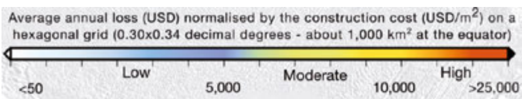
The Global Earthquake Model (GEM) now includes nearly 10,000 fault lines. This level of comprehensiveness is available only due to the confluence of improved satellite capability, expanded availability of computing power and the inputs of hundreds of national and local seismic specialists.

As the level of available detail varies by location (by region, by country and sometimes even within countries), to ensure the most up-to-date data is incorporated into a global model, it is necessary to apply consistent methodologies and tools at all levels of analysis, from local to global. This information can then be combined into a homogeneous mosaic that allows comparisons of hazard among locations and regions.

Regionally, seismic models have extended such that there are now models for a larger part of the world at a better quality with improved catalogues and geological parameters than ever before. Risk modelling has progressed to include cascading hazards in the models. An example of this new capacity is the increasing focus on modelling contingent losses or indirect losses. Pilot efforts are showing that it could be possible to estimate the price increases for certain types of goods when disaster events of different scales occur in some contexts. For risk managers and planners, this will be useful in understanding the probable knock-on effects of the event, but also to inform emergency measures.

Figure 3.1. Example earthquake mosaic map of part of Asia in 2018





(Source: GEM 2018)

Disclaimer: The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

2 (Centre for Research on the Epidemiology of Disasters 2018)
3 (Silva et al. 2019)
4 (Sobradelo et al. 2015)

In late 2018, GEM researchers released a mosaic-style model that brought together various earthquake models to create global hazard and risk maps that included the most advanced information available at the national/regional levels for seismic risk. The mosaic element refers to the fact that this model stitches together regional and national models from around the world and overlays them as tiles, using local inputs to inform the global picture.

The improved characterization of active faults and the ability to associate the locations of future earthquakes to active fault sources is an important shift. The Global Seismic Hazard Assessment Program (GSHAP),[5] launched in the mid-1990s, also promoted a regionally coordinated, homogeneous approach to seismic hazard evaluation. In a divergence from GSHAP, new assessments of risk for the largest earthquakes are now associated with specific fault sources, resulting generally in more refined and accurate estimates of the most significant earthquake risks. These advances contribute to a better understanding of the hazard. Local-level information on faults is changing how earthquakes are understood and how the movement of the Earth's plates and subplates (e.g. microfaults) accretes. The collaborative approach now includes locally generated information about faults that can be seen in the hazard map, driving the shift from a spatial pattern of past earthquakes to a detailed pattern of faults derived from local geologic and geodesic knowledge. This level of detail is available in a few places only, particularly in more developed countries and near major plate boundaries. Away from these boundaries, in stable continental regions, researchers rely on relatively simpler methods based on historical earthquakes and general knowledge of geologic conditions.

In the short term, the mosaic model accepts a degree of loss of guarantee about the pedigree of the inputs in favour of collaboration and buy-in while promoting the open data paradigm for risk assessment. This structure also provides incentives for national and local risk modellers to produce high-quality local perspectives of their own communities – the democratization of the data and the source material engenders long-term sustainability.

The open source, collaborative approach appears to be helping increase standardization and permitting shared information. This is primarily because open source modelling engines like OpenQuake[6] have provided a platform for experts to build consistent models using well-tested tools and to transparently compare and evaluate the results. Historically, public institutions, particularly in developing countries either did not have advanced analysis tools, or often relied on external consultants to model hazard and risk. The shift from reliance on private, black-box models to public, open source models enables public institutions to build their own view of hazard and risk. In turn, this provides open, transparent and high-quality information to raise risk awareness with a broader range of stakeholders.

Models are generally becoming more complex, with increased volumes of data, and leading to more robust results. Though forecasts are still discussed in terms of decades (rather than years or months), it is now possible to project probabilities of results in some areas in 30-year time periods. Most global seismic models are based on the idea that in any given year, a location would have the same probability of experiencing a 50- or 100- or 500-year event. And if one such event happened, the next year they would go back to having the same chance as the previous year of such an event occurring again.

To understand this, imagine a 50-sided die that was rolled the first day of every year – this would determine whether a 50-year earthquake would occur in that year. Even if an earthquake was unluckily rolled in a particular year, the next year when the die was rolled, there would be precisely the same probability of experiencing an earthquake.

There is research under way in Japan, New Zealand and the United States of America to produce forecasts that are time dependent. These sophisticated models can make statements like "the San Andreas Fault is now closer to failure than it was 20 years ago". In this sense, if there is a 50-year probability, towards the end of the 50-year period, if nothing has happened, the event is more likely than it was at the beginning of that period. At the end of each scenario period, model likelihood can be adjusted.

This is mathematically complicated and is even more complicated to explain to the public, but aligns well with public perceptions of the ripeness of events that have not happened in recent memory. Time-dependent forecasting will not be applicable to most other hazards. It can work in seismic science – only with sufficiently detailed data – because most seismic events are the results of increasing pressure leading to a slip or rupture, and the probability does indeed increase.

Understanding the magnitude of losses from damaging events is fundamental to informing decision makers and disaster risk managers in the development of risk reduction measures. For example, in 2002, a catastrophe insurance pool for residential buildings was created in Turkey to transfer the risk from the public sector to the international reinsurance market.[7] The establishment of this financial mechanism required an earthquake model to estimate the expected economic losses for each province. More recently, researchers demonstrated how a probabilistic loss model could prioritize which schools should be the target of a retrofitting intervention in Colombia.[8]

The open source, active fault database is freely available to use and to contribute to, thus increasingly improving forecasts about the time, location and characteristics of rupture. The comparison of scenarios with similar drivers is also being used by the volcano risk community. The objective is to include all processed data of historical unrest from all reliable sources, including that which led to eruption. The database contains volcano information, monitoring data and supporting data such as images, maps and videos, as well as the alert levels where applicable.[9] The data points are time stamped and georeferenced, so that they can be analysed in space and time.[10]

Other advanced tools are seeking to forecast seismic events from GPS measurements and land-based positioning of points that show how plates are moving. Since 2015, the Global Earthquake Activity Model has been estimating shallow earthquakes above magnitude 6 using this technique.[11] The premise is that to blend data from a record of historical earthquake events in a given region with the global strain rate map where strain rate acts as a proxy for fault stress accumulation, and earthquakes are the release of that stress.

Groupings of earthquakes can have huge implications for insurance premiums, with companies often determining what they cover (only the main shock, or covering aftershocks within a predefined period). This makes it increasingly necessary to understand how earthquakes cluster and define foreshock versus main shock versus aftershock and then ensure that the appropriate considerations are used in planning and risk transfer. For example, in Christchurch (New Zealand) in 2011, a 6.2 magnitude earthquake caused significant damage. This damage is thought to have been especially severe because a 7.1 magnitude earthquake had occurred in the same area the previous year and had weakened structures, although it caused relatively little damage. Was the Christchurch earthquake an aftershock or a separate occurrence?

Seismic science is predicted to be affected by climate change and similar dynamics as they relate to exposure and vulnerability. Historically, earthquake risk models considered only built structures in assessing exposure and the type and height of those structures in assessing vulnerability. There can be little doubt, however, that a more holistic representation of the human, social, economic and ecological impact of seismic events must be part of future research.

5 (GFZ Helmholtz-Zentrum Potsdam 2019)
6 (GEM 2019)
7 (Bommer et al. 2002)
8 (Mora et al. 2015); (Silva et al. 2019)
9 (Winson et al. 2014); (Fearnley et al. 2017)
10 (Newhall et al. 2017)
11 (Bird et al. 2015)

There is growing political interest in induced seismicity (earthquakes that are caused by human activity). Recent focus has been on fracking, but there were recorded earthquakes resulting from fluid being injected into an oilfield as far back as the 1960s.[12] Furthermore, there are several examples of water dams inducing earthquakes (reservoir induced) such as the Aswan Reservoir in Egypt.[13] Though induced seismicity may not be a new occurrence, it is a new factor in hazard models, and in selected areas where fracking is common (western Canada and central United States of America), it is being factored in to hazard maps for updating building codes.

Change exists in risk exposure and recorded losses. Most insurance companies predicting risk anticipate an escalation in losses because there is expected to be an increase in exposed assets as economies grow to meet growing populations. These losses must be put into context; many trends that have been identified in the developed world are not necessarily mirrored in their developing country counterparts. Insurance penetration and regulatory standards to reduce risk before it is constructed are vastly more prevalent in richer countries. In 2017, compared with the average emerging market non-life insurance penetration rate of 1.5%, African premiums accounted for only 0.9% of GDP. Only Morocco, Namibia and South Africa exceed 2%,[14] compared to the average in Organisation for Economic Co-operation and Development (OECD) countries of between 8.5% and 9.5% of GDP.[15] Policy changes and a greater focus on risk reduction also help to decrease risk, but in places where economic growth outstrips investment in risk management and governance structures, risk will continue to grow.

3.1.2

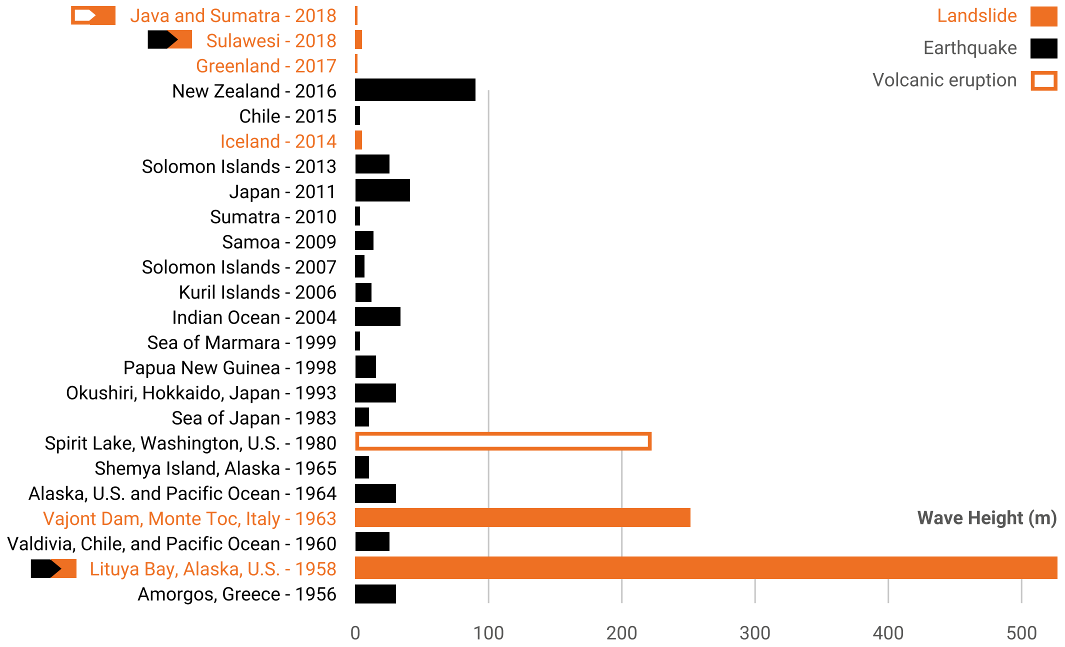
Tsunami

Tsunamis must be treated as a multidisciplinary hazard. They can be triggered by earthquakes, landslides, volcanoes or meteorological events, with large earthquakes being the most frequent trigger. Because their drivers require specific conditions to result in a tsunami, they are decidedly rarer than their triggering events. Tsunamis have a basis of historical evidence, but the data set is too sparse to characterize the tsunami risk on each specific coastline, especially in confined areas where there is a limited coastline section. Making this more challenging, over the last 100 years, only a handful of truly devastating tsunamis have occurred, contributing to most of the disaster tsunami losses across the globe. Large tsunamis occur with relatively low frequency but have potentially high impact. In the last two decades, this has been demonstrated, for instance, by the Indian Ocean (2004) and the Great East Japan (2011) tsunamis. The scale of these disasters far exceeded the previously perceived risk in these areas.

Assessing tsunami risk requires a comprehensive and multidisciplinary approach. It is a topic that includes a wide range of disciplines, such as geophysics (e.g. seismology, geology and faulting), hydrodynamics and flow modelling (e.g. landslide dynamics, volcanology, coastal engineering and oceanography), vulnerability and risk assessment (e.g. geography, social sciences, economy, structural engineering, mathematical and statistical sciences), in addition to disaster risk management and mitigation.

The tsunami maximum wave heights in Figure 3.2 do not correlate with their level of damage. The largest known tsunami occurred in Lituya Bay, Alaska, in the United States of America in 1958. The massive scale of the wave caused relatively little damage due to the limited exposed stock in the area at the time. The Great East Japan tsunami in 2011 and the Indian Ocean tsunami in 2004 were far smaller than the Lituya Bay tsunami, but they caused far more losses.

Figure 3.2. **Selected tsunami wave heights (maximum wave heights recorded)**



(Sources: National Oceanic and Atmospheric Administration National Geophysical Data Center/World Data Service Global Historical Tsunami Database 2019; National Centers for Environmental Information 2019)

Tsunami hazards are heterogeneous; smaller events can cause devastation, as evidenced by the events in Indonesia with the Palu tsunami in 2018 and the Mentawai tsunami in 2010. These events exemplify cases where unconventional mechanisms generate tsunamis that are unexpectedly large given the magnitude of the triggering event.

Due to their infrequent nature, tsunamis often catch coastal communities off-guard. Perhaps the most pertinent example is the 2004 Indian Ocean tsunami that hit a largely unprepared coastal population in nearly a dozen countries and resulted in more than 230,000 fatalities. Due to the enormous consequences of that tsunami, the need for more sophisticated and comprehensive methodologies to understand and manage tsunami risk in a wider range of locations immediately became obvious. The most obvious interventions were in risk mitigation activities such as construction of wave-absorbing sea walls, elevated facilities, evacuation routes and EWSs. After 2004, tsunami research and risk mitigation activities spread to many regions that previously had very little focus on tsunami risk – particularly South and South-East Asia.

12 (Raleigh, Healy and Bredehoeft 1976)
13 (Gahalaut and Hassoup 2012)
14 (African Insurance Organization 2018)
15 (OECD 2019)

Understanding the drivers of tsunami hazards

The use of probabilistic models for tsunami hazard analysis started in the early 2000s. A range of applications followed, from local to regional to global scales. A great deal of uncertainty is involved in tsunami hazard modelling, especially in the low-probability region of hazard curves, which is where the most extreme consequences are expected. Traditionally, probabilistic tsunami hazard assessments (PTHAs) have covered intermediate to large regions, providing quantitative estimates of maximum tsunami elevation in deep coastal waters. However, as tsunami damage is caused by the flow onshore where assets and population are located, additional effort is needed to characterize tsunami hazard intensities in those areas.

Several measures of tsunami intensity have been suggested:

- Tsunami flow depth, i.e. the maximum height the water reaches above land
- Wave current speed
- Wave current acceleration
- Wave current inertia (product of wave acceleration and flow depth)
- Wave current momentum flux (product of flow depth and square wave current speed)

While it may not provide optimal accuracy, flow depth is the quantity that is the most frequently used tsunami hazard intensity measure.[16] The reason is that most building damage observations and probability assessments of tsunami mortality risk present vulnerability as a function of flow depth as the sole damage indicator. Flow depth is also the most readily observed intensity parameter (using water or debris marks) at multiple locations once tsunami water has receded.[17]

Tsunami hazard is expressed in terms of different probabilities of exceeding a given tsunami intensity at a given location. This includes maximum values of the height of a tsunami in a given time frame. A tsunami with a maximum wave height of 20 m is much less likely than one with a maximum wave height of 5 m. This is because the drivers of tsunamis of those scales are rarer – larger earthquakes, landslides or volcanic events are less common than smaller ones. To determine tsunami hazard, PTHA methods are used to quantifying the probability of tsunami losses at a global scale. To do this, tsunami propagation was modelled globally, and offshore wave amplitudes were converted into estimates of the onshore maximum inundation height by combining amplification factors with a statistical model.

PTHA was used to quantify the tsunami hazard globally for GAR15. But because GAR15 was oriented to quantifying tsunami risk, official tsunami hazard maps were never issued. A set of upgraded global tsunami hazard maps was developed later, based on the GAR15 data and including epistemic uncertainty (uncertainty due to lack of knowledge) stemming from the probabilistic earthquake model.[18] These global tsunami hazard maps presented maximum inundation heights at the shoreline due to earthquake sources for a large set of coastlines worldwide, using global tectonic information from the earthquake model.[19]

There are other generators of tsunamis that are more difficult to model. There are also tsunamis generated by landslides and meteo-tsunamis (rare events when specific meteorological conditions create a destructive tsunami).

Risk and impact assessment require the integration of hazard estimates with exposure data and vulnerability functions (relationships describing the expected impact of several levels of hazard intensities on different types of exposure). This will establish the likelihood and severity of impacts in terms of casualties, cost of direct damage or number of damaged structures. Impact assessments estimate the consequences of one or a few scenarios (i.e. using deterministic assessment, which establishes the potential impacts of tsunamis at one or more sites). Risk assessments include a frequency component, derived from the hazard frequency, to describe the expected severity of an event within a defined time frame (e.g. the amount of loss

Evacuation route in Iquique, Chile
(Source: Flickr.com user Francois Le Minh 2007)

expected to be exceeded once on average in, say, a 50-year period), or with a given annual probability of occurrence.

Due to the complexity of simulating onshore inundation for the large numbers of events in a fully probabilistic event set, no studies have been carried out with a full range of probabilistic estimates of tsunami impact onshore, and only a few have done so for selected return periods.[20] Frequently, these scenario-based risk assessments are motivated by the need for very detailed simulations for engineering requirements; these should ideally happen due to disaggregation from probabilistic estimates, rather than using individual, detailed assessments to project a global understanding of risk. But they are indicative of an appetite for detailed and accurate risk information for tsunamis to inform building codes, mitigation measures, insurance options and public safety measures.

Researchers have a growing understanding of vulnerability to tsunamis due to post facto analysis from recent tsunami events. A variety of new data has become available in recent years. For example, findings from the 2011 Great East Japan tsunami reveals that road bridges appear to be able to withstand 10 m flow depth with only 10% probability of being washed away.[21] Further, at flow velocities of 1 m/s and 5 m/s, small fishing boats will be washed away with 60% and 90% probabilities, respectively.[22] Aquaculture rafts and eelgrass will be washed away with 90% probability when the flow velocities are 1.3 m/s and 3 m/s, respectively.

16 (Behrens and Dias 2015)
17 (Suppasri et al. 2013)
18 (Davies et al. 2018)
19 (Berryman et al. 2015)
20 (Dominey-Howes et al. 2010)
21 (Shoji and Nakamura 2017)
22 (Suppasri et al. 2013)

These details enrich the understanding of exposure and its vulnerability to other effects of tsunamis, and serves to refine the quality of the risk assessment.

In terms of global risk assessments, the probabilistic tsunami risk assessment (PTRA) method provides PML estimates for direct economic loss due to building damage for coastal nations worldwide. This is presently the most advanced global model on tsunami risk. In absolute values Japan by far exceeds other countries' risk. However, normalizing PML to the total exposed value of each country, several SIDS face similar relative tsunami risk.

Countries in the Eastern Mediterranean Basin also ranked high in the above method. The global PTRA was one of the first applications of its kind, regardless of geographic scale. Consequently, there are large uncertainties in the different methods and data applied. For exposure estimation, there are also major challenges related to the availability of topographic data sets with sufficient resolution. Those provisions indicate that while this model provides some clues about trends in global tsunami risk, in coming years with refined methods and better data, future models will provide more refined estimates of global tsunami risk.

Tsunami risk research has focused thus far on tsunamis triggered by earthquakes. Further work is required to characterize events triggered by landslides, volcanoes and meteorological loading, particularly in the frame of the current move towards understanding the systemic nature of risk, as outlined in this GAR. The understanding of tsunami risk is not yet at the same level as the understanding of the hazard. To bring tsunamis up to speed in the context of the first priority of the Sendai Framework "Understanding disaster risk", more work is needed in enriching a sound PTRA methodological framework that accounts for exposure and vulnerability in more dimensions.

3.1.3

Landslide

The evaluation of landslide hazard should entail diagnosis of the geo-hydro-mechanical processes bringing about the landslides that eventually generate damage.

The assessment of landslide hazard based upon geo-hydro-mechanical analysis of slopes is generally recognized to be the planning basis for countries experiencing high landslide susceptibility (e.g. in Afghanistan, in Himalaya belt slopes in Asia, in Bolivia, Brazil and the Bolivarian Republic of Venezuela in South America, and in Italy and Spain in Europe). But the experienced losses from contemporary landslide events testify that these assessments, or the mitigation measures they should have precipitated, are not appropriately developed.

The Multiscalar Method for Landslide Mitigation is a new methodology for the assessment of landslide hazard at the local scale, based on geo-hydro-mechanical analyses. This method seeks to identify the geo-hydro-mechanical contexts most common in the slopes of the region,[23] and for the corresponding landslide mechanisms, which are then recognized as the mechanisms typical to the region.[24] Having as a basis the set of representative landslide mechanisms can make landslide risk management at the local scale more sustainable, since it can guide the selection of the mitigation measures based on awareness of the typical landslide features and causes.

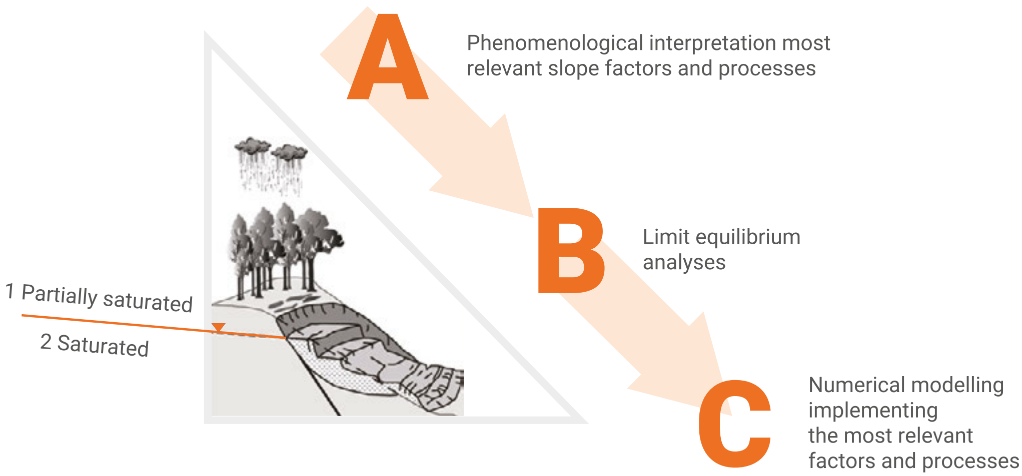
Urbanization frequently extends over unstable slopes and ancient landslides. This is particularly true for informal settlements. Therefore, landslides often affect the poorest parts of urban areas, whose expansion is restricted to land that would not withstand simple engineering tests.

Diagnosis of the landslide mechanism

Landslides are the final process of a sequence of phenomena taking place in the slope that involve strain localization and progressive failure (overall defined as the landslide mechanism).[25] The landslide mechanism can be modelled through the mathematical reduction of a boundary value problem. This requires the simultaneous integration of several differential equations, representing the different processes influencing the equilibrium of the system, which is generally in a continuously transitional state.

For the sake of efficiency, researchers usually simplify the modelling and simulate the most influential processes. The internal processes may include the features predisposing the slope to failure; the external ones are the actions that may trigger the slope failure. In the case of climate-driven landslides, the driving conditions are in continuous flux through processes such as rainfall infiltration, water evaporation from the soil and transpiration through vegetation. Changes to those conditions may bring about either the onset, or the progression, of slope failure.

Figure 3.3. Stage-wise methodology for diagnosis of the landslide mechanism



(Source: Cotecchia 2016)

Landslides have diverse drivers, and a probabilistic global model is not practical. They can be induced by precipitation, change in air pressure or seismic activity, for example. It is similarly impractical to rely on a regional model; landslide hazard can be modelled given a sufficiently small target region but the level of detail required to capture all variables is impossible for larger scales. To respond to this, researchers rely on phenomenological study of the slope topography, lithology and hydrology, the tectonic structures, the land use and the slope–structure interaction.[26] These are the morphological elements indicative of slope movement and failure. On a detailed level, they provide indications about the presence of pre-existing shear bands and guidance about the numerical strategy to be used in the definition of the initial slope conditions. The phenomenological study must also consider the

23 (Terzaghi 1950)
24 (Cotecchia et al. 2016)
25 (Chandler 1974); (Chandler and Skempton 1974); (Potts, Kovacevic and Vaughan 1997)
26 (Cascini et al. 2013); (Palmisano 2011)

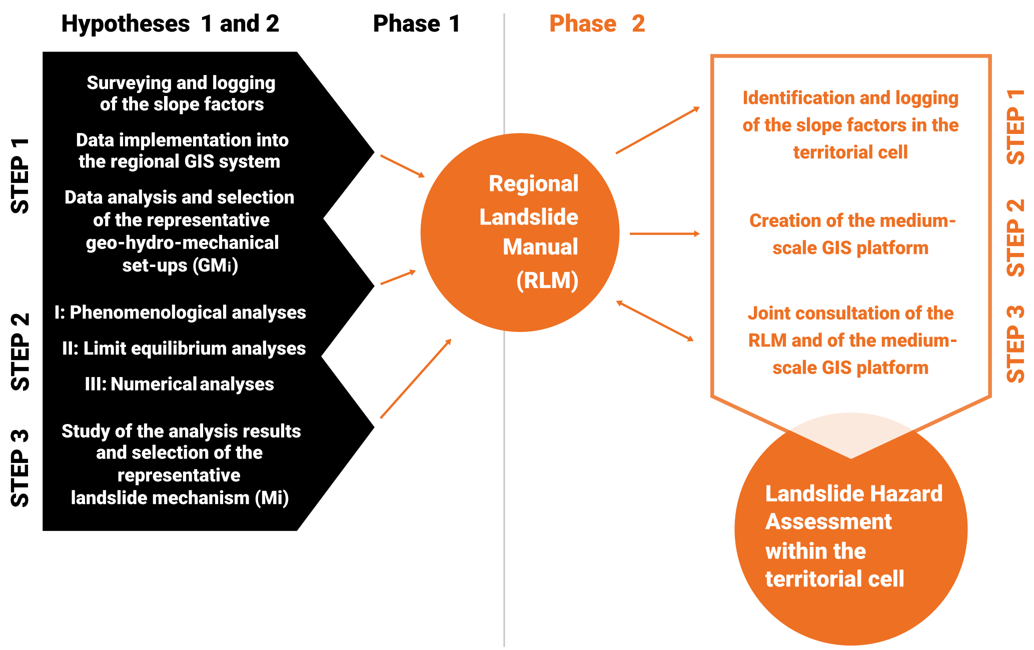
hydro-mechanical properties of the slope soils, as obtained from laboratory tests and monitoring data.

Though numerical modelling may be extremely advanced, a slope model implementing all the slope factors and processes is not feasible in most cases and could produce misleading results. Therefore, modelling alone is not sufficient for appropriate hazard diagnosis and must be paired with field studies.

Multiscalar Method for Landslide Mitigation

All the knowledge acquired during Phase 1 in Figure 3.5, along with the methodological steps to be applied for the assessment of the landslide hazard in a given specific territorial cell of interest for the region, should be reported in a landslide manual using a global information system platform.[27] This gathers together the geo-hydro-mechanical knowledge about the slopes across the region, of reference for land-use planning or in mitigation design for the unstable slopes of the region. The model should be continuously upgraded in any region.

Figure 3.4. Sequence of actions required to derive landslide hazard assessments



(Source: Cotecchia 2016)

The map database thus obtained then becomes a guideline in the assessment of the landslide hazard within the given area of interest. It will include data representing the landslide factors at the site of interest, with particular emphasis on those recognized to be predisposed to landslides in the first phase, and data about the slope movements.

Once the active landslide mechanisms for the studied region are analysed, it becomes possible to focus on design of the measures for risk mitigation. These must be carefully tailored to the characteristics of the landslide-prone area and can include the construction of drainage trenches and planting highly transpiring vegetation to stabilize the slope.

With current methods, assessment of landslide risk remains highly contextual and localized. At its most rigorous, it involves different stages of analysis, first phenomenological, thereafter mathematical/numerical, to characterize the representative geo-hydro-mechanical context and landslide mechanisms.

In principle, with sufficiently detailed data sets, risk profiles could be created with input from the specific landslide hazard assessment mentioned above. This is simply not practical in most circumstances.

3.1.4

Flooding

While seismic science has been able to move forward with a coordinated, collaborative approach to modelling the hazard, flood science faces several obstacles that make the process of reaching the same point more complicated. Floods are simply the presence of water on land that is usually dry. The causes of that flooding can be too much precipitation, snow melt that occurs too quickly, a dam break, a tsunami or storm surge, inadequate water management practices, etc. The dynamics that dictate flood risk are difficult to model – a key reason why not all flood causations can be modelled with contemporary resources. There are models for many different drivers of flooding, but not all, and the work of harmonizing the different drivers into a harmonized flood model remains a challenge for the flood community.

Several different flood models have been developed for riverine and coastal flooding. But the challenge in developing a more comprehensive global model is to combine these models together. A first step in this direction has been made by linking one hydrodynamics model with downstream boundary conditions from a tide and storm-surge data set.[28] In doing this, the linked effects of flooding at river water levels and in estuaries have been mapped globally. Other initiatives are developing methods to nest local flood models within global models, thereby increasing computational efficiency and enhancing localized accuracy in those areas where the local models exist

When assessing flood risk, a key concern is related to triggering factors. There is no single source that causes a flood; it can arise from multiple drivers. Considering the challenges in accuracy related to short-term weather forecasts, where at least some of the dynamics can be modelled, the challenge of risk projection for precipitation drivers of flooding are orders of magnitude more complex. Precipitation patterns must consider multiple dynamic sources. Even in the same catchment area, the same precipitation distributed in different ways can lead to vastly different results. Other conditions must be factored in, including the soil conditions (very dry, partial saturation, snow melt, etc.), and all those elements must then be linked to local factors that are not always possible to project at the global level. The primary difference between global and local models is not the processes – those are effectively the same – but rather the ability to tailor them to a local context that can make the difference for producing a comprehensive understanding of risk.

Older hydrological models were focused on projecting probable discharge of rivers, creating a time series of the flow in the river and applying those discharge values to a hydraulics model that incorporated flood flow and depth. Now, with the ability to run calculations on far more powerful computers, the hydrological cycle can be resolved in a more accurate way, thus enabling improved simulation of hydrology and the production of more reliable values of discharge.

Using these tools, many probabilistic flood maps are now available. Recent work to combine them has highlighted the significant advances possible in recent years. Through the Global Flood Partnership

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27 (Mancini, Ceppi, and Ritrovato 2008); (Lollino et al. 2016); (Cotecchia et al. 2012); (Santaloia, Cotecchia and Vitone 2012)
28 (Ikeuchi et al. 2017)

(GFP), work is under way to compare the various existing models and identify gaps that will require further research and development. GFP is a multi-disciplinary group of scientists, agencies and flood risk managers focused on developing efficient and effective global flood tools. Its aim is to build cooperation for global flood forecasting, monitoring and impact assessment to strengthen preparedness and response and to reduce global disaster losses.[29] Much like seismic science, the ideal case is to use locally produced models, and a plan is required to collect these and figure out how to fill gaps. The result should provide a basis for other models and enable them to be mutually improved.

In the past, people working on flood mapping and flood forecasting were working independently, but they are now using the same base data and have slowly come together to use the same timescales. Since 2015, drought and flood communities have been working together on a common framework that provides a single model which indicates simply whether there is too much or too little water. One example that clearly shows the interplay between droughts and flooding is the border between India and Pakistan. This area experiences sequential flooding and drought, both of which provide a basis for agricultural production in the region (as flooding increases the water table, the area absorbs that water during drought, and the water table is lowered before the next round of flooding).

The key is to move away from a simple hydrological risk paradigm and instead focus on impact. If exposure and vulnerability are incorporated into models, probabilistic modelling then becomes more important to provide information on the potential impact, not just to understand a hazard. It can then inform decision makers so that they are able to issue detailed early warnings, or over a larger timescale, incorporate the information into decisions on land-use planning, building approvals and infrastructure development.

Climatological models have also improved, in the analysis of the past and in their ability to forecast into the future. More detail is derived with the community working on high-resolution simulations of the climate. In 2015, the resolution of the climatological model was 80 km^2; now, detailed models are a maximum of 40 km^2, improving the overall global granularity. Unfortunately, capacity of simulating models at the global level is limited, but it is expected to improve in the coming years with even greater increases in resolution. Meteorological reanalysis has also been extended further into the past, with the twentieth century reanalysis providing global hindcasts of meteorological conditions back to 1851. GFP has been working to better represent the dynamics of the hydraulics by improving depth measures but doing this for total global coverage requires significant resources. Many researchers are working to improve the available instruments and build on current research allowing for an evaluation of the hydraulics hazards. At the local scale, further research is needed to go even further so that reliable hazard and damage computations can become a reality.

Data scarcity is a hurdle for global models and is fuelled by lack of resources for an area to produce such data and by concerns regarding the security sensitivity of the data, which inhibits the free exchange on which such a model relies. The availability of detailed data from satellites is aiding the calibration and validation of hydrological models that can be used in parts of the world where local data are scarce. An example of work that is filling in the gaps is the Soil Moisture Active Passive satellite, which provides detailed information on soil moisture. although the resource has been available for some time, it is only the latest versions of models that can incorporate this data.[30] Availability of high-quality and high-resolution digital elevation data remains a key challenge when undertaking global simulations of flooding.

The inclusion of epistemic uncertainty represents another major shift in the way the risk is calculated. It is difficult to compute flood risk due to the wide range of variables that are required for modelling flood scenarios, as well as the computational resources that are required (with a single scenario taking up to a day to run). As a result, it has become necessary to sample scenarios. The collection of samples creates a portfolio that produces a mean result and standard deviation.

Shorter-term forecasts are time dependent (e.g. three to six hours for flash flooding, normal weather forecasts of one to three days, medium range being 3 to 15 days and seasonal forecasts are longer term). Longer-term forecasts for climate change are based on Poisson distributions (representing the probability of a given event independently of the time since the last event). They are normally depicted with three different horizons: short-, mid- and long-term futures.

It is difficult to examine changes in flood risk at the global level. Temperatures are rising, and this will have drastic effects on how flood risks are studied and calculated and on the effects of floods in the world. Using this as a basis, various scenarios have been developed to examine how anticipated climatological changes will affect flood risk. The challenge is that the effects of climate change will not increase the mean temperature in all parts of the world evenly. Mean temperature changes will vary significantly from one location to the next. While flooding is likely to increase overall, as increasing temperatures melt glaciers and increase water levels, in general, the warmer temperature is expected to amplify aridity and evaporation in some regions. There will be more droughts and more floods, but this balance will serve to highlight the differences between regions.

At the global level, the consensus is that changes in mean sea-level, storm-surge levels, the frequency of storm surges, wave action and water temperature/volume will have tremendous implications for the underlying assumptions of the long-term risk models currently in use. In all scenarios, there will be an increased risk of coastal flooding in many parts of the world. Coastal flooding is projected to have a more significant impact than even riverine flooding; the value of the infrastructure and assets that stand to be damaged is increasing.

Using models to predict the probability of success and value of possible intervention methods is another important change in the scientific community, and can be used to help inform decision makers.

Global flood risk modelling is now taking a step forward from simulating scenarios of flood risk, to developing methods to assess how adaptation strategies could reduce that risk. For example, the Global Flood Risk model was applied to examine the costs and benefits of adaptation through dikes and levees with scenarios of climate change and socioeconomic development until 2100.[31] To make such research useful to decision makers, the tool Aqueduct Floods will be released in 2019 to allow anyone to assess these costs and benefits for any country, State or basin.

Recent years have seen a growing recognition in the flood risk community that many hydrological and meteorological risks (e.g. floods, wildfires, heat-waves or droughts) result from a combination of interacting physical processes having different effects across different spatial and temporal scales, and that correctly assessing the risk therefore requires scientists and practitioners to include these interactions in their risk analyses.[32] This can result in the disproportionate representation of the probability of extreme events, referred to as "compound flood events".[33] These compound events have been identified as an important challenge by the World Climate Research Programme Grand Challenge on Weather and Climate Extremes. As a result, a new process has been initiated to: (a) identify key process and variable combinations underpinning compound events; (b) describe the available statistical methods for modelling dependence in time, space and between multiple variables; (c) identify data requirements needed to document, understand and simulate compound events; and (d) propose an analysis framework to improve the assessment of compound events.[34]

Compound event analysis has been a rapidly growing field of analysis in large-scale flood risk

29 (EC 2019)
30 (NASA 2019b)
31 (Winsemius et al. 2013)
32 (Zscheischler et al. 2018)
33 (Zscheischler et al. 2018)
34 (Zhang et al. 2017)

analysis. Whereas flood risk studies traditionally examined floods from one driver (either river flooding, pluvial flooding or coastal flooding), research is increasingly examining the impact of combinations of these drivers. In 2017, the combination of unprecedented local rainfall intensities (pluvial flood driver) with storm surges (coastal flood driver) from Hurricanes Harvey, Irma and Maria led to major flood events and damage in Houston, Florida and numerous islands in the Caribbean.[35] Hurricane Harvey is now the second costliest natural hazard event in American history. Moreover, by not considering compound flooding, the risk Houston faced was, and continues to be, underestimated. Despite their potential for high impacts, compound events remain poorly understood and are typically ignored in disaster management plans. This is an omission that fundamentally and seriously biases existing flood risk assessments.

At local scale, several studies have found that there is a statistical dependence between the frequency or magnitude of coastal floods and river/pluvial floods in Australia, China, European countries and the United States of America.[36] Interactions between storm surge and discharge can lead to elevated water levels in deltas and estuaries.[37] To understand this, researchers coupled a state-of-the-art global river routing model with results from a global hydrodynamic model of storm surge and tides.[38,39] Globally, there was an increase in the annual maximum water surface elevation of 0.1 m in deltas and estuaries when dynamic sea-surface levels are used as the downstream boundary compared to when they are not, with increases exceeding 0.5 m in many low-lying flat areas such as the Amazon basin and many river basins in South-East and East Asia.

There have already been studies to investigate the effectiveness of various risk reduction measures as an aid to decision makers. These studies are based on hypothetical interventions, but they show that not all risk reduction measures are equal, and what fits for one scenario might not fit for another. For example, building up the levees of a river can protect from losses due to floods to a certain level, but the most certain measure is moving that population to a safer location. However, this also brings into play the complexities of post facto development planning and the myriad legal and social issues around resettlement.

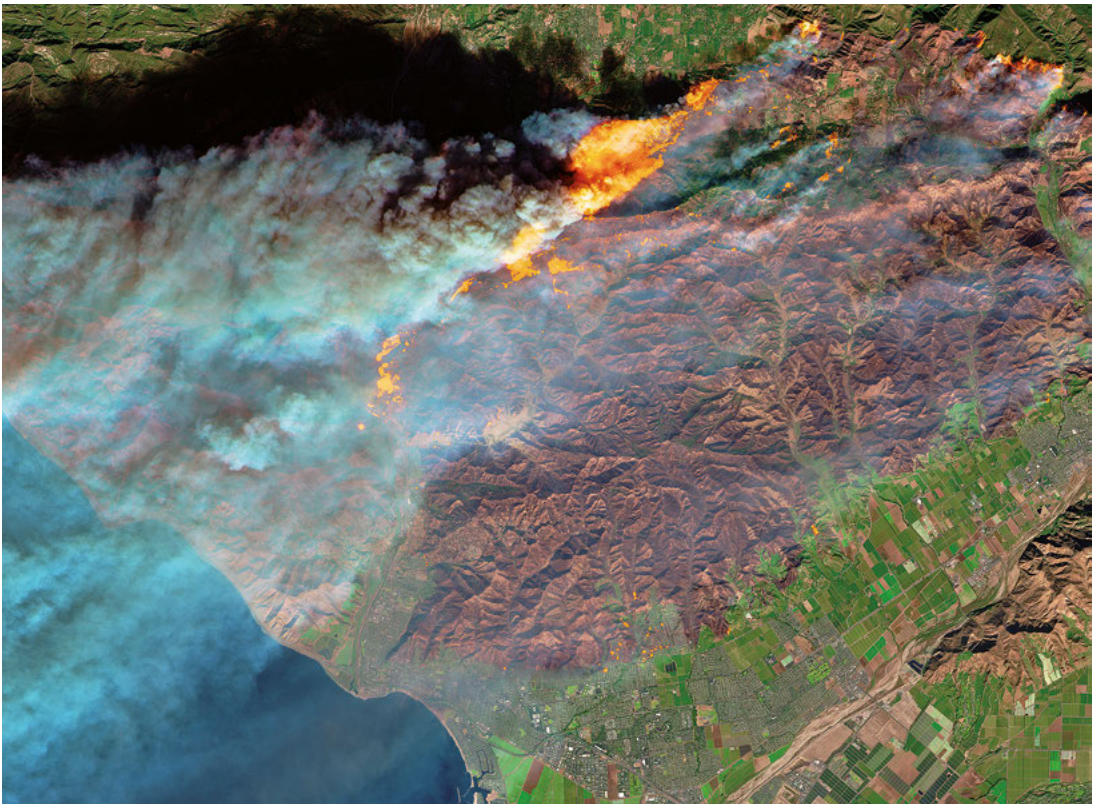
Another trend has been the increased use of adaptive pathway approaches for managing flood risk. In the United Kingdom of Great Britain and Northern Ireland, the Environment Agency has established the Thames Estuary 2100 project, with the aim of developing a strategic flood risk management plan for London and the Thames Estuary through to the end of the century.[40] This was instrumental in introducing a novel, cost-effective approach to manage growing flood risk by defining adaptation pathways that can manage a range of changes as needed. A possible path of cheaper flood defence options could be initially followed, but decision makers could switch to more expensive options if the drivers of the risk were not sufficiently addressed by the first pathway. For example, if mean sea level was found to be increasing faster than predicted due to accelerating effects of climate change, decision makers could pursue a different pathway with different costs and implications such as the installation of a new downstream barrage. The adaptive pathways approach is being developed into a tool for global application.[41]

3.1.5

Fire

The increased number of intense heat-waves and wildfires that has been recorded during recent years on a global basis has raised great concerns. It is apparent that projected climatic changes may significantly affect such phenomena in the future. Each year, wildfires result in high mortality rates and property losses, especially in the wildland urban interface (WUI). These fires affect millions of people and have devastating global consequences for biodiversity and ecosystems. Wildfire disasters can rapidly change their nature into technological disasters (e.g. in mixed areas of forest and residential, in heavy industrial or in recycling zones). In such cases, there is a global concern because toxic components such as dioxins are released, as well as fine and ultrafine particles with transboundary effects. Even though international policies and fire safety legislation have resulted in effective prevention mechanisms, environmental and technological fire hazards continue to threaten the sustainability of local populations and the biodiversity of affected areas.[42]

The year 2018 was reported as one of the warmest, affecting European Mediterranean countries such as Greece, Italy, Portugal and Spain, and also the countries of Central and Northern Europe. For example, Austria's June 2018 national temperature was 1.9°C above average and was one of the 10 warmest Junes on record.[43] Higher temperatures have generally been correlated with extreme weather events such as prolonged droughts, heatwaves and flash floods. The short-term precipitation period that is spatially intensive usually causes flash floods and hence it more often occurs in drier climates.[44] Under such circumstances, fire incidents



Wildfires in California in the United States of America in 2018
(Source: Joshua Stevens via the National Aeronautics and Space Administration (NASA) Earth Observatory)

35 (Dilling, Morss and Wilhelmi 2017)
36 (Loganathan, Kuo and Yannacconc 1987); (Pugh, Wiley and Chinchester 1987); (Samuels and Burt 2002); (Svensson and Jones 2002); (Svensson and Jones 2004); (van den Brink et al. 2005); (Hawkes 2008); (Kew et al. 2013); (Lian, Xu and Ma 2013); (Zheng et al. 2014); (Klerk et al. 2015); (van den Hurk et al. 2015); (Bevacqua et al. 2017)
37 (Ikeuchi et al. 2017)
38 (Yamazaki et al. 2011)
39 (Muis et al. 2016)
40 (Environment Agency 2012)
41 (Ranger et al. 2010)
42 (Karma et al. 2019)
43 (National Centers for Environmental Information 2018)
44 (Allan and Soden 2008)

in dry climate zones can easily be converted to megafires such as the Greek fires of August 2007,[45] which destroyed huge forest areas, and even within the Arctic Circle, as seen in the Swedish wildfires of July 2018.[46]

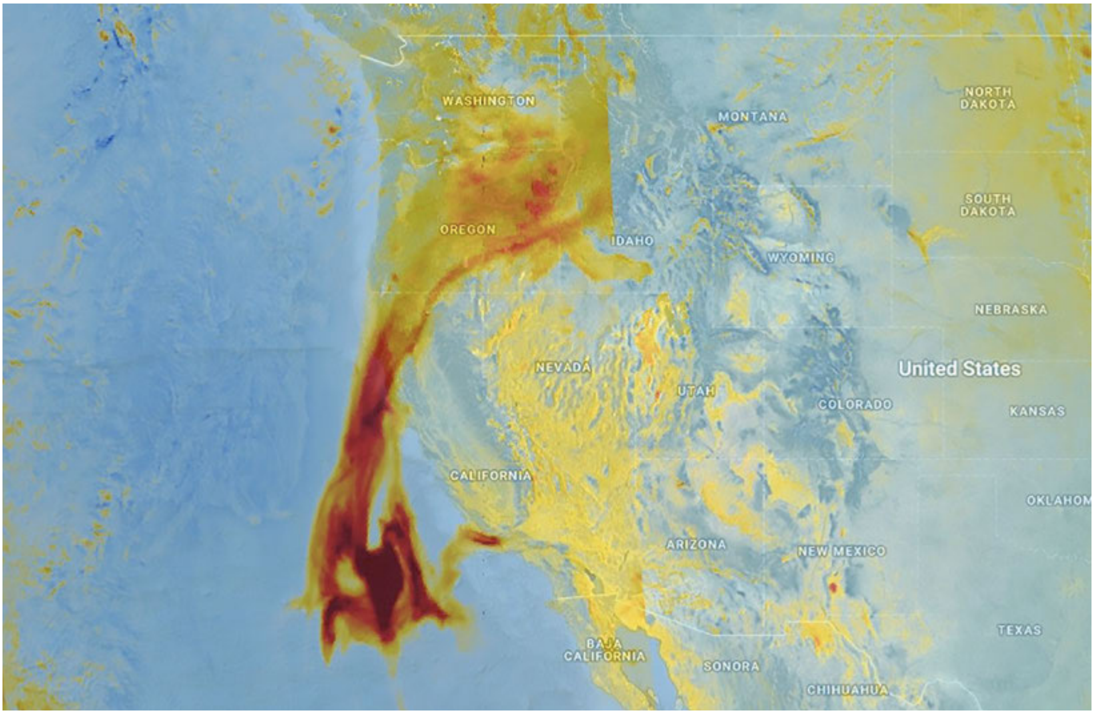
There is a general challenge surrounding the definition of fires. In the European Union (EU) the focus has been on forest fires. More frequent occurrences of wildfires have spurred an expanded definition into wildfire that does not require the fire at any point to affect a forest. A wildfire is a fire that is out of control. This excludes fires set for legitimate purposes such as crop burning but would include the same fires if they spread outside of the intended area.

A fire in WUI fire can generally be triggered either by natural (e.g. lightning strikes) or human-made causes (e.g. campfires or arson). As it spreads, it can draw fuel from all types of flammable sources, expand in size and impact, and, under specific conditions, may turn into a megafire.[47] Megafires near residential areas (WUI fires) can generally pose significant risks to populations, critical infrastructure and the environment. The dramatic and uncontrolled expansion of fire usually leads to human casualties and property losses as in Greece (2018), Portugal (2017) and the United States of America (2017).

For example, 2018 was the deadliest and most destructive fire season in California's history. Fires burned 766,439 ha, and caused more than $3.5 billion in damage. The Mendocino Complex Fire burned more than 186,000 ha, becoming the largest single fire in the California history.[48,49,50]

Apart from the fire expansion impact, smoke produced by fire also poses significant risks to health because it is a chemical mixture of a variety of substances, such as particles or gaseous

Figure 3.5. Tracking aerosols from California's fires



(Source: Copernicus Sentinel data 2017, processed by The Royal Netherlands Meteorological Institute 2017) pollutants like carbon monoxide, carbon dioxide, ammonia, dioxins and other highly toxic compounds that can be produced based on the types of materials burned towards the fire-front expansion.[51] The huge quantities of smoke produced in combination with the extreme thermal radiation emitted can cause suffocation and death for people who are directly exposed, even well after the fire has been controlled.[52]

In the past, there was often no information on fires, even at the regional level. It was frequently not possible to compile the various information together at the national level because of differences in methodology, models and definitions. A first step has been to harmonize systems by collecting fire information from countries and putting it into a common database, such as the European Forest Fire Information System (EFFIS). While this approach is a step in the right direction, it remains limited by the number of countries that have heterogeneous data-collection methods. In the EU, there are 22 countries providing information into EFFIS, but there are an additional 39 countries in the network that do not have a systematic data-collection method and thus cannot contribute data. This situation is not uncommon in other regions.

EFFIS has been in development for the last 20 years. The purpose originally was to estimate potential fire risk. When a fire occurs, the objective is then to monitor its progress and burned areas in real time including land-cover damage assessments, emissions assessments and potential soil erosion estimates, along with vegetation regeneration. The EU previously worked on computing various indexes from individual countries, but harmonization and standardization have led to countries using a standardized index.

A global fire information system has been under development since 2015 – the Global Wildfire Information System (GWIS). Its global group working on wildfire risk assessment is expected to produce a global level risk assessment by 2020. GWIS uses open source tools, is committed to open data and has records of 350 to 400 million ha of land burned every year. However, the base information used still does not include very small fires, so the total area burned is likely to be higher than these figures. In Europe alone, it is estimated that between 15% and 20% of fires are excluded from this data. This percentage is likely to be the same on the global level, putting the global estimate of burned hectares at approximately 450 million. Verification of global data on the ground is expensive. In some regions, there is a move towards using remote-sensing data to avoid the expense of data collection on the ground. Remote sensing works well for fires because the incidence and the impact are visually manifest; the combination of satellites and other sensors are useful for fire monitoring. These resources have been pooled into GWIS.

New satellites with more sensitive instruments allow access to higher-resolution sensors and will soon allow for the inclusion of smaller fires. One of the largest steps made by GWIS is the analysis of a data set that was so large at the global level that it required massive computing capacity to analyse, which was previously not accessible. With this data now available, other sectors will be able to incorporate it for inclusion in academic research, global multi-hazard risk assessment and consideration of chained, or cascading, hazards.

Analysis can be conducted on single fires to understand how they evolve. Twice-daily imagery is analysed to determine the speed of the fire and spread, which provides a view of the fire "climate" (if it is spreading and if the coverage is increasing). But the base requirement is a database of fires, and the GWIS database now covers the period from 2000 to the present.

45 (Gouveia et al. 2017)
46 (Anderson and Cowell 2018)
47 (Ronchi et al. 2017); (Intini et al. 2017)
48 (Geographic Area Coordination Centers 2019b)
49 (Berger and Elias 2018)
50 (Geographic Area Coordination Centers 2019a)
51 (Dokas, Statheropoulos and Karma 2007)
52 (Karma et al. 2019)

Figure 3.6. **British Columbia, Canada, 2017 wildfire that burned an area the size of Lebanon**

(Source: British Columbia Wildfire Service 2018)

Not all fires picked up through remote sensing are wildfires. Every summer, researchers observe unusual fire activity in Ireland, but they have learned that throughout the summer, Ireland celebrates several bonfire festivals that give false-positive readings.

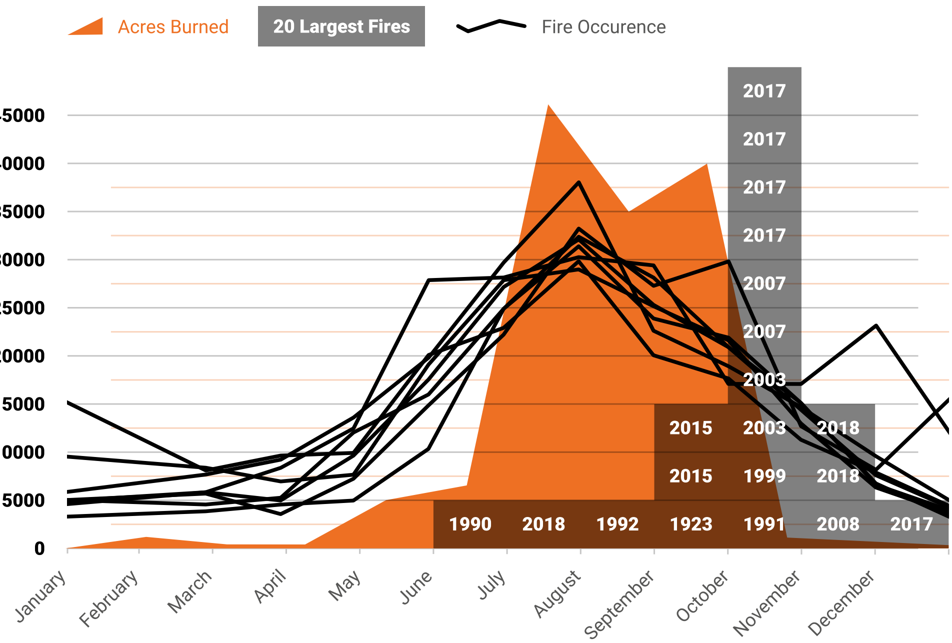
In 2017, the Canadian province of British Columbia experienced its largest single fire in its history, with 1.3% area of its total territory burned. A total of 12,160.53 km^2 of forest and residential areas was burned; almost 40,000 people were evacuated from their homes and more than 300 buildings were destroyed.

With the effects of climate change warming the planet, the incidence of fires will increase, and fires will arise in areas that have not previously been fire prone. One significant shift will see increased attention on the study of fire seasons to determine how seasons are changing. In 2017 in Europe, the most damaging fires (in June and October) fell outside of the traditional fire season (July to September). Fire seasons are becoming longer with greater areas being affected each year.

Figure 3.7 shows that peak season for fire occurrence and for average acres burned is between July and October in California. But 14 out of 20 of the most damaging fires have occurred in October or later, and all but three of the most damaging fires have occurred in the past 20 years

Another output of wildfires is emissions. The environmental impact of large-scale wildfires, particularly the huge quantities of carbon dioxide and water vapour produced, may have a significant greenhouse effect.[53] Equally, flora and fauna are heavily damaged with major impacts on biodiversity.[54] Wildfire impact on hydrology, soil properties and soil erosion by water are also of high importance,[55] and physicochemical properties and microbial characteristics of burned soils due to wildfires are strongly disturbed. Moreover, some of the toxic compounds such as heavy metals that are produced by fires are absorbed into a larger affected area than that which was burned. Ashes can be deposited on soil and water,[56] with consequences for crop quality and food chain safety. According to a recent study, severe wildfires may also endanger the water supply in downwind communities.[57] Particulate matter from wildfires is

Figure 3.7. **California fire occurrence by month and acres burned by month, 1996–2017**



(Source:UNDRR with data from California Fire Service 2018 and State of California 2019)

also a health risk (mostly the result of haze), as are dust-storms and sandstorms. While still difficult to quantify reliably, estimates indicate that 260,000 deaths a year can be attributed to smoke from forest, peat and grassland fires.[58]

State-of-the-art dynamic fire simulation models have been tested in a wildfire-prone region in Australia.[59] These have yielded a novel framework for modelling wildfire urban evacuation processes and calculating the safe escape time.[60] Personal fire evacuation plans may prove vital for the communities near areas at risk of fire. Simplified family-level plans for coping with WUI fires have been established in some regions, providing families with residential safety checklist and tips to improve family and property survival during a wildfire. However, these are available mostly in wealthy areas.

All types of fires over 300,000 deaths annually, and they are the fourth largest cause of accidental injury globally and represented 5% of all injury deaths globally in 2014.[61] Over 95% of fire deaths and burn injuries are in low- and middle-income countries. A high proportion of the urban populations in these countries are in low-income and informal settlements, with poor-quality housing, limited supporting infrastructure and services, and high vulnerability to fires and other hazards. However, little is known about the incidence, impact and causes of urban fires in these settings.[62]

53 (Kim and Sarkar 2017); (Kim et al. 2009)
54 (Boisramé et al. 2017)
55 (Shakesby 2011)
56 (Pereira et al. 2013)
57 (Robinne, Parisien and Flannigan 2016); (Hallema et al. 2018)
58 (Johnston et al. 2012)
59 (Beloglazov et al. 2015)
60 (Ronchi et al. 2017); (Kinateder et al. 2014)
61 (WHO 2014)
62 (Rush et al. 2019)

Box 3.2. Selected large informal settlement fires

- In February 2011, a fire left 10,000 homeless in three hours in Bahay Toro, Manila, Philippines.
- In May 2012, a fire affected approximately 3,500 people in Old Fadama, the largest informal settlement in Accra, Ghana.
- In April 2014 a fire in Valparaiso, Chile, destroyed about 2,500 homes and forced 12,500 people to evacuate.
- In March 2017, a fire in Imizamo Yethu informal settlement in Cape Town, South Africa, destroyed over 2,100 homes and left 9,700 people homeless.

3.1.6

Biological

Biological hazards cover a category of hazards that are of organic origin or conveyed by biological vectors, including pathogenic microorganisms, toxins and bioactive substances. Examples are bacteria, viruses or parasites, as well as venomous wildlife and insects, poisonous plants and mosquitoes carrying disease-causing agents.[63] While biological hazards also cause diseases in plants and animals, this chapter focuses on those biological hazards that affect human health.

Like other hazards, biological hazards and their associated infectious diseases occur at different scales with varying levels of consequence for public health. Diseases may be categorized by the way in which they are spread and people are infected, namely: water and food-borne diseases, where the pathogen can enter the body via contaminated food or water; vector-borne diseases, which involve mosquitoes, ticks and other arthropod species, or other animals that transmit the disease from animals to humans (zoonotic diseases) or among humans; air-borne or respiratory infections, which are spread between humans by the respiratory route; and other infectious diseases involving contact with bodily fluids such as blood.

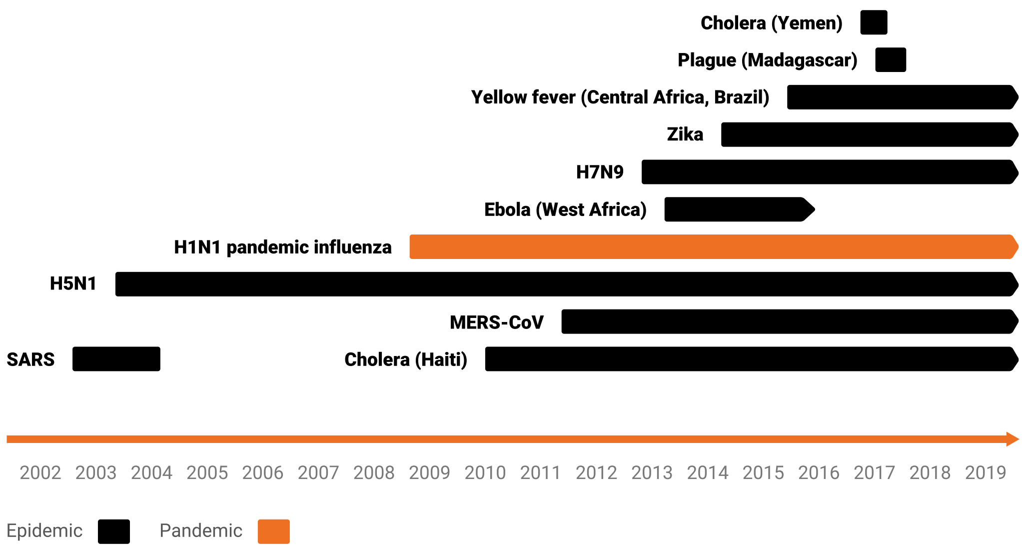
Biological hazards affect people at all levels of society. At the extreme, epidemic infectious diseases affect millions of people every year, with potentially severe consequences for individuals, communities, health systems and economies, especially in fragile and vulnerable countries where they are most common. However, no country is immune to the risk. New pathogens continue to emerge by mutating, re-assorting and adapting. Previously well-understood infectious agents change their behaviour or scale of impact as the world is getting warmer and more populated, with associated animal husbandry strategies, and with ecosystem changes, increasing speed of transportation and mass distribution systems.

As infectious diseases travel easily across administrative boundaries, the world's defences are only as effective as the weakest link in any country's efforts to anticipate and prevent emergence and outbreak at all scales. Biological hazards and their impact on global public health have brought to prominence the need for a collective and coordinated mechanism involving all sectors to prevent new risks, reduce and mitigate existing risks, and strengthen resilience. This approach is being promoted and reinforced by the integration of biological hazards in whole-of-society and all-hazard approaches to the management of risks, as reflected in the Sendai Framework, SDGs and the Paris Agreement, which are complemented by the International Health Regulations (2005) (IHR)[64] and other relevant global, regional, national and subnational strategies and agreements.

Trends in biological risk

The twenty-first century has already experienced major infectious disease epidemics. Old diseases such as cholera and plague have returned, and new ones like severe acute respiratory syndrome (SARS), Middle East respiratory syndrome (MERS), and H1N1 pandemic influenza have emerged. Another Ebola epidemic or a new influenza pandemic are likely and almost certain. The only unknowns are when and where they, or a new but equally lethal threat, will emerge.

Figure 3.8. Major infectious threats of the twenty-first century



(Source: World Health Organization (WHO) 2018)

Plague, for example, is commonly considered a scourge of a past age. However, a major outbreak in Madagascar in 2017 led to 2,417 cases and 209 deaths, as well as alerts for several countries with links to the island nation.[65] The outbreak was characterized by pneumonic plague, a far more fatal and infectious form of the infection than bubonic plague. The outbreak was the result of a scenario of unfavourable factors occurring over an endemicity in the country such as crowded living condition in the capital, increased mobility, lack of disease awareness, and poor infection prevention and control (IPC) measures. Nine countries and territories with trade and travel links to Madagascar were put on plague preparedness alert, highlighting the transboundary, multisectoral effect of biological hazards.

A novel coronavirus emerged from China in 2002 and swept the globe, causing an unheard-of deadly illness. More than 8,000 people fell ill with SARS, and 774 died. The illness spread to several countries, causing global panic and inflicting enormous economic damage across multiple sectors before it was finally contained about six months later. The

63 (United Nations General Assembly 2016b)
64 (WHO 2016)
65 (WHO 2017)

estimated economic loss ranged from $30 billion to $100 billion, depending on the methodology for counting indirect costs. Following SARS was avian influenza A(H5N1) virus infection in humans. Once controlled in Hong Kong in 1997, by effectively eliminating the transmission in poultry, the virus re-emerged from Quin Hai Lake of China, a crossroad of migratory birds and a huge waterfowl reserve. The virus spread across Asia and Africa and resulted in a huge economic loss in the agricultural sector. In 2009, a novel influenza virus, H1N1, known to originate in swine, started to spread, creating the first influenza pandemic of the twenty-first century. Thankfully, it was not as severe as expected due to strengthened health monitoring and prevention structures. But in 2012, a new coronavirus emerged, causing an illness similar to SARS. MERS is a viral respiratory disease caused by the coronavirus that was first identified in Saudi Arabia in 2012 and entered the human population via contact with infected dromedary camels.[66] MERS cases remain active at the time of this publication, causing concerns that the virus could cause a catastrophic epidemic in the Middle East and beyond.

The 2014 Ebola epidemic in West Africa was another unexpectedly severe event (in Guinea, Liberia and Sierra Leone). Instead of being restricted geographically, Ebola affected three African countries, spread to several others and sparked global alarm. The 2018–2019 Ebola outbreak in the Democratic Republic of the Congo, the country's tenth outbreak in four decades, was officially declared on 1 August 2018. The outbreak is centred in provinces where geographic challenges and security hazards have hindered containment and management of the outbreak.

Antimicrobial resistance (AMR) has become another health threat, compromising the medical community's ability to treat infectious diseases.[67] Inappropriate use of antimicrobials in the medical field and unregulated use in animal husbandry and food products – added to the natural capacity of microbes to acquire resistance to antimicrobials – are contributing to and accelerating AMR risk globally. It is predicted that the AMR problem will claim more lives and provoke massive increases in costs of management.[68]

Box 3.3. HIV/AIDS

One of the largest pandemic killers ever recorded, AIDS (acquired immunodeficiency syndrome) is an example of how rapidly a new infectious disease can take hold globally. Within a decade of its identification in 1981, over 10 million people across the world had become infected. The cumulative total is 70 million, half of whom have died. Thirty-seven million people worldwide now live with HIV (human immunodeficiency virus), 1.8 million new infections occurred in 2017, and every country has been touched. Death rates have been dramatically slowed by combination antiretroviral therapy, now reaching nearly 22 million people globally through massive mobilization of domestic and international resources, including in the poorest countries of the world.

As was often observed at the height of the pandemic, AIDS exploits the fault lines of a society. Marginalization, disruption and conflict become conduits for the spread of HIV. Some 53% of the global total number of people living with HIV is in Eastern and Southern Africa, where the epidemic's spread was fuelled by the combined effects of poor access to diagnosis, scarce treatment of sexually transmitted infections, sexual mixing patterns dominated by labour migration, post-conflict demobilization and effective response delayed by stigma, denial and resource scarcity. But in the past two decades, the region has shown the greatest progress in curbing new infections and expanding treatment access and reducing deaths.

However, a re-emergence is not inconceivable if the response is neglected in these high prevalence regions, or through the widening spread of the epidemic – the annual number of new HIV infections has doubled in less than 20 years in Central Asia, Eastern Europe, the Middle East and North Africa. Disaster and related issues of treatment supply chain (e.g. in the post 2010 earthquake in Haiti), war, or any major stresses or shocks to fragile national health systems could easily disrupt treatment regimes and give rise to a resurgence of the disease.

The case of the global HIV pandemic is a systemic risk, with roots spread through socio-economic, cultural and behavioural dimensions. The high incidence of comorbidities such as tuberculosis (TB) and viral hepatitis in immunocompromised persons with HIV infection calls for comprehensive and coordinated responses to HIV, TB, viral hepatitis and other sexually transmitted infections. The wider approach to the disease requires population-wide responses that transcend the diagnosis and treatment of individuals, looking for long-term, collective and multidisciplinary measures that include education, behavioural change, social services, testing, care and programme evaluation. Addressing these challenges demands strengthening of health systems: communication, IT, logistics, drug and vaccine supplies, and, particularly, building the capabilities of health personnel and community leaders and the platforms for them to work in synergy.

(Sources: UNAIDS 2015, 2018; WHO 2019; Schneider 2011)

Drivers of biological risk/causal factors

Unlike some other hazards (e.g. earthquakes or floods), biological hazards can be constantly present in the community – endemic – and usually pose low risk when the population is largely immune. Biological hazards, which are endemic in some communities, pose a risk of becoming epidemics when they are introduced to a new host community with no immunity. When people migrate from disease-free areas to endemic regions, they typically lack immunity, making them susceptible to infection and transmission of the disease, resulting in cases in excess of normal expectancy. These hazards have the potential to cause many cases and high rates of morbidity and mortality, and may spread to other areas of the country or across borders. The risk may also change when crises or emergencies such as droughts, floods, earthquakes and conflicts arise, exacerbating the conditions favourable for disease transmission and causing population displacement.

The pattern is clear. Old diseases such as plague and cholera continue to reappear, and new ones invariably emerge to join them. This is driven by a complex and challenging interplay of factors, reflecting the interaction between biological hazards, people's exposure to hazards, their susceptibility to becoming infected and the capacity of individuals, communities, countries and international actors to reduce risks and manage the consequences of outbreaks.

Almost all the newly emerging or re-emerging viral infections have come from transmission from animals. Potentially hazardous changes in land use, agricultural practices, animal husbandry and food production have led to increased contact between people and animals, with little regard for the ecological and human consequences of connected systems. Key drivers from domesticated animals include contemporary farming and livestock production systems and live animal markets.[69] Wildlife zoonoses can arise from factors related to hunting practices, deforestation and ecosystem breakdown.

66 (Zaki et al. 2012)
67 (WHO 2015)
68 (WHO 2014)
69 (Jones et al. 2008)

The probability that a new disease threat will spread is influenced by pathogen- and population-specific factors.[70] In the twenty-first century, ecological changes such as climate change and water scarcity have emerged as strong drivers of disease transmission. In a growing number of countries, rapid and unplanned patterns of urban development are making rapidly growing cities focal points for many emerging environmental and health hazards. Zika virus outbreaks are a case in point; the larvae of the Aedes mosquitoes thrive in stagnant water, which is abundant, for example, in slum areas where open containers, tyres, barrels and drums are used for gathering rainwater for household and garden use. Improving the human environment can therefore reduce exposure to the vector mosquitoes.[71]

War, civil unrest and political violence and their repercussions, such as refugee populations, displaced people and food insecurity, can result in a resurgence of previously controlled infectious diseases such as cholera, measles and diphtheria.[72] The movement of large numbers of people creates new opportunities for the spread and establishment of common or novel infectious diseases. For example, one of the worst cholera outbreaks in recent history is occurring in Yemen. Since April 2017, more than 1.3 million suspected cases of cholera and 2,641 deaths have been reported.[73] The catastrophic spread of disease is a consequence of two years of conflict and the resulting decimation of the country's health, water and sanitation systems and facilities, coupled with widespread internal displacement and alarmingly high rates of malnutrition.

One intention of this GAR is to help understand how the true nature of risk mirrors the systemic risk approach practised in public health services for several decades. The systemic approach for assessing biological risks affecting human health begins with the characterization of biological hazards. These include aspects such as infectivity, pathogenicity and virulence, infectious dose and survival outside the host. Next, exposure is defined by criteria such as host factors, environmental factors, transmission, reservoirs and vectors. Finally, vulnerability, a field exhaustively explored in public health, is characterized by factors such as population characteristics and population infrastructure. These factors are further disaggregated into the so-called social determinants of health: (a) social and economic environment: education, health services, social support networks – greater support from families, friends and communities, culture, customs, traditions, beliefs, income and social status; (b) physical environment: clean water and air, healthy workplaces, safe houses, communities and roads all contribute to good health; employment and working conditions; and (c) person's individual characteristics: behaviours, genetics and coping skills.[74] The intricacy of the measurement and interaction of the three risk factors – threats, exposure and vulnerability – are reflected in the complexity of the modelling used to assess the systemic health risk for biological hazards.[75]

Biological risk management and international instruments

With regard to biological risk, the health and epidemiology fields rely on a rich network of partnerships that span the health sector link with social and development partners. For non-influenza pathogens, sharing takes various forms: ad hoc, routine surveillance set up internationally, nationally or locally for the Extended Program on Immunization or through existing networks of institutions and researchers.

To respond to the emergence and spread of zoonotic pathogens, WHO has strengthened collaboration with the Food and Agricultural Organization of the United Nations (FAO) and the World Organization for Animal Health by forming a tripartite agreement for sharing responsibilities and coordinating global activities to address health risks at the animal–human–ecosystem interfaces.[76] In the context of influenza, risk monitoring, preparedness and response are continuous processes, requiring constant access to circulating viruses. This involves sharing viruses every year from as many countries as possible with the Global Influenza Surveillance and Response System (GISRS), a WHO-coordinated global network of laboratories. Based on these samples, WHO and GISRS can conduct risk assessments, monitor the evolution of seasonal influenza virus and the disease activity. Vaccine manufacturers use materials and information generated by GISRS to produce influenza vaccines. In return, the manufacturers contribute financially and by in-kind committments for pandemic preparedness and response (PIP Framework). GISRS also serves as a global alert mechanism for the emergence of influenza viruses with pandemic potential.

Disease risks can often be prevented or mitigated, and their harm reduced through vigilance coupled with a rapid response at all levels.[77] The basis of effective and efficient, well-targeted risk management measures is provided by different forms of risk assessment.

Strategic risk assessment is used for planning for risk management with a focus on prevention and preparedness measures, capacity development, and medium- to longer-term risk monitoring and evaluation, including tracking changes in risk over time. Strategic risk assessments enable the analysis of risks through a combination of hazard, exposure, vulnerability and capacity analyses, so that action can be taken to reduce the level of risk and consequences for health. Several common risk factors are addressed in risk assessments for biological and other hazards, such as population demographics (age or gender), health service availability and the capacity of the health and other systems in society. In addition, some more specific risk factors or sources of vulnerability apply to populations who are exposed to biological hazards, overcrowded living conditions, population displacement and the environmental factors in which the disease or vector may survive or grow.

It is also important to assess the risk of biological hazards after natural or human-induced events, including diseases. For example, the functioning of health facilities including diagnostic function and the vaccine cold chain can be affected by damage and interruption of services such as water and power. Disaster impacts on safe water, sanitation facilities and hygiene conditions may result in water-related communicable diseases or vector-borne diseases.

Risk management measures

Risk assessments inform policymakers to act to prevent, detect, prepare for and respond to biological hazards. This includes measures to reduce exposure of groups at increased risk of infection due to biological hazards, containing the spread of the risk, and eventually stopping it. Community-based actions and primary health care are at the core of strengthening community and individual resilience to all types of emergencies, by boosting the heath, immunization and nutritional status of individuals to reduce their susceptibility to diseases. The provision of primary care in epidemic, disaster and post-conflict situations is critical for prevention, early diagnosis and treatment of a wide range of diseases.

Effective water, sanitation and hygiene (WASH) planning can prevent or mitigate the risk of severe diarrheal diseases. The health sector must work with planners and engineers to ensure safe water and sanitation infrastructure. Chlorine is widely available, inexpensive, easily used and effective against most important waterborne pathogens. Some specific preventive interventions will reduce risks of vector-borne diseases such as malaria. Disease-specific strategies such as bed-nets, improving drainage to reduce vector breeding sites or insecticide spraying can help reduce these risks.

National disease surveillance and an EWS that extends to the community level is essential for

70 (Sands et al. 2016)
71 (WHO 2019)
72 (Blumberg et al. 2018)
73 (WHO 2018b)
74 (Sarmiento 2015)
75 (Sarmiento 2015)
76 (WHO 2010)
77 (Morse et al. 2012)

the rapid detection of cases of epidemic-prone diseases and rapid control. Surveillance and EWSs to detect outbreaks should be established, and cases reported through national systems to WHO when meeting the criteria for reporting under the IHR. Further risk management measures include protective equipment, IPC, behaviour-change practices by raising awareness and education of the public through risk communication, and effective treatments and/or routine and emergency vaccinations. Risk information is also used to inform response planning at various levels and capacity-development measures for health systems, including the training of health workers and key personnel from other sectors, such as logisticians, water and sanitation engineers, and the media.

Biological risk can often be prevented and harm can be reduced through vigilance coupled with a clear regulatory framework.[78] In 2005, all countries agreed to the revised IHR, which are designed to assist the global community in preventing and responding to acute public health risks that have potential to cross borders. The IHR were originally developed for only three diseases – smallpox, cholera and yellow fever – and were focused on arresting the spread of disease at borders and other points of entry. However, smallpox was eradicated in the 1970s, cholera reporting was disfavoured by countries because of negative effects on travel and trade, and yellow fever control has become easier thanks to an effective vaccine. But the value of an internationally recognized regulatory structure was not lost. A warning episode of H5N1 in Hong Kong in 1997 and the international spread of SARS in 2003 showed that an update to the IHR was required to deal with globalization and the interconnectivity of systems to forestall yet-unforeseeable microbial threats that have since become a reality. The IHR (2005) that came into force in 2007 are more flexible and future-oriented, requiring countries to consider the possible impact of all biological hazards, whether they occur naturally, accidentally or intentionally.

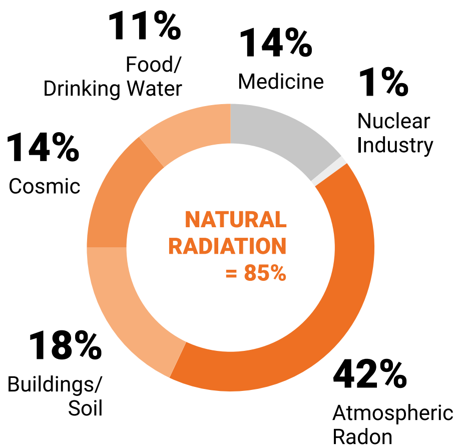
3.1.7

Nuclear/radiological

Radioactivity and the radiation it produces existed on Earth long before life emerged. In fact, they have been present in space since the beginning of the Universe, and radioactive material was part of the Earth at its very formation. But humanity first discovered this elemental, universal phenomenon only in the last years of the nineteenth century. Most people are aware of the use of radiation in the nuclear power production of electricity or in medical applications, yet many other uses of nuclear technologies in industry, agriculture, construction, research and other areas are hardly known at all. The sources of radiation causing the greatest risk to the public are not necessarily those that attract the most attention (Figure 3.10). In fact, everyday experience such as air travel and living in well-insulated homes in certain parts of the world can substantially increase exposure to radiation.[79]

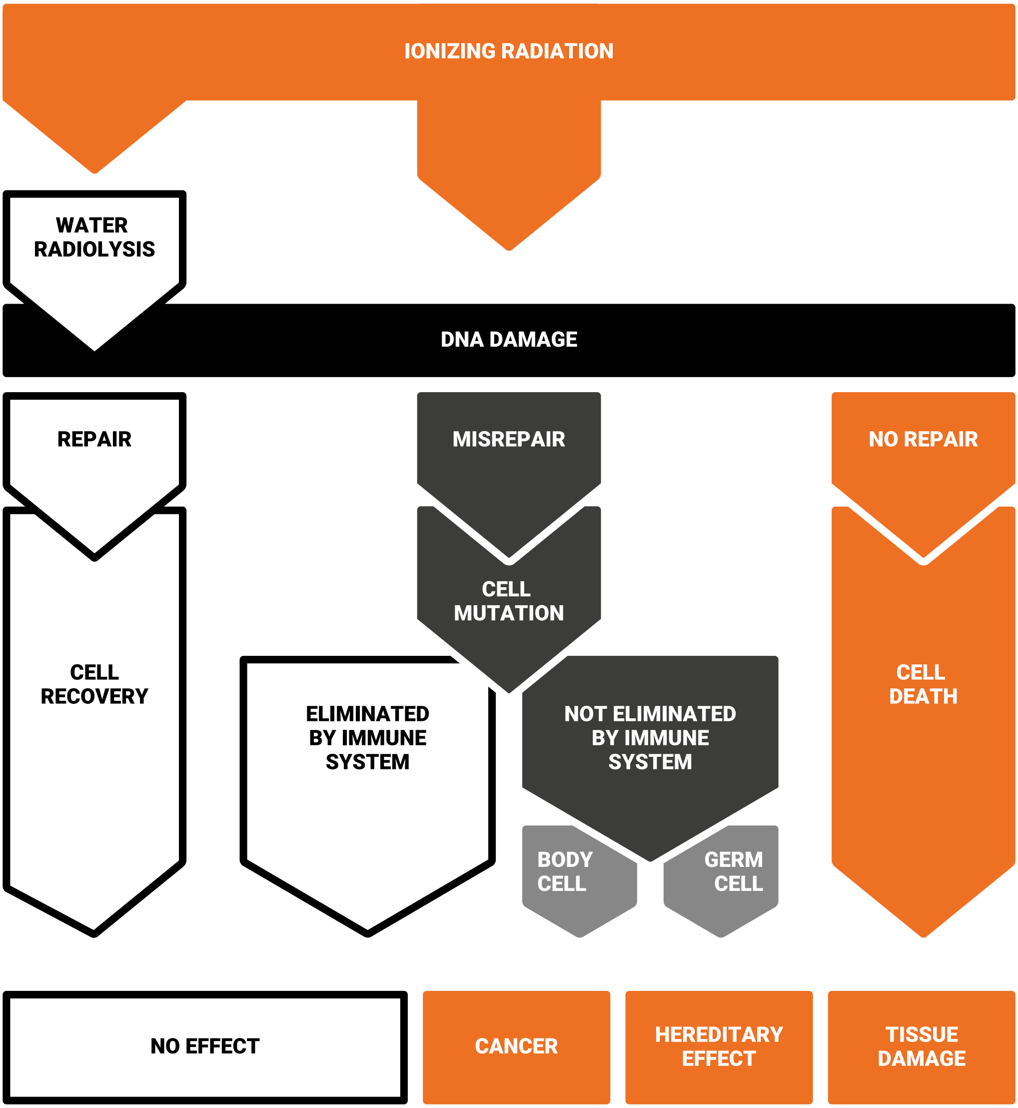
There is no formal distinction between nuclear and radiological risks and thus between associated safety arrangements. However, it is a well-established practice to distinguish exposures related to nuclear power generation from other radiation

Figure 3.9. Sources of radiation



(Source: World Nuclear Association 2018) exposures. From the physical point of view, both situations may result in the same kind of radiation exposure, so this distinction considers the different characteristics of the source of the risk. This GAR assumes that nuclear risks arise (or may potentially arise) from the uncertainties in the management of a nuclear chain reaction or the decay of the products of a chain reaction. Consequently, the radiological risks arise from uncertainties related to any other activities involving ionizing radiation.

Figure 3.10. Potential biological impacts of radiation damaging a cell



(Source:UNDRR)

78 (Morse et al. 2012)

79 (UNEP 2016)

The starkest manifestation of physical risk associated with nuclear power is when it affects living things. Cellular damage caused by ionizing radiation can do one of three things:

a. Repair itself successfully

b. Fail to repair itself and die

c. Fail to repair itself but survive

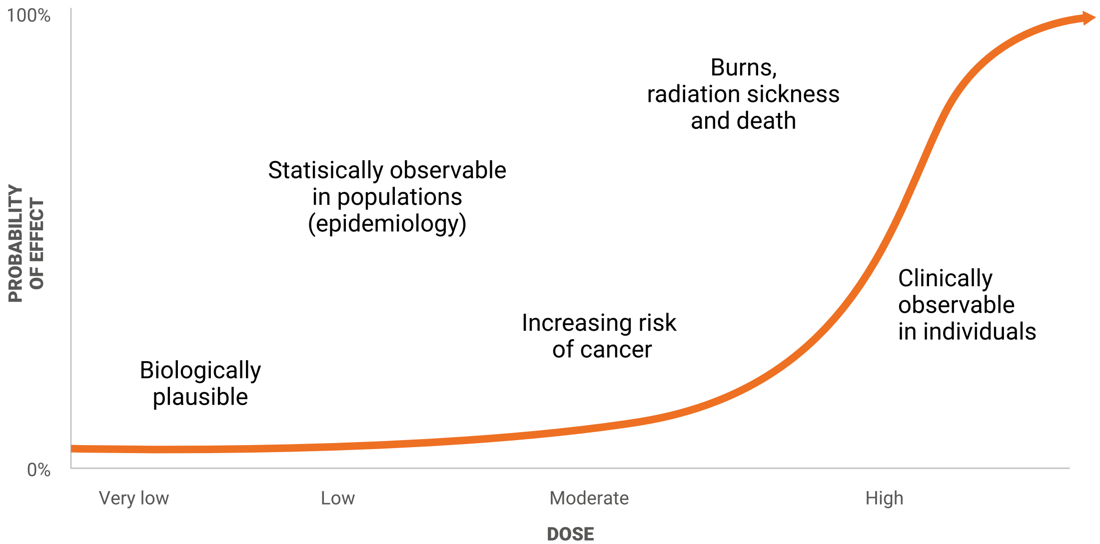
Outcomes (b) and (c) have very different implications for the organism as a whole.

Very high doses of radiation can cause serious damage to the blood-forming organs, stomach, intestinal tract and central nervous system, which can lead to death. Doses at this level will normally only occur because of very serious accidents, and only in case of exposures very close to the source of radiation.

Lower doses of ionizing radiation can cause leukaemia and cancer, appearing even many years after exposure, and can have effects that are manifest in future generations. High doses of radiation can cause other health problems, such as heart disease, strokes and cataracts.

Even though there is no clear scientific proof that cancer is caused by low doses of radiation, to be conservative, regulatory authorities around the world assume that any dose, no matter how small, is a risk and could be dangerous. It is assumed that the risk is in linear proportion to the dose.

Figure 3.11. **Relationship of radiation doses and health effects**



(Source: Data adapted from UN Environment 2016)

In addition to health effects such as acute radiation syndrome and increased incidence of cancer, adverse effects on mental health are observed. Mental health was the biggest long-term public health problem that ensued from the nuclear accidents of Three Mile Island and Chernobyl. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) found that in the case of the Fukushima Daiichi accident, the most important consequences on health were mental health and social well-being. Existing international safety standards include generic requirements for provisions that are necessary to consider mitigation of the psychosocial and mental health impacts of nuclear accidents. However, they do not offer explicit descriptions of the required tools. A recent joint initiative by WHO and the OECD Nuclear Energy Agency (NEA) aims at proposing practical solutions/tools for support of the decision-making process while planning for and responding to nuclear and radiological emergencies. These actions are based on the development of a policy framework that adopts existing WHO guidelines on mental health and psychological support in nuclear and radiological emergencies.

The burden of nuclear accidents on mental health, while specific, is not unique to the nuclear field. The inclusion of mental health in the Sendai Framework marks a pivotal point in the recognition of the impact of disasters – of both natural and anthropogenic – on mental health, and a global commitment to its reduction.

The United Nations General Assembly acted to resolve the question of how objectively adverse health effects can be attributed to radiation as compared to the subjective inference of potential radiation risks.

The UNSCEAR report:[80]

- Distinguishes the objective attribution of health effects to retrospective exposure situations from the subjective inference of potential risks from prospective exposure situations.
- Concludes that increases in the incidence of health effects in populations cannot be attributed to low doses, but risk from planned situations may be prospectively inferred for purposes of radiation protection and allocation of resources.

For the safety standards outlined in the report it is assumed that there is no threshold level of radiation dose below which there are no associated radiation risks.[81] The term "radiation risks" is used in these standards in a general sense to refer to detrimental health effects of radiation exposure, including the likelihood of such effects occurring (and to any other safety related risks, including those to ecosystems in the environment). The fundamental safety objective in these standards is to protect people – individually and collectively – (and, in addition, the environment) from the harmful effects of ionizing radiation. The standards recognize that the effects of radiation on human health involve uncertainties; in particular, "assumptions have to be made owing to uncertainties concerning the health effects of radiation exposure at low doses and low dose rates."

The most harmful consequences arising from nuclear facilities and activities have come from the loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or other source of radiation.

To reduce the likelihood of an accident having harmful consequences, several design principles, concepts and tools for optimizing nuclear safety, as well as the defence in depth (DiD) concept, have been developed. DiD is based on the military philosophy of providing multiple barriers of defence and may be summarized as a sequence of preventive, control (protective) and mitigative measures in performance of three basic safety functions: (a) controlling the power, (b) cooling the fuel and (c) confining the radioactive material. It comprises five levels, as shown in Table 3.1.[82]

The effectiveness of protection is established using the principles of, inter alia, redundancy, diversity, segregation, physical separation and single-point failure protection. The protective layers comprise the physical barriers and also the administrative procedures and other related arrangements.

80 (UNSCEAR 2015)
81 IAEA Fundamental Safety Principles are jointly sponsored by multiple organizations: European Atomic Energy Community (Euratom), FAO, the International Labour Organization, the International Maritime Organization, OECD NEA, the Pan American Health Organization, the United Nations Environment Programme (UNEP) and WHO; (IAEA 2006).
82 (NEA 2016)

Table 3.1. DiD levels

Level of DiD	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

(Source: IAEA 1996)

Both nuclear risk analysis methods (deterministic and probabilistic) use "postulated initiating events". These are "all foreseeable events with the potential for serious consequences and all foreseeable events with a significant frequency of occurrence are anticipated and are considered in design."[83] Examples include: loss of coolant accident (break in the cooling system), loss of off-site power (station blackout), reactivity-initiated accident (boron dilution, pump flow increase, etc.) or external events such as earthquakes or fires. The principal deterministic approaches seek to verify if the frequency of the postulated initiating events stays within acceptable criteria.[84]

In the aftermath of the Chernobyl accident, the International Atomic Energy Agency (IAEA) and NEA jointly developed an International Nuclear

Figure 3.12. International Nuclear and Radiological Event Scale

(Source: IAEA 2019)

and Radiological Event Scale (INES). This is a tool for promptly and consistently communicating the safety significance of events associated with sources of radiation.[85]

Initially developed for nuclear events, INES now explains the significance of events from a range of activities, including industrial and medical use of radiation sources, operations at nuclear facilities and transport of radioactive material. The scale is based on a numerical rating including seven levels (each increase in level implies 10× greater severity). Evaluation of the level is made on the basis of the impact on three areas:

a. People and the environment

b. Radiological barriers and control

c. DiD

The evaluation of economic impacts of a nuclear accident is controversial and strongly dependent on subjective assumptions about the types of losses included in the analysis, the resilience of the economy to the event, and the behaviour of authorities and population after the accident.[86]

One of the factors evoked by an NEA report concerns the damage to agriculture.[87] Many of the world's nuclear installations are surrounded, at least in part, by agricultural lands. These areas are usually lightly populated, and small farms and gardens are not uncommon. In such situations, dealing with post-accident contamination of agricultural areas, while very personal, can also be important from economic and social standpoints. These issues need to be addressed in the context of active involvement by affected individuals in planning and decision-making processes.

Moreover, the importance of trust has been highlighted in recent lessons learned through analysis. Trust in processes that authorize, verify and confirm safety of domestic and international consumer markets is central to maintaining viable agricultural production in radiologically contaminated areas. This suggests the need for a coordinated communications strategy involving farmers, fishers, distributors, consumers, experts (including universities), and local and central governments to bring stakeholders in closer contact with the efforts being made and the results being achieved. Independent, international validation and inviting co-expertise, for example through non-governmental organizations (NGOs), could be considered as trust-building approaches.

Of the many important lessons learned about nuclear safety over years, the one that has been most difficult to communicate and difficult to address is that human aspects of nuclear safety may be as important as any technical issue that arises during nuclear operations. Nuclear power is a highly technical undertaking and those who design, build and operate nuclear plants are highly qualified specialists in a wide range of engineering and scientific fields. However, technical aspects cannot be the only area of focus to ensure safety: attention to the safety culture that exists in the work environment is also required. Organizations need to consider how people interact and communicate with each other, when issues are raised and how are they addressed, what priority is given to safety – especially when presented with competing priorities.[88]

The ethical and social dimensions are important, and radiological protection and social sciences should work together. A better understanding of the radiation protection system, involving the social sciences, could facilitate incorporation of new findings, and make the system more flexible.

The effects of climate change might have an impact on the risk related to nuclear power plants in two ways.[89] The gradual change in climate slowly affects

83 (IAEA 2016)
84 (IAEA 2010)
85 (IAEA 2013); (IAEA 2014)
86 (NEA 2018a)
87 (NEA 2018a)
88 (NEA 2018b)
89 (IAEA 2018)

a plant's operational environment. The main potential threats are: sea-level rise, which could result in inundation of coastal sites; the increase of ambient temperature decreasing a nuclear power plant's thermal efficiency; lower mean precipitation reducing the cooling effectiveness; and higher average wind speeds affecting the construction of a plant. Another category arises from the fact that nuclear power plants, like any other construction, are prone to the effects of extreme weather events. Notably, existing site selection and design criteria anticipate a variety of extreme weather events. Examples of such events include extreme heat and drought, which could decrease the cooling efficiency, floods resulting in inundation or fires affecting plant construction. Like any other complex technology, nuclear power generation brings benefits and risks. Continuous development of more efficient nuclear risk management brings to the fore a discussion of value of nuclear power generation as a potential element in zero-emission energy generation worldwide. With low GHG emissions over a plant's lifetime, nuclear energy is an alternative to the high-emission fossil fuel technologies that dominate electricity generation worldwide. A system-wide shift to a combination of renewable energy sources and nuclear would contribute to reductions of carbon dioxide emissions and help to limit global temperature rise.

No industry is immune from accidents, but all industries learn from them. There have been three major reactor accidents in the history of civil nuclear power: Three Mile Island, Chernobyl and Fukushima Daiichi. All three have had a significant impact on nuclear risk management and public perceptions of the risks of nuclear energy. The lessons learned have been carefully identified and are incorporated worldwide. They have contributed to a level of excellence in risk management in the nuclear field.

The root causes of nuclear accident have been found to be cultural and institutional.[90] A follow-up of the International Nuclear Safety Group (INSAG) emphasizes that "to achieve high levels of safety in all circumstances and against all challenges, the nuclear safety system in its entirety must be robust."[91] It identified three stakeholder groups to be engaged in building a robust and effective nuclear safety system:

- Regulator – responsible for independent safety oversight
- Industry – including the licensee who holds the prime responsibility for safety of nuclear power plant
- Stakeholders – primarily members of the public.

In its recommendations for the protection of people from exposure to radiation, the International Commission on Radiological Protection emphasizes the effectiveness of directly involving the affected population and local professionals in the management of post-accident situations, and the responsibility of authorities at national and local levels to create conditions and provide means favouring the involvement and empowerment of the population in the aftermath of a radiological event.

Lessons learned from accident recovery management include the following:

- Trust needs to be built before accidents occur
- A flexible regulatory framework is needed to best address the accident conditions that occur
- Medical community networks should be identified around known hazardous installations, and relevant plain-language radiological information should be ready to send so that they can address affected stakeholder concerns
- Governmental decisions should actively reflect that stakeholder concerns have been considered
- Expert resources needed to address affected stakeholder concerns can be extensive, and should be planned in an all-hazards framework
- Personal dosimetry and area monitoring equipment should be available

For all types of hazards, societal understanding and acceptance of risk depend on scientific knowledge and evaluations, and also on perceptions of risk and benefit. Radiological hazards are among the most studied risks in modern society. While the risk of death from exposure to the annual public dose limit (1 mSv) is small – approximately 0.00005% – and certainly much lower than other cancer risks (e.g. age, alcohol, diet, obesity, immunosuppression, sunlight, tobacco and asbestos), evidence for any effects on individuals at low doses is still very limited. This inability to satisfactorily describe effects at the exposure levels commonly encountered in most exposure situations can lead to misunderstanding, mischaracterization of the risk and disproportionate responses.

The radiation protection and nuclear community has continued to encounter difficulties in effectively communicating risk and uncertainty – whether in respect of siting new nuclear plants or waste disposal facilities, selecting endpoints for decommissioning or legacy-management operations, or managing emergency or post-accident recovery operations. However, awareness of the negative effects on health has evolved over the last decade, leading to the development of new approaches to radiation risk communication.

3.1.8

Chemical/industrial

Industrial production is a central characteristic of the modern world economy. Industry creates jobs and provides a wide range of essential materials, products and services. However, authorities, in cooperation with industry, must ensure that industrial facilities producing, handling or storing hazardous substances such as tailings management facilities (TMFs), pipelines, oil terminals and chemical installations are safely located and operated, as accidents can have far-reaching and severe effects on people, environments and economies.

Industrial hazards originate from technological or industrial conditions, dangerous procedures, infrastructure failures or specific human activities.[92] These include toxic releases, explosions, fires and chemical spills into the air, adjacent water courses and land. In many countries, industrial hazards are exacerbated by ageing, abandoned or idle installations. These problems are amplified by insufficient institutional and legal capacities to deal with technological risk reduction. Natural hazards – for example, storms, landslides, floods or earthquakes – can also cause industrial accidents by triggering the release of hazardous substances from industrial facilities that are located within their path of destruction (see section 3.1.9). The impact associated with industrial accidents relate to loss of life, injury, or destruction or damage of assets that could occur to a system, society or a community.[93] Effective management of risks requires cooperation within and across systems, sectors, countries and scales.

Most industrial accidents entail the release of hazardous substances into water bodies with grave impacts on water resources, threatening the availability of safe water for drinking, household use and agriculture, as well as human safety.

90 (IAEA 2015); (IAEA 2017)
91 (IAEA 2017)
92 (United Nations General Assembly 2016b)
93 (United Nations General Assembly 2016b)

For many decades, the issue of industrial accident prevention, preparedness and response has been of concern to governments, as well as industry. In the mid-1980s, the issue took on a new level of urgency and political importance in response to the Bhopal accident in India, which resulted in more than 15,000 deaths and more than 100,000 people affected. While regulation and new standards have driven significant progress in industrial safety in the past 40 years, major accidents still occur as countries face new challenges and emerging risks. In recent years, extreme weather-related events triggered industrial accidents with severe environmental and economic consequences, such as Hurricane Harvey in the United States of America.

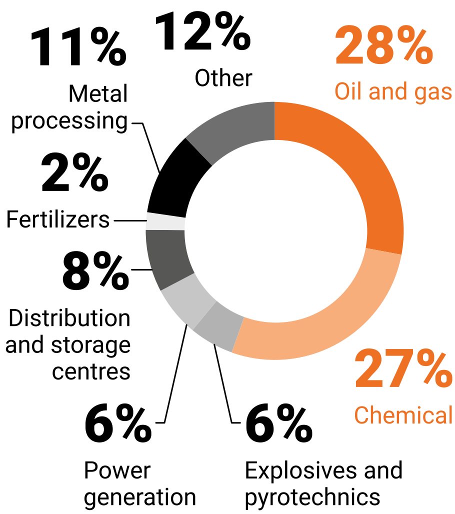
A multidisciplinary and cross-sectoral approach to addressing industrial accident risk is required. The Sendai Framework promotes this across its four priorities in the systems-based approaches to risk management.

This section explores the trends in industrial risks and the underlying drivers of these risks (identifying the casual factors). It examines how progress in managing risks is measured, introduces industrial accident risk reduction approaches, and explores challenges and opportunities for effective risk management in the future.

Trends in industrial hazards and risks

Industrial accident risk is highly dependent on the activity of the site, the processes it operates and the types of dangerous substances it uses. There are hundreds of processes in oil and gas or chemicals processing industries. They may be present in land-based facilities (also known as "fixed facilities" such as chemical establishments, oil terminals and TMFs), pipelines, transport by rail, road and water, and offshore oil exploration platforms. Explosives industries, involving manufacture and/ or storage of explosives, fireworks and other pyrotechnic articles, are also prominent sources of industrial accident risk. Widespread use of dangerous substances, such as cyanide and arsenic, in metals processing means that the mining industry also represents a high risk.

Figure 3.13. Distribution of high hazard, fixed facility sites (Seveso Directive) in EU and European Economic Area countries in 2014

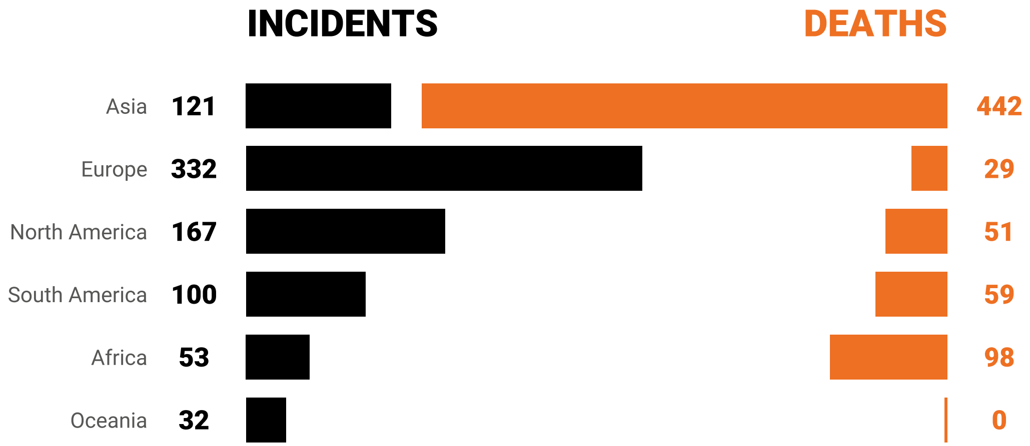


(Source: Wood and Fabbri 2019)

In addition, numerous other industries can be sources of industrial risk. Sometimes known as "downstream users", these include industries such as food production, power plants and metal plating; these use dangerous substances in large quantities for refrigeration, fuel, metal treatment and various other specialized uses. The latter are particularly challenging in risk management because awareness about these materials may be lower than in those industries whose core business involves exploitation, manufacture, storage or handling of highly regulated substances.

Figure 3.14 shows information in media reports worldwide on chemical accidents over a one-year period, demonstrating that hundreds of people die every year and at higher rates in some areas of the world than others. Media reporting does not represent a complete picture of all incidents that have occurred, but it does tend to be consistent and reasonably reliable when citing major impacts, especially for deaths, injuries, evacuations and environmental contamination. Of these incidents, 12% (77) involved at least one death, 25% (163) involved death and/or injury, and evacuations and

Figure 3.14. Chemical incidents in the media by continent, 1 October 2016 to 30 September 2017



(Source: Wood and Fabbri 2019)

environmental impacts were involved in an additional 4% (26) of cases.

There is limited data collected for assessing the status of industrial accident risk globally. There are some sources of data on industrial accidents in government and industry that can be used to quantify the frequency and severity of some types of events, but they fall short of providing a complete perspective that covers all accidents occurring in industry and commerce globally. Systematic identification and recording of causal trends and impacts is largely driven by government requirements (this excludes "incident notification" databases) and industry initiatives, so that existing data is fragmented and disjointed in nature.[94]

While industrial accidents are deterministic events that cannot be fully evaluated with a simple measure of counting the occurrences or trends of a particular scale, an industrial accident is still clear evidence of a failure to control risk. Past accidents can also provide diagnostic information, particularly if some accidents have common features (e.g. location, or type of industry, equipment, substance or cause).

Major accidents are generally rarer events. The average frequency of events in any one country across a period of even 10 years will tend to be extremely low, especially in small countries and those with a low level of industrialization. However, many emerging economies have experienced rapid growth in hazardous operations from expansion of particular segments of oil and gas, chemical and petrochemical and mining industries, driven by a combination of factors including increased demand in emerging economies, access to raw materials and the need to lower production costs, facilitated by a decline in trade barriers and government incentives to attract foreign investors.

Tailings management facilities

The consequences of failure in the design, construction, operation or management of TMFs – essentially large dams storing chemical waste at oil terminals and mining facilities – can release contained hazardous waste products that pose grave risks to human health, infrastructure and environmental resources. No publicly accessible inventory of TMFs or data on the global volume of stored tailings exists. However,

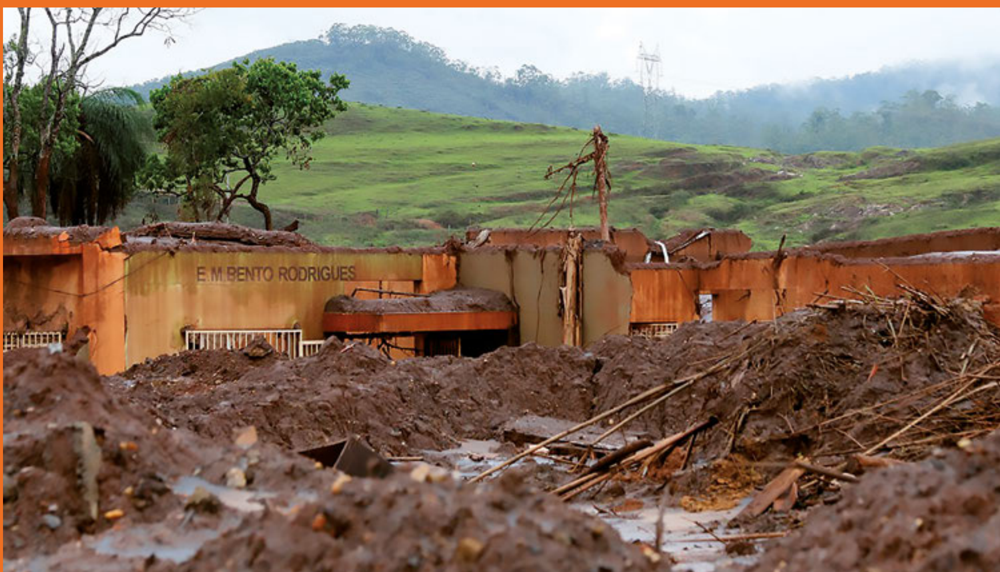
94 (Wood and Fabbri 2019)

the scale of accidents of this nature can be seen in recent disasters. The Mount Polley spill in Canada in 2014 and the Bento Rodrigues accident in Brazil in 2015 each released more than 25 million m^3 of hazardous substances, which, when combined, represent the volume of 20,000 Olympic swimming pools.[95]

Box 3.4. Bento Rodrigues TMF accident, Brazil, 2015 and Brumadinho, Brazil, 2019

The collapse of two TMFs of an iron ore mine located in Bento Rodrigues, Brazil, resulted in one of the worst human and environmental disasters in Brazil's history. Some 40 million m^3 of waste laden with heavy metals flooded villages downstream, causing 19 deaths and contamination of the Doce River basin, with huge damage to biodiversity and drinking water supplies. The toxic slick flowed 650 km down river, contaminating 2,200 ha of land and affecting about 40 municipalities. The disaster revealed critical gaps in regulation, monitoring, enforcement, information flow, early warning, response and coordination mechanisms between the operator and authorities at all scales. Three years later, remediation measures had still not been effectively implemented, and affected populations continued to endure the environmental and socioeconomic repercussions of the failure. At the time of writing, Brazilian state prosecutors are bringing a case against the mine and dam operators, alleging that as early as 2011, the board was apprised of seepage in the dam, advised to consider suspending operations, relocating the town of Bento Rodrigues and installing early warning sirens, but had failed to act.

In early January 2019, another dam failure in Brumadinho, Brazil, collapsed, causing the death of 186 people and a further 122 missing. The TMF in Brumadinho, owned by one of the two parent companies who owned the Bento Rodrigues dam released 12 million m^3 of tailings. The spilled chemicals have been incorporated into river soil and affect the region's ecosystem permanently.

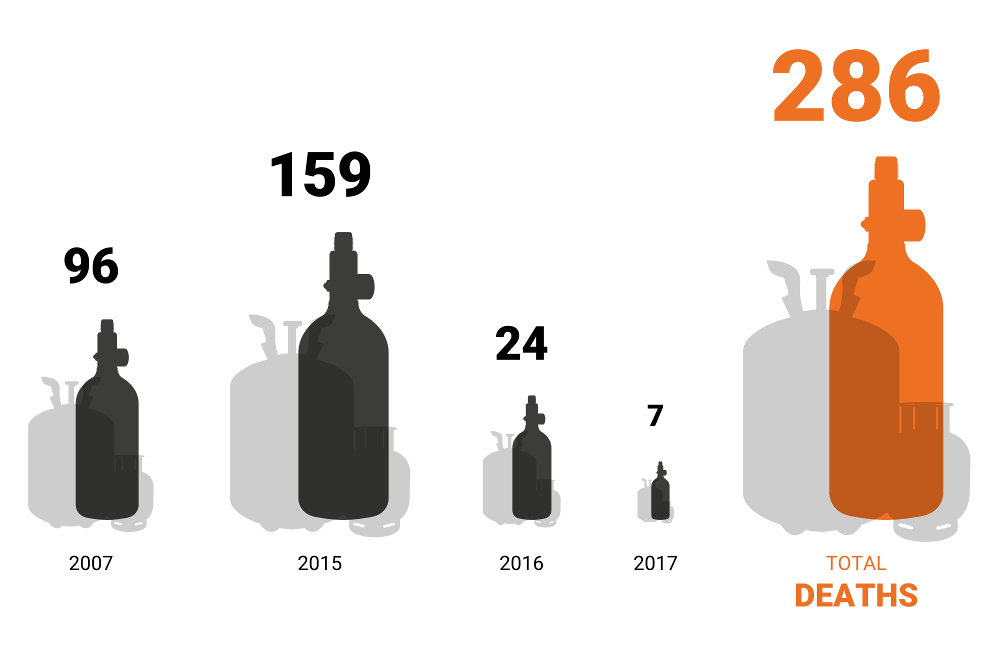


Debris and damage at a school in Bento Rodrigues, Brazil from the upstream dam failure
(Source: Rogério Alves/TV Senado 2017)

Box 3.5. Liquefied petroleum gas (LPG) accidents in Ghana

In October 2017, seven people were killed at an LPG distribution point, taking the number of deaths from LPG accidents at industrial and commercial sites in Ghana to 286 since 2007.

Figure 3.15. Fatalities in Ghana related to LPG accidents since 2007



(Source:UNDRR with data from Citimfonline 2016)

An analysis of TMF failures worldwide over the last decade indicates that while the overall number of failures has decreased, the number of serious failures has increased.[96] Despite the many advances in the mining sector, TMF failures still occur. In the past six years, there have been eight major TMF failures in Brazil (three times), Canada, China, Israel, Mexico and the United States of America. Identifying TMFs and their hazard potential (including the risk of failure) is important to target intervention measures and adjust the legal and policy framework.

95 (Roche, Thygesen and Baker 2017)

96 (Roche, Thygesen and Baker 2017)

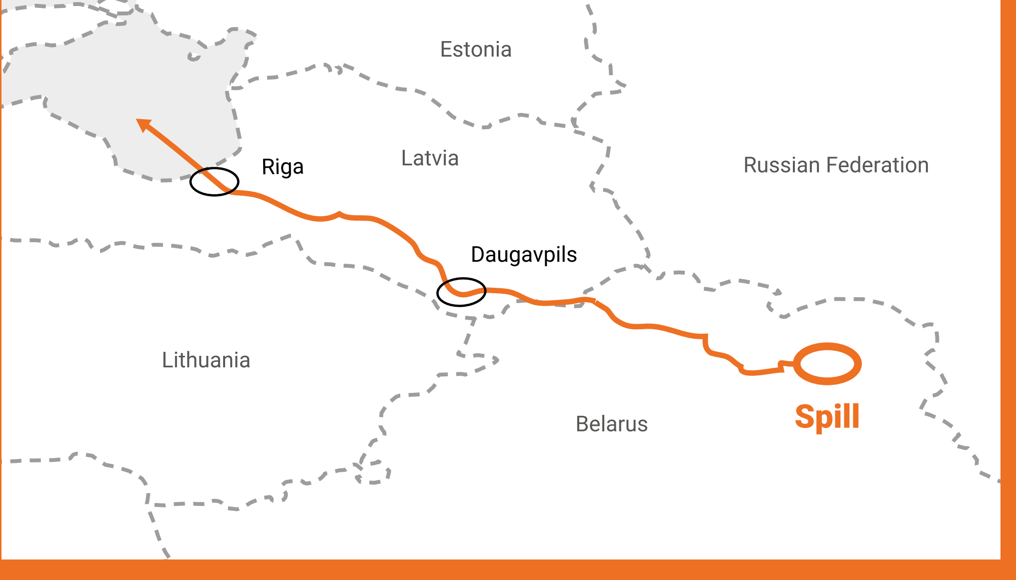
Petrochemical facilities

Petrochemical plants, oil terminals and wells store and process large amounts of hazardous substances. In the event of improper design, construction, management, operation or maintenance, this can provoke uncontrolled spills, fires and explosions, with potentially catastrophic consequences in terms of loss of life or environmental damage. The effective and safe extraction, storage and distribution of oil products present technical and environmental challenges, while remaining essential for economic activity. As each facility is unique, a tailor-made and comprehensive approach is needed to ensure that these facilities are operated in a safe, environmentally sound and economic manner.

Box 3.6. Daugava pipeline spill in Belarus, 2007

The rupture, due to ageing infrastructure, of a pipeline on 23 March 2007 in Belarus resulted in a spill of approximately 120 tonnes of diesel fuel into the Ulla River, a tributary of the Daugava River. The slick extended over 100 km downstream through Daugavpils and Riga to reach the Gulf of Riga in the Baltic Sea. Long-term damage from the spill was averted by coordinated international emergency action and coordinated assessment methodology (Bonn Agreement Oil Appearance Code) applied by Belarussian and Latvian experts, which resulted in payments by the company commensurate to assessed environmental damage.

Figure 3.16. Path of the spill in the Ulla River



(Source:UNDRR 2019)

Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations

Box 3.7. Buncefield accident, United Kingdom of Great Britain and Northern Ireland, 2005

On 11 December 2005, overfilling of a petroleum storage tank at a fuel storage depot led to several explosions and a fire that burned for five days, with no loss of life and relatively few injuries. It caused the evacuation of approximately 2,000 people, destroyed 20 homes and caused damage to 60 businesses, incurring an estimated total cost of over 750 million euros.

Pollutants contaminated soil and groundwater and toxic plume dispersed over southern England to northern coastal regions of France and Spain. The Major Incident Investigation Board established in the aftermath provided recommendations for industry, regulators and the emergency services related to safety and environmental standards for fuel storage terminals and emergency response measures. Following the accident, inspections were also conducted inside fuel storage terminals in France and other European countries.

Toxic plume emanating from the explosion at the Buncefield fuel storage depot, United Kingdom of Great Britain and Northern Ireland, 2005
(Source: Flickr.com user Ken Douglas 2005)

While data on industrial accidents is often insufficient to assess the full range of potential impacts and is difficult to quantify in any standardized manner, it does exist. Table 3.2 explores the strengths and limitations of various impact data available in public databases of chemical incidents.

Table 3.2. Strengths and limitations of different sources of impact data to measure industrial risk

Type of impact data	Strengths and limitations
Human health	Historically, fatalities are identified and recorded. Injuries are also usually quantified, but the precision about the number and severity increases with the severity of the accident varies.
Environmental	Environmental impacts are reported using a variety of denominations to quantify the impact (cubic metres, length of a river, duration of the power outage, etc.) and rarely include secondary effects or costs of clean-up and restoration or economic costs from loss of the resources.
Property damage	Data on cost of on-site property damage is often provided, but not as reliably as human health impacts and usually only for insured losses. Off-site property damage, when it has occurred, is frequently excluded from reports, rarely appearing in either accident databases or insurance company statistics. Sometimes, the media will make an estimate for a particularly prominent accident. For large incidents, the data can sometimes be found in annual insurance reports.
Evacuation and shelter-in-place	This data is frequently provided as estimates, it is often sufficient for estimating severity of this aspect but cannot be easily summed for aggregating effects of major accidents over a period of time.
Social disruption	Disruptions to roads and public utilities are among other impacts that generally are ill-defined in terms of what they include and how they are quantified (hours of disruption, population size disrupted, etc.).
Economic	Temporary and permanent shutdown of product lines and sites are a significant economic impact of many accidents. This data is usually provided only in investigation reports and the media.
Long-term health and social	These effects may include injuries and/or acute exposures with long-term effects, mental health impacts, as well as long-term effects on the local economy and social life. These effects can be observed only long after an accident and could not easily be captured in an accident investigation or analysis report.

(Source: Wood and Fabbri 2019)

Complex nature of industrial accident risk and risk management processes

The heterogeneous nature of chemicals, the infinite ways in which chemical engineering transforms chemicals into products, and the vast infrastructure of road, pipelines, ships and railways, facilitating product distribution, are intrinsic to the challenge of assessing global industrial accident risk and predicting the next catastrophe. The likelihood of an incident occurring depends significantly on how well the risks are managed (the safety management system) and by decisions of the organization(s) that affect the functional effectiveness of the safety management system.[97]

At all types of industrial facilities, continuous efforts by experts and authorities, on site and off site, are required to avoid accidents. The safety of industrial facilities and the effectiveness of risk management is contingent on the quality and implementation of planning, analysis, design, construction, operational diligence, monitoring and regulatory actions at every level.

With the advent of the Sendai Framework has come a suite of regulation process and initiatives. Government and industry seeking to understand industrial accident risk began data collection and analysis in the 1980s, and by the 1990s, collected data on accidents and near misses was widely accepted as inputs to understand and correct weaknesses in the risk control system.

The primary purpose of the databases that ensued was to foster learning from accidents, but many of the databases were not publicly accessible. By contrast, collecting data to assess performance in controlling industrial accident risk is driven by lessons learned from disasters as well as contemporary developments in national and international law that unequivocally assign responsibility for chemical accident risk reduction to site operators.

Frequency and severity of past accidents can provide no indication as to where the next accident could occur and how severe it might be. For this reason, additional data and analysis are necessary to provide insight on causal trends, typical failure mechanisms and other signs of elevated risk, to guide strategies that can help reduce accidents occurring in future. This type of information generally includes causal patterns emerging from past accidents and near misses, evidence of the presence of potential accident precursors, and other circumstantial data about a particular site, or that can be generalized in regard to a specific industry or geographic location.

The nature of industrial accidents however poses significant challenges to measuring progress in reducing this type of risk, as shown in Box 3.8. Obtaining sufficient incident frequency and severity data to calculate chemical accident risk metrics is not practical. Chemical accident statistics measure only disastrous failures that became accidents; they cannot measure the disastrous failures that could happen but have not happened yet.

Box 3.8. Industrial accident risk reduction is difficult to measure using accident data

- Industrial accident risk is not a stable figure. Numerous variables that influence industrial accident risk make it more likely that actual risk levels fluctuate significantly over time.
- High-severity industrial accidents are low-frequency, high-probability events. Accident data can greatly underestimate actual risk.
- Industrial accident risk sources are distributed over many industries and geographic areas. It is challenging to have a complete picture.
- Data on industrial accident causality mainly belongs to companies. Data on what caused the accident is usually not in the hands of government.
- Loss data obtained following an accident is due to many actors, and is difficult to collect and quantify.

The variables that influence the probability of a chemical accident are unstable so that the risk figure associated with any one hazard source is surrounded by uncertainty and can change dramatically in a short period of time. For every chemical process, there are some conditions that must be maintained to prevent a release. Any modification in those conditions changes the risk. Some leading industries and authorities have developed diagnostic tools that can suggest elevated risks for specific types of activities and geographic regions. A relatively new practice, the use of safety performance indicators to diagnose potential risk, may eventually be an option for industry-wide self-assessment or for inspection authorities to assess risks across specific types of sites and problem areas.[98]

Methods have also been developed by government and international organizations to measure the strength of management systems in industry or government for controlling industrial accident risk. However, measuring performance in reducing accident risk is complicated. The use of frequency and severity of past accident as a risk measure is not a solution for global assessment of industrial accident risk. National governments require more information to understand their industrial risk and target their interventions to reduce them.

97 (Wood and Fabbri 2019)

98 (Wood and Fabbri 2019)

There is activity seeking to enhance national and global assessment of industrial accident risk. Three main data sources are being cultivated to correlate causal factors and other information in association with specific hazard sources.

a. Incident data together with causal and failure trends drawn from analysis of near misses

b. Safety performance indicator programmes identifying safety-relevant weaknesses

c. Hazard ranking systems geared to forecast the likelihood that certain weaknesses are present

Strengthening land-use planning policies

Land-use planning is central to reducing industrial risk. Decisions on the siting of industrial facilities and the planning of surrounding land use are critical in protecting and minimizing the effects of accidents on the surrounding populations, environment and property. The enhancement of land-use planning schemes and zoning mechanisms to enhance the level of safety and reduce risk to industrial facilities has been observed in several countries, primarily by:

- Developing risk-informed land-use policies and plans and establishing land-use zoning schemes that set requirements on the use of land, siting and development proposals
- Updating land-use planning and industrial safety procedures to require formal consultations among the relevant authorities, experts and the public at an early stage in the planning process
- Ensuring that risk assessments and other industrial safety aspects are incorporated into decision-making procedures
- Creating tools to simplify the identification and communication of risk assessments to planners, decision makers and other experts for a common understanding of the risks

Convention on the Transboundary Effects of Industrial Accidents

The Industrial Accidents Convention is a multilateral legal instrument that supports countries in establishing and enhancing governance, policymaking and transboundary cooperation on industrial accident prevention, preparedness and response. Developed initially for the European region following the Sandoz accident in 1986, the approaches and experience offer insights to countries pursuing Sendai Framework commitments in technological risk management.

The convention's legal provisions, policy forum, guidelines and capacity-development activities support countries in preventing accidents from occurring, reducing their frequency and severity and mitigating their effects at the local, national and cross-border levels. The scope of the convention also applies to industrial accidents that are triggered by the impacts of natural hazards.

3.1.9

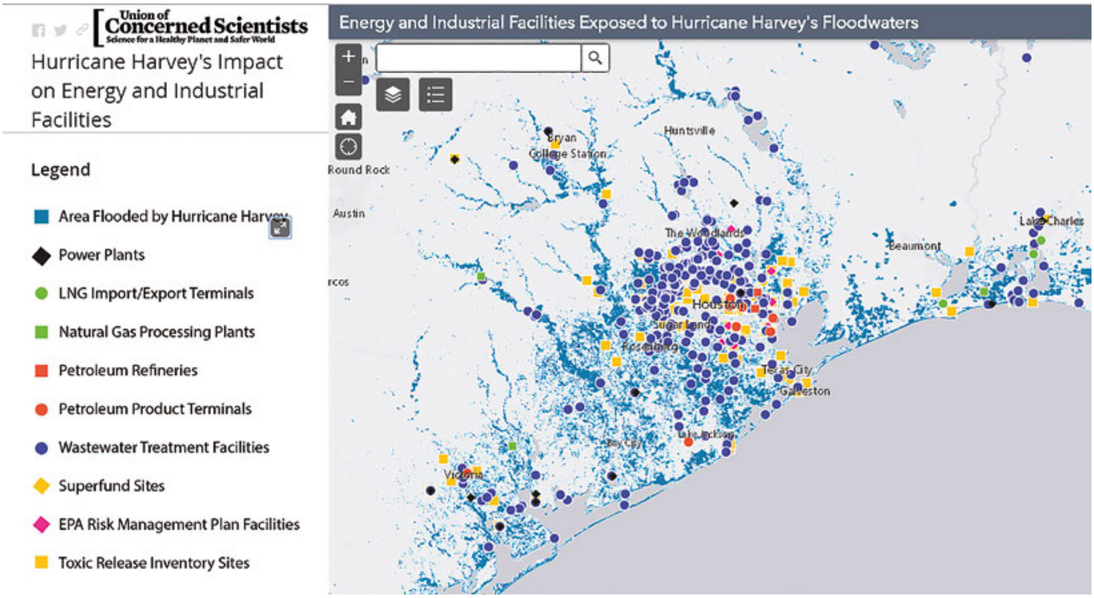
NATECH

Many of the goods and services upon which societies depend are provided by industrial activities. From refining, oil and gas production and transport, to nuclear power generation or the preparation of specialty chemicals, many of these activities have constructed inherent susceptibility to shocks, including those provoked by natural hazards.

Natural hazards have the potential to surpass safeguards, triggering negative impacts that may entail hazardous substance release, fire, explosion or indirect effects with wider repercussions than those felt in the immediate proximity. The cascading technological side effects of natural hazards are called NATECH accidents.[99]

NATECH events are a recurring but often overlooked feature in many disaster situations. They can add significantly to the burden of a population already struggling to cope with the effects of the triggering

Figure 3.17. **Hurricane Harvey caused several oil spills and chemical releases in Texas, 2017**



(Source: Union of Concerned Scientists 2019)
Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

natural event. NATECH event consequences can range from health impacts and environmental degradation (e.g. during the 2008 Wenchuan earthquake)[100] to major economic losses at local or regional levels due to damage to assets and business interruption (e.g. due to the 2011 Thai floods).[101] In some cases, ripple effects across sectors can reach global proportions, resulting in a shortage of raw materials and finished products (as was the case following the 2011 Great East Japan earthquake and tsunami)[102] and price hikes (e.g. the impact of Hurricanes Katrina and Rita on the offshore infrastructure in the Gulf of Mexico).[103]

This section introduces the concept of NATECH risk and the challenges associated with its management, with particular emphasis on industrial facilities and critical infrastructure that process, store and transport hazardous substances. It presents the principal factors that influence the risk, and proposes proxies of how progress in NATECH risk reduction can be measured.

NATECH risks exist anywhere where hazardous industry and critical infrastructure are located in natural hazard-prone areas, which is the case in many parts of the world. While NATECH events can, in principle, be triggered by any natural hazard type, they are not contingent upon catastrophic events. Many NATECH events with major consequences have been triggered by natural hazards that were considered of minor importance, such as lightning,

99 (Krausmann, Cruz and Salzano 2017)
100 (Krausmann, Cruz and Affeltranger 2010)
101 (Aon Benfield Corporation and Impact Forecasting 2012)
102 (Fearnley et al. 2017)
103 (Pan and Karp 2005); (Grunewald 2005)

low temperature or rain.[104] In the Baia Mare accident in Romania in 2000, heavy rain and unexpected levels of snowmelt coupled with design deficiencies led to the failure of a tailings dam, releasing large amounts of cyanide-laced wastewater into the river system, polluting some 2,000 km of the Danube River's catchment area.[105]

No single registry of the location of industrial facilities in natural hazard zones exists, nor are NATECH events systematically tracked over time. Hence there is no baseline available to compare risk trends. Few statistical analyses exploring NATECH trends exist. An analysis of NATECH events in the onshore hazardous liquid pipeline network of the United States of America for the period 1986–2012 using the official database of the United States Pipeline and Hazardous Materials Safety Administration concluded that NATECH accidents experienced increases in impact while the relative number of NATECH events remained stable and the absolute number of pipeline accidents from all causes decreased.[106]

Where legal obligations for reporting incidents do not exist, relevant information is lost from the lesson-learning process. However, even where accident reporting is mandatory, it usually applies only to incidents where the impact exceeds a defined severity threshold. This is also seen in public records, where media rarely report on low-impact events and near misses are seldom captured. Underreporting is further exacerbated as the attribution of NATECH triggers to a natural hazard is often difficult. Natural hazard information is often absent in industrial accident databases; vice versa, information on NATECH events is often missing in disaster loss databases. Quantitative NATECH event trend analysis is therefore difficult, and proxies are needed for measuring progress in NATECH risk reduction.

Radiation warning sign in Kashiwa, Japan, 2012
(Source: Abasaa 2012)

The positive news is that awareness of NATECH risk and the need for management has increased over the past decade, not least due to some landmark events. In Europe for example, the overwhelming of protection barriers of a chemical facility in Czechia – that had been designed for floods with a 100-year return period – caused the release of chlorine and other hazardous substances into the River Elbe.[107] This and other accidents prompted the EU to initiate action to combat NATECH events. The Great East Japan earthquake and tsunami and subsequent Fukushima Daiichi nuclear accident in 2011 put NATECH risks on the global agenda. With growing industrialization (notably in emerging economies), rising vulnerability (e.g. due to community encroachment and often unplanned urban development), as well as changing hazard frequency and occurrence (including as a result of a changing climate), NATECH risk is expected to trend upwards.[108]

Drivers of NATECH risk

Different factors determine NATECH risk. Some are of a technical nature and linked with the characteristics inherent to NATECH events; other underlying causes are a consequence of risk governance challenges and socioeconomic context. The boundaries between these risk factors are often blurred with links between the various causes.[109] Disaster risk reduction (DRR) frameworks have not fully addressed the issue of technological hazards in general, and NATECH hazards in particular, although they usually highlight it as an example of a cascading multi-hazard risk. Furthermore, instruments for reducing technological risks, such as chemical accident prevention and preparedness programmes, often tend to overlook the specific drivers of NATECH events, leaving an important gap in managing this type of risk.[110]

NATECH risk is a multi-hazard risk that cuts across different domains and stakeholder communities that traditionally have not interacted much with each other (technological risk, natural risk, industry, civil protection, etc.). For governing such a cascading risk, a paradigm change is required that acknowledges the diverse and interdisciplinary nature of the risk and the challenges associated with it. What is also crucial is a departure from the "act of God" mentality, which has often kept stakeholders from taking responsibility for NATECH risks and protecting against them. While in the past, this mindset may have been partly justified by the unavailability of reliable natural hazard forecasting, lack of knowledge no longer justifies inaction thanks to readily available modern prediction systems for many triggering natural hazards.

The risk management of an industrial installation cannot be viewed in isolation from its surroundings, but should take account of potential interactions with other industry, lifelines and nearby communities to capture the potential for cascading events. Since natural hazards often affect large areas, this is even more relevant for NATECH risks. A systemic view is required for the effective management of NATECH risks, requiring a territorial approach to risk governance and incorporating physical (e.g. industrial facilities, lifelines and building stock), organizational and socioeconomic factors into the analysis of natural hazard risks.[111] In some regions, rules for land-use planning around high-risk chemical facilities aim to ensure the protection of the surrounding communities by compelling risk management analysis to consider domino effects on nearby industrial installations.

While NATECH accidents in non-nuclear industrial activities have been happening regularly, it was only after the Fukushima Daiichi disaster that the public truly started to take notice of the potential

104 (Krausmann and Baranzini 2012)
105 (UNEP and OCHA 2000); (EC 2000)
106 (Girgin and Krausmann 2016)
107 (Hudec and Lukš 2004)
108 (Krausmann, Cruz and Salzano 2017)
109 (Girgin, Necci and Krausmann 2019)
110 (Krausmann, Cruz and Salzano 2017)
111 (Cruz, Kajitani and Tatano 2015)

magnitude of the consequences. Following the sudden media visibility and public interest, regulators stress-tested nuclear power plants around the world, updated nuclear emergency-response plans, and research programmes were launched in many countries to improve NATECH risk management. This is an example of how the risk perception and risk tolerance of society can shape decisions on protection against safety risks. However, risk perception is highly subjective, and overreactions can lead to unsustainable responses. For instance, a recent study showed how the perceived NATECH risk in the EU from high winds and earthquakes as compared to the natural hazards that triggered a NATECH accident was overemphasized, while the risk of accidents due to lightning and low temperature was significantly underestimated.[112]

Instruments for NATECH risk management

Mechanisms for the management of NATECH risks can take different shapes, ranging from legal frameworks, research programmes and development of risk assessment tools to capacity-building and other initiatives, all with the aim to better identify and control the risk.

Following several major NATECH accidents, and with climate change raising the profile of the risk, several countries have taken measures to enhance risk control. In the EU, major chemical accident risks are regulated by the provisions of the Seveso Directive on the control of major-accident hazards, and its amendments.[113] The directive requires stringent safety measures to be implemented to prevent major accidents from occurring, and in case they cannot be prevented, to effectively mitigate their consequences for human health and the environment. From a NATECH perspective, the Seveso Directive is the most important legal act at EU level. Thirty years after its inception, it now explicitly requires that environmental hazards, such as floods and earthquakes, be routinely identified and evaluated in an industrial establishment's safety document. There are other legal instruments in the EU that indirectly address NATECH risks (e.g. the Water Framework Directive or the Floods Directive), as well as the Union Civil Protection Mechanism with a requirement for EU member states to prepare a national disaster risk assessment.[114]

In the global arena, several international bodies have picked up on NATECH risk management. For example, recognizing the potential for severe health impacts, WHO has recently issued information for public health authorities in the wake of chemical releases caused by natural events.[115] The document focuses on earthquakes, floods and cyclones and aims to provide brief information to planners in the health sector and to public health authorities who wish to learn more about chemical releases resulting from natural events. In support of implementing the Sendai Framework,UNDRR has gathered a team of experts who prepared Words into Action Guidelines for National Disaster Risk Assessment and for Man-made/Technological Hazards, which contain chapters that discuss actions and guidance for NATECH risk reduction.[116] OECD issued a NATECH Addendum to its Guiding Principles on Chemical Accident Prevention, Preparedness and Response, to provide guidance to all stakeholders on how to better manage NATECH risk.[117]

Research initiatives aim to better understand NATECH risk from a scientific perspective and to develop the much-needed methodologies and tools to assess and control the risk. For example, following calls by governments, the European Commission (EC) Joint Research Centre (JRC) developed the Rapid NATECH Assessment Tool system, which helps industry and authorities to identify and reduce NATECH risks by supporting the detection of NATECH risk hot spots.[118] It supports land-use and emergency planning, rapid NATECH damage and consequence assessment to inform emergency-response decisions before dispatching rescue teams or issuing public alerts. The current version of the system analyses and maps earthquake and flood-triggered NATECH risks for fixed chemical installations and onshore pipeline networks, and is available at http://rapidn.jrc.ec.europa.eu.

Measuring progress in NATECH risk reduction

Traditionally, it is very difficult to measure progress in reducing NATECH (and technological) risks. There are no universal performance measures, and there is no reliable point of reference that can be used for comparison. To provide a measure of progress, qualitative indicators can be used as proxies for the status of NATECH risk reduction. The nature, complexity and scale of such indicators can vary (e.g. at facility, community or national levels), and they may differ across countries and implemented legislative regimes, and according to country priorities. For example, indicators for

Table.3.3. Examples of qualitative criteria for measuring NATECH risk reduction in a country

Criterion	Level of NATECH risk reduction			
	None	**Low**	**Medium**	**High**
Awareness of NATECH risk	None	Awareness of natural and technological hazards but not of their potential interaction	Awareness of NATECH risk by industry and authorities	Awareness of NATECH risk by industry, authorities and the public
Legal framework for NATECH risk reduction	No industrial risk control legislation	Legislation considering only conventional industrial risks	Legislation considering NATECH risk	Legislation considering NATECH risk and guidance on NATECH risk management
Collection of accident data	No accident data collection	Data collection for industrial accidents and natural hazards, without considering interactions	Data collection including NATECH accidents but without details	Data collection including details of NATECH-specific conditions
NATECH risk maps	None	Simple overlay of industrial facilities and natural hazard maps	NATECH risk maps with type, extent and probability of expected natural hazard-specific consequences	NATECH risk maps from multiple natural hazards and all hazardous facilities
Natural hazards considered	None	Major natural hazards	Major natural hazards with different severities	All natural hazards including those considered minor
Type of activity that considers NATECH risk	None	Major onshore hazardous facilities	Major onshore and offshore hazardous facilities and hazardous critical infrastructure (e.g. pipelines)	All hazardous facilities (including small- and medium-size facilities and hazardous materials transport)
NATECH risk assessment	None	Qualitative NATECH risk assessment at local (i.e. facility) level	Quantitative NATECH risk assessment at local (i.e. facility) level	Qualitative or quantitative NATECH risk assessment at local, regional and national level
NATECH preparedness	None	Preparedness by industry	Preparedness by industry and authorities	Preparedness by industry, authorities and communities

(Source: Krausmann, Girgin and Necci 2019)

112 (Krausmann and Baranzini 2012)
113 (EU 2012)
114 (Girgin, Necci and Krausmann 2019)
115 (WHO 2018a)
116 (UNISDR 2018e)
117 (OECD 2003b); (OECD 2015)
118 (Girgin and Krausmann 2012)

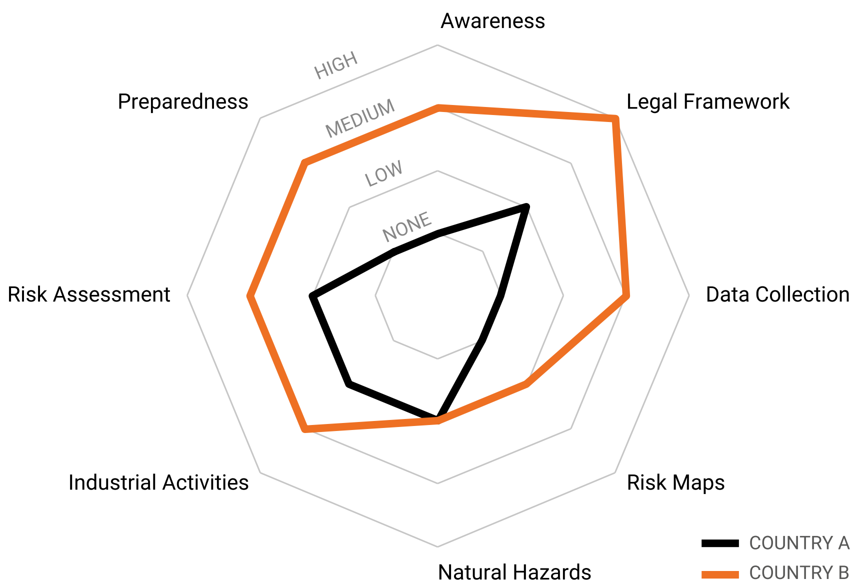
countries in which legal frameworks cover NATECH risk might differ from those used where no such instruments exist. Some indicators might be considered more appropriate than others depending on the scope of the analysis. Similarly, some indicators may address only government resources and systems, while others evaluate industry infrastructure and competence, or social norms and risk perception.[119]

Proxies for measuring progress in NATECH risk reduction should relate to human, financial and physical resources, as well as the legal and administrative infrastructure in a country. Table 3.3 gives examples of qualitative performance indicators on a four-level scale, which assumes as a minimum level the complete absence of tools for reducing NATECH risk. The choice of these indicators is based on expert judgment and assumes that basic information on technological and natural hazards already exists (e.g. industrial facility registers including type of activity, type and amount of hazardous substances present, industry location; and natural hazard information including maps).

The indicators proposed are markers that can consist of one or more subindices. For example, the indicator on a legal framework for the control of NATECH accident risk can include subindicators such as land-use planning, safety cases and emergency planning.

Work is under way to develop a method for the compilation of the individual indicators into a composite indicator that reflects the many dimensions of the measured risk. This also includes weighting of the single indicators according to their importance for reducing NATECH risks. In the absence of such a composite indicator, individual performance measures from Table 3.3 can be compared separately or all measures can be visualized by using radar charts as in Figure 3.19, comparing two hypothetical country examples with low and high levels of NATECH risk measures.

Figure 3.18. Example visualization of comparative NATECH risk reduction measures proposed in Table 3.3 for two hypothetical countries



(Source: Girgin, Necci and Krausmann 2019)

3.1.10

Environmental

Evidence from the latest intergovernmental and global assessments shows that the planet is overheating and becoming increasingly densely populated. Climate change, food insecurity, rapid urbanization and growing levels of pollution are damaging human and ecosystem health. Growing inequalities in wealth and access to technology and resources are leading to malnutrition, conflicts and the displacement of millions of people.[120]

Understanding of environmental hazards and associated risks and distributional impacts caused by these pressures has been enhanced through the assessments of various key international scientific bodies.[121] The concept of inter-linkages among environmental risks lies at the heart of the concept of planetary boundaries and dynamic systems. Four out of the nine planetary boundaries (climate change, loss of biosphere integrity, land-system change, altered biogeochemical cycles (phosphorus and nitrogen)) have now been crossed.[122] Fifteen out of 24 categories of ecosystem services are in decline due to overuse of resources. The spread of zoonoses and invasive alien species is being exacerbated by climate change and global trade, and is already posing direct threats to native and endemic species and ecosystem functioning. Overharvesting, land-use change, unsustainable use of – and lack of fair access to – genetic resources, and climate change are key drivers of the decline in wild plant resources, including those used commercially for food and medicinal purposes. Approximately 15,000 species or 21% of global medicinal plant species are now endangered due to overharvesting and habitat loss.[123]

Intense heat-waves, wildfires and storms occurred in 2018. The 20 warmest years on record have all occurred in the last 22 years. Meanwhile, GHG emissions keep rising (another 2.7% increase in 2018) and extreme weather-related events continue to spread and intensify globally.

By 2050, the median projected population is expected to rise to 10 billion, and to grow to nearly 12 billion by 2100. These figures are based on current declines in infant mortality coupled with female education, improvements in health care and increases in life expectancy. When linked with rising levels of consumption, the pressures on global resources will be greater than at any other time in human history, creating competition for resources and overstretching the planet's regenerative capacity.

To fully understand the nature of environmental risks, it is important to understand their sources. This means understanding the dynamics of the hazards themselves, the exposure of human populations and ecosystems to these hazards, the vulnerability of the affected people and ecosystems and their resilience to change.[124] This section examines some of the principal threats that we face, now and in the future, emerging from a combination of natural and anthropogenic factors.

These must be considered when determining how best to deliver frameworks and intergovernmental agreements such as the 2030 Agenda, the Sendai Framework, the Paris Agreement and NUA in a coherent way. In adopting the Sendai Framework, Member States identified as prerequisite the need to understand the dynamic interactions among economic, ecological, social, political, health and infrastructure systems when considering risk-informed decision-making across sectors, geographies and scales. In so doing, the Sendai

119 (Baranzini et al. 2018)
120 (IPBES 2018); (United Nations 2017); (IPCC et al. 2018); (OECD and OCDE 2018); (FAO 2018); (International Resource Panel 2017)
121 (IPBES 2018)
122 (Rockström et al. 2009)
123 (Schippmann 2006)
124 (European Environment Agency 2013)

Framework provides the frame for the application of systems-based approaches in pursuing the goals and targets of other 2015 agendas.

Given the intensification of many environmental hazards and their complex interactions, risk reduction strategies and risk informed decision-making cannot afford to ignore the integrated, multiscalar, multiplier effects of environmental hazards.

Climate change

Climate change is a hazard and threat multiplier. It is an aggressive driver of environmental change, affecting human and ecosystem health, and changing the complex interrelationships among living organisms and ecosystems. Climate change is having a detrimental effect on the environmental and social determinants of health, from the availability of clean air and water, to heat shocks, food security and shelter, and has the potential for wide-ranging systemic impacts on food availability and large-scale disasters. In this century, it has been identified as the defining issue for public health[125] and also the biggest global health threat.[126]

Ongoing increases in GHG emissions have put the world on an extended warming trajectory. Without rapid decarbonization,[127] this will lead to further sea-level rise, ocean warming and acidification, and more extreme weather that will amplify existing and emerging risks, such as the spread of zoonoses and infectious diseases, especially for the poor and vulnerable. Cautious estimates from WHO under a medium-high emissions scenario indicate that 250,000 additional deaths could potentially occur each year between 2030 and 2050 because of climate change.[128]

Air quality and pollution

As one of the most significant environmental hazards after climate change, air pollution contributes to the global burden of disease (GBD) through atmospheric concentrations of GHG emissions and their precursors, particulate matter, heavy metals, ozone and associated heat-waves, leading to approximately 7 million premature deaths and economic losses of $5 trillion annually.[129] The most susceptible are the elderly, children and poor, with air pollution exposure highest for urban residents compared with rural communities.

Transboundary flows of air pollution are also a matter of serious concern, hindering countries as they attempt to meet their own goals on ambient environmental quality and public health. Studies suggest that the sum of the health impacts of transported pollution in foreign nations downwind of a source can sometimes be larger than the health impacts of emissions in the source region.[130] Making matters more complicated, reducing some air pollutants (e.g. sulfates), which would be in line with air quality remediation guidelines, is likely to reduce cloud cover and increase incoming solar radiation, leading to further global warming.

Atmospheric concentrations of carbon dioxide and other long-lived GHGs continue to increase. This is driven primarily by fossil fuel energy, industry, transportation, land-use change and deforestation, and making significant, adverse, irreversible changes in climate and sea levels inevitable. Decreasing emissions of short-lived climate pollutants such as black carbon, methane, tropospheric ozone and hydrofluorocarbons, can help to limit warming in the near term, but are no substitutes for mitigating long-lived GHGs.

Some of these biodiversity-related environmental hazards and associated risks are being addressed through multilateral environmental agreements and their protocols (e.g. United Nations Conventions on Biological Diversity, Climate Change and Combating Desertification). However, the complexity of the feedbacks and dynamics of ecosystems and biodiversity means that safeguarding species and ecosystems requires more than conservation and protection of natural habitats. It also requires risk-based decision-making to be represented in sectoral policies and agreements such as in agriculture, fisheries and forestry.

Land

Agriculture is the single, largest use of land, accounting for more than one third of the world's land surface, excluding Antarctica and Greenland. Deep tilling, and overuse of pesticides, fertilizers and antibiotics in agriculture, has led to significant levels of soil erosion, pollution of surface waters and the spread of AMR, with very real risks to human and wildlife health.[131] Rising global temperatures and changing rainfall patterns are having a detrimental effect on crop yields, especially in tropical regions, where the effects of higher temperatures are greater than in temperate zones. As the growing seasons change, yield growth has also slowed down. Shifting rainfall patterns and greater variability in precipitation poses a risk to the 70% of global agriculture that is rain-fed.[132] It is estimated that over 1.3 billion people are now trapped on degrading agricultural land.[133] Farmers and pastoralists on marginal lands, especially in semi-arid and dryland areas, have limited options for alternative livelihoods.

The environmental impact of industrialized farming practices cost the environment $3 trillion per year,[134] and contributes up to one third of global GHG emissions.[135] Livestock takes up 75% of agricultural land for feed production, pasture and grazing, yet it only generates 16% of dietary energy and 32% of dietary protein demands.[136] Approximately one third of global edible food is being lost or wasted before getting to market.[137]

Deforestation is creating a wide range of impacts in the biophysical world, from feedbacks to the climate system itself, loss of biodiversity and soil erosion. It is leading to a significant reduction in the resilience of local communities.

Coasts and oceans

The marine environment provides multiple ecosystem services, and is therefore key to any consideration of environmental hazards, climate regulation, resource extraction and food production. Storms and ocean weather events are the most prominent of the environmental hazards, but there is also ocean warming and acidification, and waste and chemicals pollution. The degradation of coastal zones and watersheds exacerbates the effects of natural hazards such as floods and storms, while land degradation severely exacerbates the effects of drought and causes an increase in flash floods.[138]

The cumulative pressures and multiple stressors on the marine environment are affecting the health of oceans and their ability to support human populations. The major risks come from the high dependency of humans on the oceans for food and livelihoods. More than 3 billion people rely on the marine environment for 20% of their dietary protein.[139] The annual value of fisheries and aquaculture is more than $250 billion, and up to 120 million people rely on the sea for their livelihood.[140] But overfishing, illegal and unregulated fishing, and damaging fishing practices are placing many fish stocks at risk. Marine pollution, litter and plastics expose marine ecosystems and marine life to a wide array of chemicals, including microplastics, and heavy metals, which are accumulated throughout the marine trophic food chains leading to human exposures when they eat marine food species. Approximately 8 tonnes of plastics enter the oceans from land-based sources annually.[141] The hazards from eating contaminated marine sources of food have been well documented and do not yet have a simple mitigation solution.

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125 (Chan 2019)
126 (Watts et al. 2015)
127 (Rockström et al. 2017)
128 (Hales et al. 2014)
129 (Health Effects Institute 2018)
130 (Task Force on Hemispheric Transport of Air Pollution 2010)
131 (UNEP 2019)
132 (United Nations 2017c)
133 (United Nations 2017c)
134 (FAO 2015a)
135 (Campbell et al. 2017)
136 (United Nations 2017)
137 (United Nations 2017)
138 (UNEP 2019)
139 (UNEP 2019)
140 (UNEP 2019)
141 (UNEP 2019)

Ocean warming and acidification have stressed some marine ecosystems to the point of collapse.[142] Chronic bleaching has led to the death of many tropical coral reefs, to a point where they will not have sufficient time to recover between bleaching events that occur every 6 to 10 years.[143] Ocean acidification is also becoming a significant environmental hazard, affecting plankton populations in various oceans, causing unpredictable and potentially irreversible losses across the wider marine ecosystem.

Waste and chemical pollution

It is estimated that poor environmental conditions are the cause of about 25% of GBD and mortality.[144] Environmental hazards arising from inadequate waste management, including food waste, electronic waste and plastics, is a global concern. Many countries still face basic waste management challenges with uncontrolled dumping, open burning and inadequate access to waste services. Globally, two out of five people lack access to controlled waste disposal facilities.[145] Synthetic chemicals and toxic compounds eventually leak into lakes, rivers, wetlands, groundwater, oceans and other receiving water systems, as well as aerosolizing into the atmosphere.[146]

Emerging chemical hazards include: (a) endocrine disruption, which is likely to have a multigenerational effect on human and wildlife health, (b) antibiotic resistance, which will create a new family of hazards within public health systems and (c) bioaccumulation of chemicals in the tissues of crops and livestock.

Poisoned chalice: toxic crops

Over 80 important plant species and crops are known to cause poisoning when environmental conditions trigger nitrate accumulation at the plant cellular level. Droughts are exacerbating this in key staple crops such as the pea because they trigger a defence mechanism at the cellular level, which has the side effect of producing prussic acid and other toxins. Even after a drought, the growth in water-stressed crops can result in accumulation of these toxins, making some plants poisonous to humans and livestock. Over 100,000 people suffered paralysis caused by oxalyldiaminopropionic acid[147] accumulation due to water stress in certain legumes during the drought in Ethiopia in 1995–1997.[148]

There are some interesting innovations in the environmental policy space, where it is not uncommon to see efficacy dividends from the integration of different policies. Policy developments in water resources management, and specifically drought and flood risk management, are increasingly situated at the nexus of water, food, energy, climate change and human health. Blending policy approaches allows decision makers to extend beyond technical fixes and adopt truly multisectoral risk management approaches to transdisciplinary challenges.

3.2

Exposure

In past GARs, the production of the Global Risk Model and standard risk metrics (AAL, PML and hybrid loss exceedance curves) relied on a global data set of standardized and homogeneous exposure data. Due to the heterogeneity of national reporting and the availability of data, model-based exposure calculations relied on an understanding of the constructed environment and used data from satellite observations. These satellite-based exposure layers were often validated locally through ground truthing. A team of on-the-ground analysts would visit a satellite-modelled site and verify if the model layer accurately depicted the extent of construction, building use, construction type, density, floors, materials, etc. The advantage of this approach was that the loss and replacement value of construction materials is relatively easy to describe country by country, even considering local market variability. A second advantage was that the use of built assets meant that in the cases of disaster events that affected areas that were more often insured, modelling data could be validated and corrected based on loss claims. Third, many of the hazards that were modelled were major natural hazards for which extensive engineering tests had been done to better understand their robustness faced with certain natural phenomena. For example, extensive testing has been done to understand the maximum ground acceleration due to earthquakes that the different types of building materials can withstand or the scales of modelled flooding a typical family home would be expected to experience.

3.2.1

Structural exposure

There are several difficulties in relying on structural exposure. Huge regions of the world rarely experience seismic hazards. For example, much of Africa is at relatively low risk from a seismic perspective. Furthermore, the nature of construction materials, population densities and other elements of structural exposure as modelled for Africa dictate that the true risk of many African countries was not fully revealed. As past GARs have noted, the prevalence of extensive risk in many parts of the world have been historically underrepresented. When the predominantly extensive risk profile is coupled with relatively low rates of insurance penetration and very diverse construction types, it becomes evident how difficult it has historically been to reveal the true cost of risk in many countries. Droughts, epidemics, epizootics, agricultural infestations, etc., imply effectively no damage to structures, but their economic cost in direct and indirect terms could be devastating.

The Ebola virus outbreak in Guinea, Liberia and Sierra Leone in 2014–2015, which killed more than 11,000 people, is estimated to have cost 9.4% of GDP in Guinea, 8.5% in Liberia and 4.8% in Sierra Leone.[149] Liberia lost more than 8% of its healthcare workers. Surveillance, treatment and care of HIV/AIDS, malaria and TB were set back, and the entire region suffered economic effects of the stigma.[150] An exposure model predicated on counting and categorizing buildings would have captured effectively none of the above exposed elements and thus failed to show the true risk faced by those countries.

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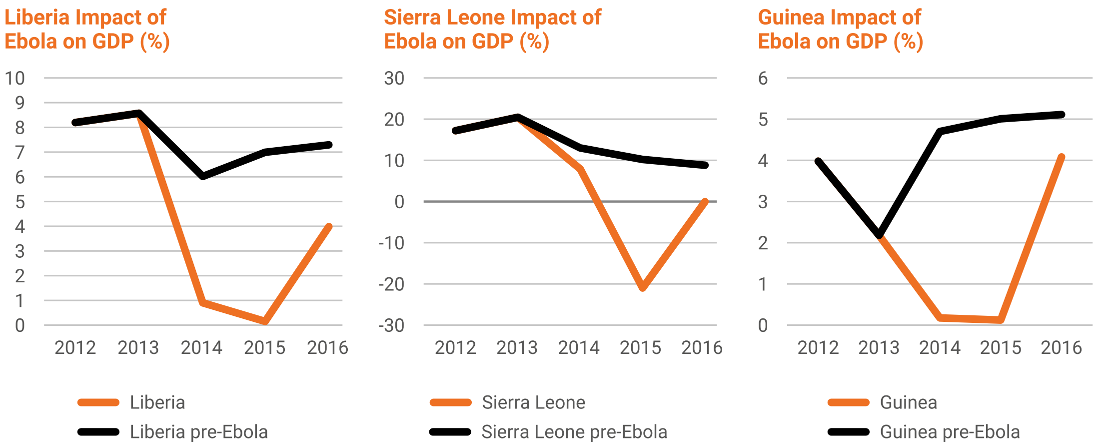
142 (UNEP 2019)
143 (UNEP 2019)
144 (UNEP 2017)
145 (UNEP 2019)
146 (UNEP 2019)
147 (UNDP 2016b)
148 (Surya and Rao 2013)
149 (World Bank 2016)
150 (Centre for Disease Control and Prevention 2019)

Figure 3.19. **Projected economic losses due to Ebola in Liberia, Guinea and Sierra Leone, 2010–2016**



(Source: World Bank 2016)

None of the above should detract from the continued development and refinement of understanding of structural exposure. It represents an important part of the equation. While it is the best-developed description of exposure in contemporary use, it benefits from continual improvements.

The increased availability of high-resolution satellite data and crowdsourcing are fostering a capacity to develop better building profiles, which is important for modelling risk for some hazard types. It is possible to use remote sensing and crowdsourcing to characterize a building's physical exposure. The development of building portfolios through a combination of high-resolution satellite imagery and crowdsourcing has helped to improve the base understanding of structural exposure. Knowing the size and structure of a building can make models far more accurate and enables better risk assessment in its ability to describe the likelihood of damage. The damage caused by an event can also be better and more quickly understood using satellite imagery by comparing before and after photographs to see if the height of a given building had changed (indicating damage or destruction). Using this information, simulations can identify to what degree changes in adherence to various building codes would affect outcomes in other areas.

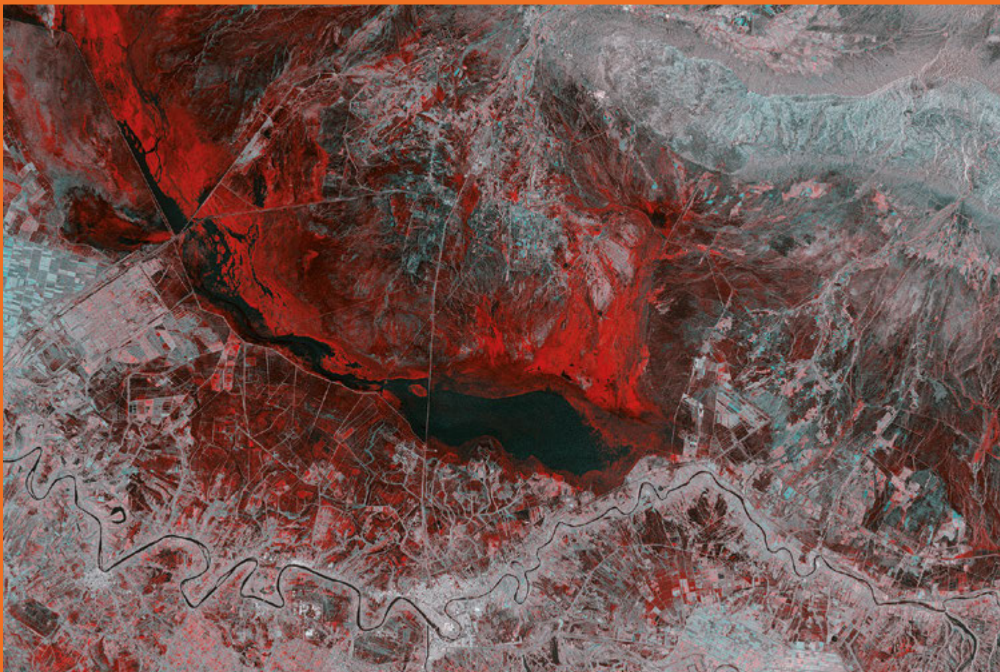
There are challenges with using satellite data to impute even structural exposure. For example, some administrative districts cover very large areas within which the hazard effects can vary considerably. For this reason, an additional step is needed to spatially redistribute assets within each area, based on other sources of information. To identify where buildings are expected to exist, several auxiliary data sets are considered, such as night-time lights,[151] population maps, the location of smaller roads and public infrastructure information from open source mapping resources. The evenly spaced exposure data set can be aggregated following different approaches to illustrate the distribution of the building stock at the national, regional or global scales. The estimated number of buildings at the global scale is depicted at 0.5 × 0.5 decimal degrees. Unsurprisingly, the resulting global exposure database indicates a large concentration of buildings in South-East Asia, Western Latin America, Central and South Europe, and Eastern sub-Saharan Africa.

It is technically possible to validate country-level data by collaborating with local experts and institutions. Bringing the local level into understanding exposure is necessary, and there is a clear appetite among underrepresented governments and citizen groups, but a more enabling environment is required

Box 3.9. Global human settlements layer

The existing exposure information used in the global human settlements layer was built using data from the European Space Agency (ESA) satellite Sentinel-1. With the launch of Sentinel-2 researchers expect to be able to provide much more detail, with smaller communities being captured that might have been missed under Sentinel-1. Information can then also be informed through other sources such as social networks.

Figure 3.20. Iraq flooding revealed by high-resolution satellite imagery, 2019
Detailed satellite imagery is providing a richer picture of the impact of hazards. This image combines two acquisitions over the same area of eastern Iraq, one from 14 November 2018 before heavy rains and one from 26 November 2018, after the storms. The image reveals the extent of flooding in (false colour) red, near the town of Kut.



(Source: ESA 2019: 1 February 2019 10:00 a.m. Contains modified Copernicus Sentinel data, processed by ESA, CC BY-SA 3.0 IGO)

to encourage people to contribute and share data about their communities.

At the time of writing, GEM results indicate an average global loss of $63.47 billion per year due specifically to earthquakes. Residential building stocks contribute 64% of the total annual modelled loss, while commercial and industrial stocks represent 22% and 14%, respectively. In terms of the total absolute losses per country; Japan, the United States of America, Indonesia and China lead the ranking, mostly due to the considerably high

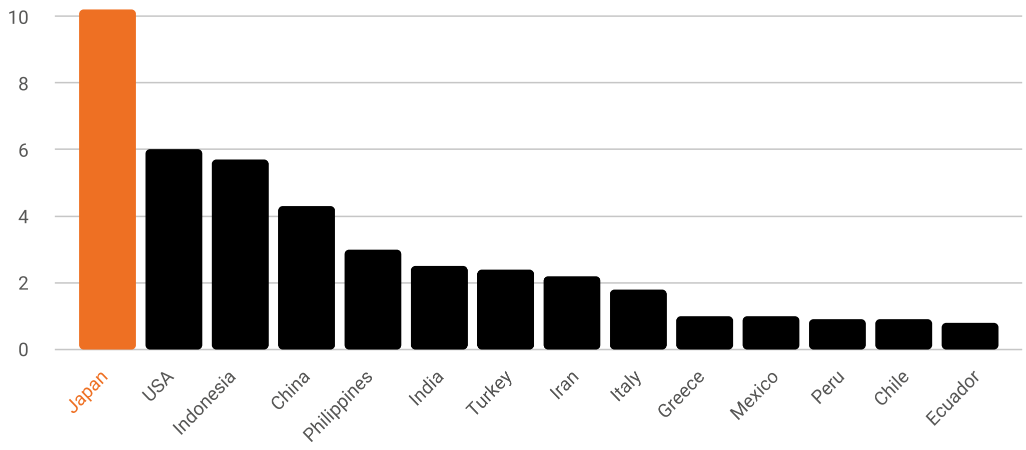
151 (Elvidge et al. 2012)

economic value of the building stock, as presented in Figure 3.21.[152]

The evaluation of risk in terms of absolute economic losses can be misleading, as poor or lesser populated countries with vulnerable structures will have annual losses several orders of magnitude below nations such as China, Japan or the United States of America. It is thus useful to normalize AALs based on the total exposed value. Unsurprisingly, the high range of Figure 3.22 is dominated by countries with a history of high-impact disastrous events (in 2001, a magnitude 7.7 event in El Salvador, in 2007 a magnitude 8.0 event in Peru, and in 2015 a magnitude 7.8 event in Nepal).

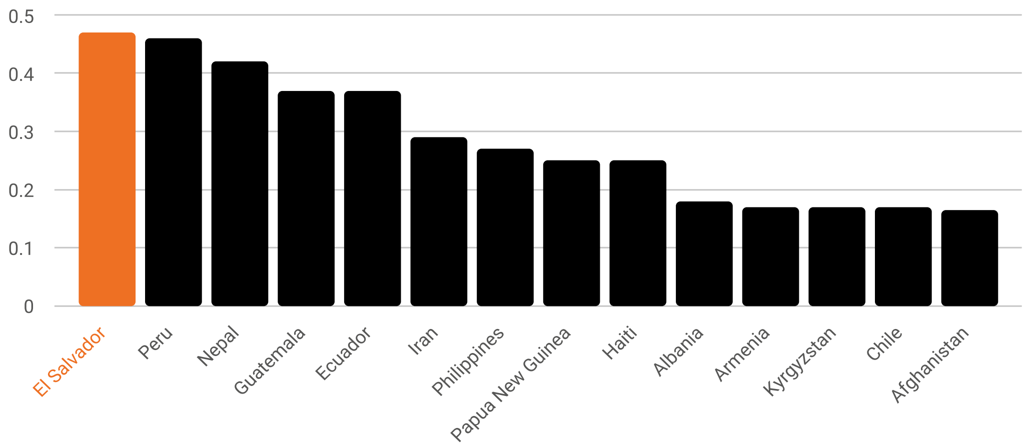
The development of the global residential exposure model relied predominantly on data from the national housing census of each country. These surveys are performed at different timescales

Figure 3.21. Highest average annual economic losses due to earthquake risk (in billion $)



(Source: GEM 2018)

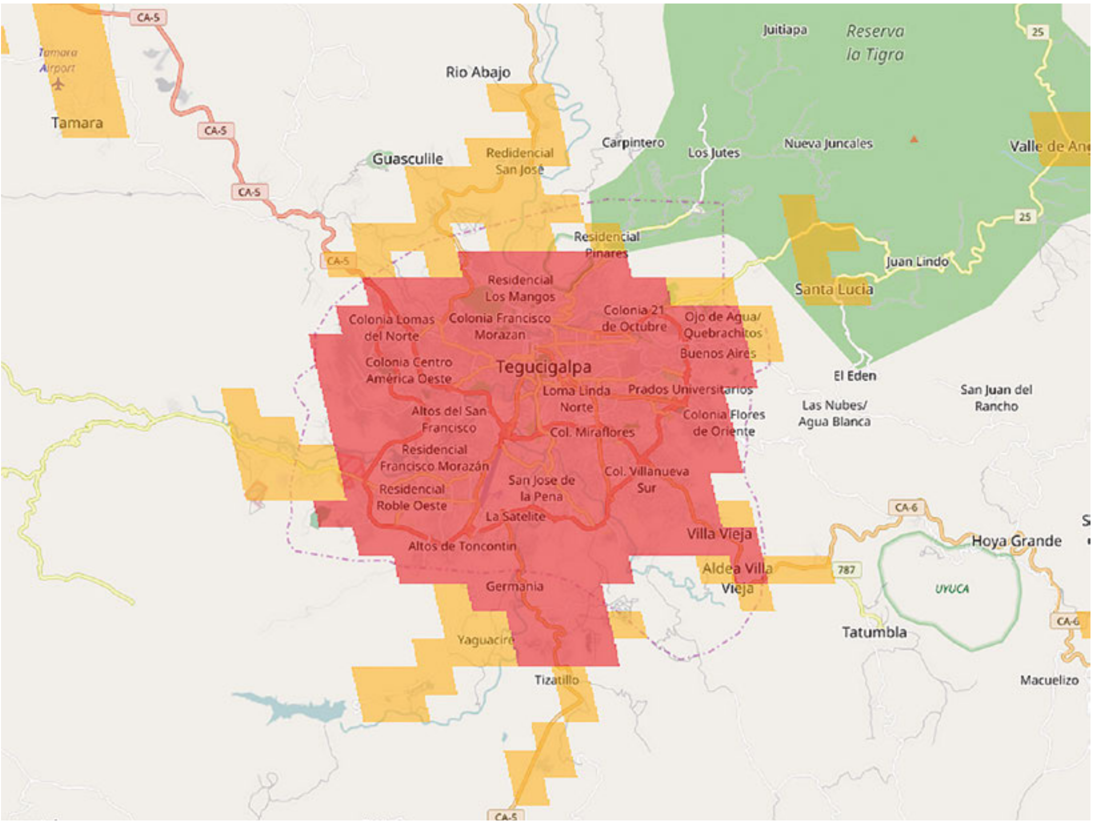
Figure 3.22. Earthquake AAL as a percentage of GDP



(Source: GEM 2018)

around the world, occasionally at the lowest administrative level. In the best cases, the survey data comprises information concerning the number of buildings, type of structures (e.g. individual houses or collective accommodation), main material of construction, material of the roofs, material of the floors, number of storeys, year of construction and sometimes the state of the building.

Figure 3.23. Degree of urbanization: red = urban centre; yellow = urban cluster; transparent = rural grid cell



(Source: EC 2018)
Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

For many nations, the survey data provides information only about the type of dwelling and the main material of the structure. In these cases, a system is applied using alternative sources of information and the judgment of local experts. For some countries, the mapping schemes must be derived using different techniques within the same region (urban versus rural areas).

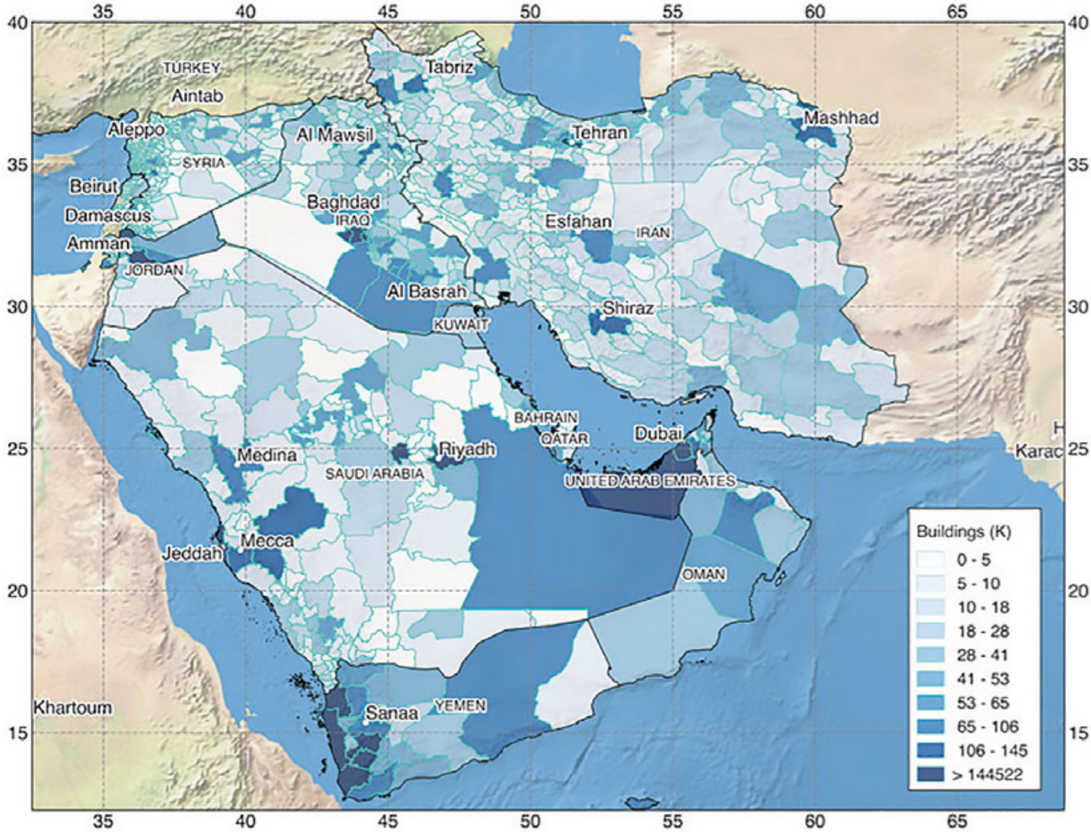
However, there are some challenges with this approach, such as different definitions of the distinction between urban and rural (in Japan, areas with

152 (Silva et al. 2019)

more than 20,000 people are urban; in Australia, areas above 1,000 people are urban). To solve this, global human settlements researchers have created three artificial but homogeneous categories: urban centres, urban clusters and rural areas. Urban centres are assumed to have contiguous grid cells of 1 km^2 with a density of at least 1,500 inhabitants per km^2 and a minimum total population of 50,000. Urban clusters are contiguous grid cells of 1 km^2 with a density of at least 300 inhabitants per km^2 and a minimum total population of 5,000. Rural areas are grid cells of 1 km^2 with a density below 300 inhabitants per km^2 and other grid cells outside urban clusters or centres.[153] At the time of writing, the data layer that contains information about human settlement is being updated with data from 2018.

For a few countries there are highly reliable data sets available. This applies to the Australia, Canada, New Zealand[154] and the United States of America.[155] On the other end of the spectrum, there are also countries that have no housing information available or have been so heavily affected by disasters that after completion of the national census, the information is no longer accurate (e.g. Haiti or Nepal). In these cases, an alternative approach must be adopted that capitalizes on population data sets, satellite imagery and open source mapping data.

Figure 3.24. Distribution of number of residential buildings at the smallest available administrative subdivision for 12 countries in the Middle East as of 2018



(Source: GEM 2018)

Disclaimer: The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

Exposure information regarding non-residential buildings is rarely compiled systematically at a regional or national scale. In most cases, secondary sources of data such as economic census surveys provide data regarding the number of employees and various other indicators that are related to commercial and industrial structures. As a result, the development of the exposure sources for non-residential occupancy types relies on three main sources of data sets: (a) demographic data concerning the workforce across different sectors; (b) data concerning the number of permits, which may also specify the date, type of business, size of the facility and number of workers; and (c) large-scale data sets that identify regions according to occupancy.[156] The combination of these data sets permits an estimate of the average number of facilities per occupancy, which is then distributed across several classes.

The combination of various sources of exposure information will inevitably lead to a global exposure data set that is not uniform in resolution, quality or vintage. And by integrating alternative data sources to validate information for structural exposure, for example, a collection of other exposure data is becoming enriched and validated. And by integrating data about roads, infrastructure installations, use of water, distance to food sources, electricity demand, availability of primary health care, education attainment, etc., the global understanding of exposure beyond the structural level will grow. In this way, challenges related to the heterogeneity in data availability and scale will eventually become obviated as availability of open exposure data grow.

3.2.2

Exposure related to growth

Leaving aside the above-mentioned challenges of keeping pace with the exposure drivers for the built environment, the exposure for people, infrastructure and systems implied in those growth rates represents an astronomically complicated computation.

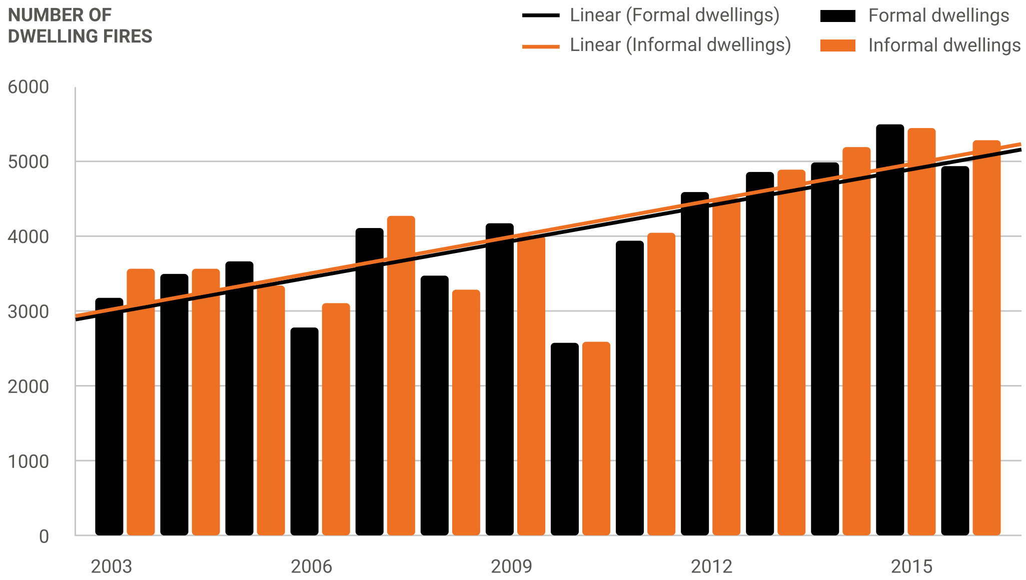
Exposure is not static, risk can increase with changes in exposure (e.g. a three-storey building can become five storeys over the course of a few weeks, populations can displace en masse very quickly or border crossings can be closed). In Africa, average GDP growth for 2018 was above 4%, with one third of African countries experiencing real GDP growth of more than 5% year on year.[157] In developing countries and countries in transition, growing middle classes and expanded access to the global market are fuelling growth of exposed assets while regulatory structures and risk management capacity struggle to keep pace. The result is a compounded risk, as the scale of exposed assets and lower likelihoods of careful application of safety standards overtake public investment in risk management strategies. This applies equally to construction regulation as to food safety inspection, industrial facilities verification, disease surveillance, biodiversity preservation, etc.

Urbanization is one of the twenty-first century's most transformative trends, posing challenges in terms of exposure and vulnerability, with implications in housing, infrastructure and basic services. The developing world is experiencing 90% of this urban growth, and it is estimated that 70 million new residents are added to urban areas in developing countries each year;[158] infrastructure development cannot keep pace with growth.[159] Africa is the fastest urbanizing continent; between 1990 and 2015, the population in urban clusters increased by 484 million,

153 (Melchiorri et al. 2019)
154 (Nadimpalli, Edwards and Mullaly 2007)
155 (FEMA 2017)
156 (Tsionis et al. 2017)
157 (African Development Bank 2018)
158 (UN-Habitat 2015)
159 (Gunter and Massey 2017)

while Asia has 89% of its population living in urban clusters.[160] Low-income countries have seen a 300% increase in built-up areas and an 176% increase in population over the past 40 years.[161] For example, the number of fire incidents in formal and informal dwellings per year are similar, but with approximately 18% of the population living in informal settlements, the informal settlement dweller is 4.8 times more likely to be affected by fire than someone residing in a formal dwelling. The propensity of informal settlements to fire indicates that the burden of fire disasters is often borne by the poor.[162]

Figure 3.25. Growth in formal and informal urban dwellings in South Africa



(Sources: Fire Protection Association South Africa 2018)

Historically, many megacities such as Chicago, London and Tokyo have experienced major urban fires,[163] but have been able to progressively improve infrastructure and build structures that take into consideration the hazard. Similar intervention is needed in new megacities and other growing urban areas to protect urban communities from preventable risk.

Informal settlements present an increasing challenge for municipalities. In such areas, as many as 10,000 people can be left homeless in a single event like a fire. The urban morphology of informal settlements contributes to disasters propagating rapidly, resulting in loss of life, homes and belongings, devastating already-vulnerable communities. In this way, structural exposure drives other aspects of exposure to risk.

Fire has as many political, social and economic properties as physical ones. Fire is a material condition dependent on ignition, combustion and fuel. It is also embedded in the history of a location, its governance and class structures, and its specific cultural attitudes towards risk and understandings of exposure. Poverty and other forms of marginalization generate conditions of vulnerability, contributing to poor housing quality, overcrowding and failure to invest in protective measures.[164] Of course, this profile of the multiple dimensions of intertwined exposure is not unique to fire.

Though flooding is relatively common, damage data is incomplete because there are so many kinds of floods that affect so many different forms of exposed assets. Floods often do not cause structural damage so there is not the same focus on data collection that there would be in the wake of an earthquake.

The exposure calculation for wildfires does not include human settlement; it includes only the value of the natural area that was lost (meaning the cost of wood stocks and the time to replace). For the EU in 2017, economic losses due to fires were $11.2 billion, but this did not include the cost of built assets. Housing has not been traditionally relevant for fire risk, but is increasingly important to consider as the economic impact of fires on human settlements is growing. In densely populated areas, fires are often started in proximity to human settlements, and the economic cost and mortality is increasing.

Despite what may seem to be the dehumanization of disaster impact, it is important for some users of risk information to measure losses and, by consequence, exposure in monetary terms. This is particularly important in making the case for effective mitigation methods like risk-transfer services such as insurance. The fact is that the return on investment of risk reduction initiatives is positive (usually several times over) compared to projected losses; but not all risk reduction is equal. Public policy planners are better equipped to make good decisions when the economic case is made clear. In many cases, risk reduction initiatives, on their own, are not politically popular. A politician in a poor jurisdiction may struggle to justify to their constituents an investment in a warning system that may not sound the alarm about a hazard for years when there are children not in school or people who are hungry.

3.2.3

Environmental exposure

Exposure in a global environmental sense takes into consideration systems for which individual quantitative figures do not exist. Over the last two decades, approximately 20% of the productivity of the Earth's vegetated surface has shown a persistent downward trend, due to climate change, biodiversity loss and poor management practices. With overharvesting of resources and land-use change remaining as key pressures, more than half of the world's ecosystems services are in decline.

The widespread loss of biodiversity and ecosystem health is evidence of a failure to account for and manage the breadth of exposed global assets. That loss also has a major effect on risk reduction and the mitigation of environmental hazards.[165] This is because ecosystem services help to regulate climate, filter air and water, and mitigate the impact of natural hazards. There are other direct benefits such as availability of timber, fish, crops and medicines, all of which support human health. These are often lost in the immediate aftermath of a disaster and can take many years to restore. Freshwater biodiversity and ecosystem services are threatened more than any others. Rivers and wetlands the world over are distorted, dried and overwhelmed with waste, toxic pollution, invasive species, and are damaged by overfishing and overuse of irrigation water. Two thirds of all rivers are highly degraded,[166] along with the freshwater habitat they support. This problem affects nearly 5 billion people living in high-water-threat areas.[167]

Marine biodiversity is at risk from overfishing, ocean warming and acidification, melting of sea-ice with the loss of under-ice biota, oil and gas development, shipping, coastal habitat destruction, loss of coral reefs, eutrophication and pollution (including marine

160 (Devigne, Mouchon and Vanhee 2016)
161 (Rush et al. 2019)
162 (Rush et al. 2019)
163 (Knowles 2013)
164 (Rush et al. 2019)
165 (Pacifici et al. 2015)
166 (Hassan et al. 2005)
167 (Hassan et al. 2005)

plastics, toxic algal blooms and invasive species). Terrestrial biodiversity is at risk from rising temperatures, loss of grasslands to deserts and drylands making them unsuitable for wildlife or agriculture, deforestation and degradation of tropical forests, and melting of glaciers in high mountain ecosystems and polar regions.

Exposure to unsafe drinking water and poor sanitation already results in 2 million preventable deaths per year from waterborne infections.[168] With droughts on the increase in many parts of the developing world, water-based sanitation will become even more difficult to implement and sustain, with the result that the occurrence and extent of hazards and risk will rise.

Overall, the pressures on exposed biodiversity and ecosystems (caused by climate change, habitat destruction and transformation, as well as land-use change) mean an irreversible and continuing decline of genetic and species diversity, and ecosystem degradation at all scales.[169] When ecosystems decline or disappear, important ecosystem services such as pollination are lost, and so are natural resilience builders such as carbon sinks, natural pest control, and access to herbal and traditional medicines, which are important for the health of much of the world's population.[170] In the loss of ecosystem biodiversity, there is the near-certain prospect of more-frequent hazard events occurring, in addition to sacrificing one of the remaining resources to mitigate the risk.

In summary, there are different dimensions of exposure beyond what any individual stakeholder is interested in. This is not an indictment of the analysis of past versions of this GAR, but is reflective of the new paradigm that the Sendai Framework has elucidated. Risk is a function of natural and anthropogenic hazards and is a question of management for all levels of governance, all sectors and all dimensions of society. A robust health system and a well-managed road system and network of well-trained monitors are all mutually building resilience. For this reason, throughout the Sendai Framework's applicability until 2030, it is important that research and science seek to better understand and represent as many dimensions of exposure as possible.

3.3

Vulnerability

The impact of disasters encompasses more than just affected people or economic losses. While every society is vulnerable to risk, some suffer significantly more and recover more slowly than others when adversity strikes. Much of the existing literature on risk remains sector specific and treats vulnerability as people's exposure to risk. This section, building on the analysis offered in previous GARs and empirical evidence on the multidimensional aspects of risk exposure, reiterates the need for a more holistic and people-centred approach to vulnerability. It asks why some people do better in overcoming adversity than others by assessing the main obstacles that individuals, households and societies may face in managing risk, including challenges in terms of information, resources and incentives to build back faster and better.

Vulnerability is defined as the "conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, community, assets or systems to the impacts of hazards."[171] It occurs in connection with the incidence of disasters of varying magnitudes, which negatively affect the economic, social environmental/ecological profiles of countries over time. Implicit here is the notion of "differential vulnerability", referring to the different facets and variant levels of risk, to which populations are exposed, accounting for differentiated impacts and outcomes in disasters.[172]

Hazard identification is only an initial step within a risk management strategy. While the intensity remains important, of greater importance is the profile of a population whose economic, demographic, environmental, institutional and social characteristics may place its members at greater risk before, during and after a disaster. Whereas evidence suggests that wealthier countries with more developed institutions or governance are better able to reduce disaster risk,[173] several countries have witnessed rapid economic growth in the last few decades without a commensurable rate of vulnerability reduction.

The Sendai Framework was conceived as the world was witnessing impressive reductions in extreme poverty, major progress in improving access to schooling and health care, and the promotion of the empowerment of women, youth, persons with disabilities and older persons. Yet, four years later, despite such achievements, poverty reduction remains uneven across regions, within countries and among various population groups. While more than 1 billion people have risen above the $1.90-a-day line since 1990, millions fall back into poverty annually due to shocks.[174]

Across the globe, in developing and developed economies alike, those left behind (e.g. people living in poverty, unemployed and underemployed, persons with disabilities, women and girls, displaced populations and migrants, youth, indigenous groups and older people) are often considered to be stuck in cycles of compounding vulnerability. People living in poverty may be caught in protracted cycles of unemployment and underemployment, low productivity and low wages, and are particularly vulnerable to extreme weather. Disenfranchised minorities, displaced populations and migrants are often exposed to discriminatory practices, have interrupted or no access to formal justice systems and health services. For those households, vulnerabilities may have evolved and persisted over long periods leading to disparities in income, gender, ethnicity, household and social status, and job type, which are difficult to overcome.[175] The governmental challenges of how to adapt and implement DRR plans in fragile and complex contexts such as conflict, famine and other situations where people are displaced or migrating in large numbers are discussed further in Chapter 15.

3.3.1

Measuring vulnerability

Disasters significantly interfere with daily life. They disrupt livelihoods, family and social networks, and interrupt schooling trajectories, access to health services, infrastructure networks, supply chains and connections of essential services, all of which are critical for people's well-being. Conceptually, the quantification of vulnerability has been surrounded by debate in recent decades about appropriate methodologies, metrics and indicators applied within quantitative, survey-based methods (single cross sections, panel surveys and community surveys) and qualitative ones. Empirical literature on risk and vulnerability is extensive. It is therefore inevitable that there would be differences in how analysts/organizations define and measure vulnerability in relation to disasters. However, considering the increasingly damaging impact of disasters, an improved ability to measure vulnerability – albeit incomplete and imperfect – should be a welcome step towards the promotion of a disaster-resilient culture.[176]

Vulnerability and risk

Vulnerability must be defined in terms of what it is that a population is vulnerable; its measurement therefore requires precise characteristics. Exposure to risk should be analysed as one of the many dimensions of vulnerability. For instance, vulnerable households are typically more exposed to risk

168 (WHO 2018c)
169 (Heywood 2017)
170 (United Nations 2016a)
171 (OEIWG 2016)
172 (Shupp and Arlington 2008)
173 (UNISDR 2009); (UNISDR 2011b); (UNISDR 2013b); (UNISDR 2015b)
174 (United Nations Economic and Social Council 2018b)
175 (UNDP 2014)
176 (Wei et al. 2017)

and less protected from it.[177] Such exposure has a direct effect on their socioeconomic status and welfare. Equally important is how risk exposure causes vulnerability or increases its profundity.[178] For instance, households, in their efforts to avoid risk exposure, may be forced to take costly preventive measures, which increases the likelihood of falling into poverty. Consequently, the decision not to invest in a high-risk but high-return activity means foregone income and also a higher likelihood that a household remains or becomes poor.[179] For example, a disaster can push an already income-poor household further into poverty or drive a non-poor household below the income poverty line.[180] A shock may account for the decision to take children out of school, affect people's health permanently, the ability to obtain sufficient nutrition, a reduction in life expectancy or access to remedies for treatable diseases.

The direction of causality between vulnerability and risk should also be assessed in reverse order. Hoogeveen and colleagues offered useful conceptual insights on reverse causalities while incorporating vulnerability in poverty analysis.[181] For example, to avoid deprivation or food insecurity, a household may choose low-value crops or may be forced to cultivate in insecure areas (e.g. landmine-contaminated land or areas in conflict) or to live in a hazard-prone environment (e.g. landslides, flood plains or along railway lines). It is thus not only exposure that may lead to detrimental welfare outcomes. The manifestation of risk (as a shock) also leads to undesirable welfare outcomes.

Vulnerability Assessment

Vulnerability assessments can be sectoral or multi-dimensional, demonstrating the distribution of the vulnerability indicators used and disaggregating by sex, family size, location, etc. While several methodologies exist, they are often ex ante and limited to specific sectors. In addition, many vulnerability measurements focus on hazards and risks while overlooking information on capacities to address them, hence solving only one piece of the vulnerability puzzle. They are initiated at the request of a specific policy question for a specific group or area (e.g. vulnerability profiles of displaced population due to disasters in an area), and their importance is largely overseen for other policy planning purposes. Lastly, such assessments are often conducted by international organizations, NGOs and the private sector within a project life cycle, compromising opportunities for systematically integrating their findings into the overall risk management process and often making suppositions about categories that are influenced more by stereotypes of vulnerability than measured vulnerability.

Vulnerability profiling is used to identify groups that are "liable to serious hardship" – a term coined by economist and Nobel Laureate, Amartya Sen. Typical examples include to children and orphans, pregnant women or girls, nursing mothers, sole or primary carers (of dependent children, elderly people or people living with disabilities), people at risk of sexual or gender-based violence (GBV), adults or children experiencing family violence, exploitation or abuse, people living with HIV, elderly, ethnic minorities, certain castes, internally displaced persons (IDPs), and households headed by single women or children. These groups are often described as vulnerable in the common usage of the term. However, one point that merits specific attention is that even though these groups are characterized as vulnerable, risk is not a core characteristic of their problems, even if in some cases, risks may have contributed to their destitution as their opportunities to cope with those risks are limited.[182] In other words, personal characteristics can be linked to vulnerability, but not define it, and it is precisely the correlations between vulnerability profiles and risks that vulnerability assessments can help determine.

Risks vary by their frequency, intensity and welfare impact.[183] Although the sources of vulnerability are multiple and diverse, some of the most important factors that are recurrent in vulnerability assessment revolve around poverty, inequality, gender,[184] education and health status, disability and environmental concerns. A few examples are presented in Table 3.4. These outline the risk categories and possible indicators that measure vulnerability in disaster contexts.

There is no perfect answer to the question of which indicators are most appropriate, as each context dictates a different approach. However, a common denominator is that indicators should be selected based on: (a) their validity to represent their underlying concepts appropriately and (b) their ability to inform action and policy planning.

Haitian woman takes refuge from Tropical Storm Hanna, 2008
A woman stands in the entrance of the cathedral in Gonaives, Haiti, where up to 400 people took refuge after Tropical Storm Hanna flooded the region, stranding thousands and killing more than 160 people.
(Source: United Nations 2008; Logan Abassi)

177 (Hoogeveen et al. 2003)
178 (Bergstrand et al. 2015)
179 (Bergstrand et al. 2015)
180 (UNISDR 2013b); (Sen 2000); (Narayan et al. 2000); (UNDP 2014); (World Bank 2013)
181 (Hoogeveen et al. 2003)
182 (Hoogeveen et al. 2003)
183 (Holzmann and Jorgensen 2000)
184 (Nelson 2015)

Table 3.4. Selected risk categories and indicators in vulnerability assessments

Risk category	Domains	Indicators
Life-cycle/ demographic risks	Birth, maternity, old age, family break-up, death	**Family size**: household size, number of dependents, recent births, gender of head, old age, deaths in family, family dissolution, etc. Women's access to resources. **Education levels**: literacy rate, out-of-school population, pre-primary school gross enrolment ratio, primary school gross enrolment ratio, primary school net attendance ratio, secondary school net attendance ratio, secondary school net enrolment ratio. **Age structure**: percentage of elderly population, percentage of children under five, residents aged 65 and older. **Population characteristics**: resident population density, population per settlement area. **Population growth**: crude birth rate, positive birth rate, growth rate of resident population.
Economic risks	Unemployment, harvest failure, business failure, resettlement, displacement, cross-border migration	**Poverty**: proportion of population below the international poverty line, by sex, age, employment status and geographic location (urban/rural); proportion of population living below the national poverty line, by sex and age; proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions; proportion of population covered by social protection floors/systems, by sex, distinguishing children, unemployed persons, older persons, persons with disabilities, pregnant women, new-borns, work-injury victims, the poor and vulnerable. **Income**: per capita income, ratio of high incomes (men/women), average number of wage earners per household. **Employment**: employment to population ratio, status in employment, employment by sector/occupation/education, informal employment, unemployment rate, labour productivity, social protection, high qualification employed, percentage of women with no economic activity, distribution of working populations in different sectors.
Health and welfare risks	Illness, injury, accident, disability, epidemic (e.g. malaria), famine, etc.	**Physical and mental health status**: risk of suicide, elderly person, substance addiction destitution, under five child mortality, neonatal mortality. **Safe water**: population using safely managed drinking water services; population using safely managed sanitation services; population using modern fuels for cooking/heating/lighting; air pollution level in cities. **Nutrition**: prevalence of undernourishment (food deprivation), prevalence of critical food poverty (income deprivation) and prevalence of underweight children (child undernutrition).
Disability and special needs risks	Access to and benefit from public services	Percentage of persons with disabilities living off less than $1.25 per day; percentage of persons with disabilities covered by social protection, or percentage of persons with disabilities receiving benefits; percentage of deaths from persons with disabilities among all deaths due to disasters; proportion of households with persons with disabilities facing impoverishing health expenditure.

Environmental risks	Pollution, climate change, deforestation, land degradation, landslides, volcanic eruptions, earthquakes, floods, hurricanes, droughts, strong winds, slash and burn agriculture, overharvesting of forest products, desertification, Industrial logging/ illegal logging, overgrazing/cattle ranching, soil erosion	**Infrastructure**: quality of housing, age of construction, population density, dwelling in five or more storey apartments, air quality, drinking water, ultraviolet exposure, climate change. **Agri-systems**: percentage of land-use changes, proportion of land area covered by forest and vegetation, percentage of land degradation, arable and permanent cropland area, reduced dependency on fertilizer and pesticide use, proportion of land area covered by forest, percentage of area under sustainable forest management. **Wetlands/rivers**: percentage of area maintained as wetlands, riverbank vegetation maintained, water quality and turbidity, river fragmentation. **Coastal/marine**: area of healthy seagrass beds and marine algae, proportion of marine area protected, health of marine ecosystems, as measured by marine trophic index, coverage of live coral reef ecosystems, area of healthy mangroves as buffer zones as measured by area, density and width.

The feasibility of applying one methodology over another is often dictated by data considerations. While risk analysts for the past decade have increasingly recognized the importance of assessing the differentiated impacts of disasters through vulnerability assessments, a cross-sectional household survey is usually the minimum available for most countries. Identifying data sources, assessing their suitability for measurement and proposing suggestions for complementary measures are crucial in developing a vulnerability assessment methodology.[185]

Data sources for vulnerability assessments

In a vulnerability survey context (single cross sections, panel surveys or community surveys), quantitative indicators measure the degree to which a characteristic is present, while qualitative data comprises numeric observations that point to the presence or absence of a characteristic to a single category. Qualitative data may also include textual or visual data stemming from interviews, observations, project data, administrative data or records and can support inferences. A qualitative mapping of the strategies that individuals, households and communities choose to use to anticipate, mitigate and cope with these disaster risks is also helpful, not least in terms of broadening the policy options available.

In the absence of large household surveys, a small panel component may also serve to understand dynamic issues of vulnerability as related to systemic risks. As they only cover a certain year range, retrospective models can assist in bridging the gap between survey years. In the (fortunate) event where panel data was collected before and after a disaster, analysts can examine variables across the disaster continuum (before, during and after) by assessing earlier periods for ex ante mechanisms and later periods for ex post response.[186] For instance, information on displacement, migration, income diversification and livelihood opportunities are useful for ex ante mechanisms, while variations on employment and underemployment, remittances and informal transfers are ex post mechanisms.[187]

Secondary data

Secondary data sources may include administrative data, geographic information system (GIS) data, development/resilience/ livelihoods project data, census and demographic data, and demographic and health surveys. Information from such sources can complement vulnerability analysis given their ability to capture intertemporal dimensions of risk,

185 (UNDP 2016a)
186 (UNISDR 2013b); (UNISDR 2015b)
187 (Hoddinott and Quisumbing 2003b)

particularly when risk analysts have a single cross-section survey to base their assessment on.

GIS data is also an extremely useful source of information, as it allows analysts to map and spatially reference units of vulnerability information, hence exploring relationships among natural hazard and vulnerability variables. It allows improved visualization of the spatial distribution of data, stratification of sampling, identification of spatial correlates of vulnerability, geographic targeting, and assessment of the local and non-local (externality) impacts of some types of shocks.[188]

Enumerator in Bamyan district, Afghanistan, 2010
(Source: United Nations 2010)

Qualitative, interview and focus group data at the community level will be valuable sources in understanding how people react and are thus projected to react in the future, in the wake of a disaster. During the 2017 Hurricane Harvey in the United States of America, more women than men decided to not evacuate despite alarming messages from EWSs. Across the world, women and girls are overwhelmingly tasked, personally and professionally, with caring for children, housework, the elderly and people with disabilities. They are often the last to leave. So, simple life-saving decisions, like deciding when and whether to evacuate a disaster area, become a difficult choice.[189]

Translating the above into action for vulnerability assessments dictates that questions on disasters preparedness and response should be asked at the household and community levels for cross-validation. In cases where shocks are multiple and covariant, community information can provide the context for individual responses to be analysed and go beyond the obvious yes or no answers. The use of proxy questions to ascertain the probability of certain groups benefiting or, conversely, of being excluded from risk management plans is also critical. Vulnerability assessments have repeatedly proven that disasters discriminate on the same divisions that societies discriminate against people.[190]

Lastly, census data and demographic surveys (e.g. demographic and health surveys) are especially valuable for mapping and analysing life-cycle risks.[191] Census data can improve understanding of the size of age cohorts as well as the geographic distribution. Matching the geographic distribution of the population to, for example, rainfall and seismic hazard data could prioritize population groups that are most vulnerable to weather and earthquake shocks. Furthermore, nutrition and health surveys can also provide information on issues related to health and diet, food components, food production, food safety, food insecurity and highlight regions with higher likelihood of malnutrition prevalence, as well as high incidence of contagious diseases.

3.3.2

Life-cycle vulnerability

Risks and capacities to cope accumulate over lifetimes. The life-cycle approach has been commonly used to cluster different vulnerable groups and prioritize action among them.[192] It is founded on a multidimensional concept of vulnerability, initially conceived by the World Bank, which allows the identification of risk factors for each group and thereafter forecasts the long-term consequences of those risks into next stages in life.[193] Life trajectories are the result of investments made in preceding stages as the consequences of shocks may cascade into long-term consequences. A setback in early childhood has compounding effects throughout the rest of a person's life, in terms of growth, job and social status and the uncertainties involved with growing older and the transmission of vulnerability to the next generation.[194] This GAR argues that the cumulative and cascading nature of vulnerability requires timely and continuous investment to effectively protect those groups whose vulnerability profiles – many structural and many tied to the life cycle – make them more susceptible to risks.

Once metrics for observation have been selected, the life-cycle approach can be used to rank various groups, by degree of destitution, by their numbers or a combination of both. As vulnerable groups are clustered according to their specific characteristics, poverty data can be extremely useful as a touchstone because it is well measured and relates to most of the other characteristics (age, gender, health and asset ownership).[195] If such basic data is not available, the survey-based approach is preceded by a qualitative analysis to cluster population groups.[196]

The advantages of a life-cycle approach to vulnerability is that it can forecast socioeconomic impacts for different population groups and thus prioritize risk-coping mechanisms but also develop policies to prevent these risks from cascading into the next stages in life. In other words, the analysis is not static; rather it adapts based on learning from the dynamic processes that perpetuate vulnerabilities over time.

In practical terms, when it comes to assessing such vulnerabilities this means that if a vulnerable group is identified at an early stage of analysis, analysts can better measure the elements of such vulnerabilities over time by tracking those indicators through longitudinal surveys. This type of information does not need to be collected in isolation. Rather, vulnerability analysis can inform the development of existing and future surveys and census data developed by national statistical offices (NSOs). In ideal cases, the inclusion of disaster-sensitive indicators

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188 (Hoddinott and Quisumbing 2003a)
189 (Vidili 2018)
190 (Hallegatte et al. 2016)
191 (Hallegatte et al. 2016)
192 (Bonilla Garcia and Gruat 2003)
193 (Irving 1996)
194 (Morrissey and Vinopal 2018)
195 (Hoogeveen et al. 2003)
196 (Lokshin and Mroz 2013)

offers improved measurements of disaster incidences, identifies linkages with other aspects of welfare and integrates those with risk management instruments.

3.3.3

Socioeconomic vulnerability

An overreliance on asset losses to explain vulnerability obscures the relationship between risk and poverty. By definition, wealthy individuals have more assets to lose; therefore, their interests dominate in risk assessments that are limited to asset losses. But measuring asset losses misses a major dimension, particularly in the developing world; the poor are less likely to have assets to lose. Just as highly developed countries are more exposed to risk (by virtue of having more to lose), so too are wealthy people. But the losses felt by less-wealthy countries and less-wealthy people are not less important. In fact, they also lack the means and opportunity to smooth the impact of shocks while maintaining their consumption, and to recover and rebuild their assets.

To compensate for the bias towards asset losses as the key metric of vulnerability, the Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters report introduced the concept of well-being losses. In addition to traditional asset losses, well-being losses account for people's socioeconomic resilience, including:[197]

- **a.** Their ability to maintain their consumption for the duration of their recovery
- **b.** Their ability to save or borrow to rebuild their asset stock
- **c.** The decreasing returns in consumption – that is, poorer people are more affected by a $1 reduction in consumption than richer individuals

Traditional risk assessments evaluate asset exposure and vulnerability to hazards to determine expected asset losses. The Unbreakable model additionally incorporates the socioeconomic resilience of the communities to predict well-being losses.

There has been progress towards understanding and representing socioeconomic vulnerability in a systematic way. Multi-partner projects like INFORM, led by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), have identified several structural vulnerability indicators that are tracked globally. These include static measures of socioeconomic vulnerability such as the Gini coefficient and aid dependency and more dynamic data such as the number of IDPs, prevalence of certain diseases and malnutrition rates. These are useful as a starting point but are limited to usually years-old static data, national-level resolutions and certain kinds of vulnerability. Still, the information is standardized and validated by many contributing partners.

New metrics of disaster impacts – including poverty headcount, poverty gap and well-being losses – can be used to quantify the value of interventions outside the traditional risk management toolbox. Asset-informed risk management strategies primarily focus on protection infrastructure, such as dikes, and the position and condition of assets, for instance with land-use plans or building norms.[198]

Strategies informed by well-being information can utilize a wider set of available measures, such as financial inclusion, private and public insurance, disaster-responsive social safety nets, macrofiscal policies, and disaster preparedness and contingency planning. Even if they do not reduce asset losses, these measures can bolster communities' socioeconomic resilience, or their capacity to cope with and recover from asset losses and reduce the well-being impact of disasters.

Social vulnerability accounts for the inability of people and society to withstand the effects of the multiple stresses they are exposed to. In contrast to physical vulnerability, social vulnerability is independent of hazard intensity. Methodologies for measuring components of social vulnerability vary greatly, but can be broadly grouped into quantitative, index-based assessments and qualitative, community participatory ones.

Tent city, Vancouver, Canada
(Source: flickr.com user Sally T. Buck 2010)

Index-based assessments

A vulnerability index is built by a combination of vulnerability indicators. In turn, the vulnerability indicators are a direct measure of, or a proxy for vulnerability characteristics. Vulnerability characteristics can then be grouped into vulnerability categories. For example, a building has multiple physical vulnerability categories, such as a roof and number of storeys, and each category has one or more characteristics, such as roof shape and covering and number of storeys above ground and below ground. For social vulnerability, examples of vulnerability categories are education and food security. These categories have a variety of vulnerability characteristics such as education level and access to education, and food availability, accessibility and stability.[199]

By analysing different clusters of variables to determine the level of vulnerability and resilience of target populations, it is possible to begin to quantify social vulnerability.[200] The target variables are divided into two groups. The first includes variables about individuals (e.g. education, age and gender) that are aggregated to produce community-level

197 (Hallegatte et al. 2017)
198 (Walsh and Hallegatte 2019)
199 (Murnane et al. 2019)
200 (Cutter, Boruff and Shirley 2003)

results. The second group covers variables about the community as a whole, such as population growth, infrastructure quality and urban/rural division that need not be disaggregated. Eleven composite factors can be extracted to formulate a social vulnerability index.

This method was used in 2015 to calculate the social vulnerability to floods in the city of Vancouver, taking into account the:[201]

- Ability to cope (age, gender), ethnicity (minority status, immigration)
- Access to resources (income, property value, percentage of renters, education, unemployment, income from government transfers)
- Household arrangement (single-parent households, single-member households)
- Public transport (as the main family transportation mode)
- Built environment (quality of housing, age of construction, population density, dwelling in five or more storey apartments)

Another initiative built a socioeconomic vulnerability index specific to landslide hazards, by looking into the three subindices relating to different issues of vulnerability/disaster risk:[202]

- Demographic and social index (age distribution, number of workers who may be exposed to disasters, population density, foreigner ratio, education level and housing type)
- Secondary damage triggering index (number of public offices, road area ratio, number of electronic supply facilities, school area ratio, and commercial and industrial area ratio)
- Preparation and response index (disaster frequency, Internet penetration rate, number of disaster prevention facilities, perceived safety, number of medical doctors and financial independence of the borough)

Qualitative approaches

Through a vulnerability and capacity assessment (VCA),[203] the International Federation of Red Cross and Red Crescent Societies (IFRC) employs various participatory tools to gauge people's exposure to and capacity to resist natural hazards. It is an integral part of disaster preparedness and contributes to the creation of community-based disaster preparedness programmes at the rural and urban grass-roots level. VCA enables local priorities to be identified and appropriate action taken to reduce disaster risk, and assists in the design and development of programmes that are mutually supportive and responsive to the needs of the people most closely concerned.

VCA is complementary to national and subnational risk, hazard, vulnerability and capacity-mapping exercises that identify communities most at risk. VCA is undertaken in these communities to diagnose the specific areas of risk and vulnerability and determine what action can be taken to address them.

The United Nations Development Programme (UNDP), the Office of the United Nations High Commissioner for Refugees (UNHCR) and the United Nations Children's Fund (UNICEF) broadly use participatory tools for VCAs that enable communities to identify their own capacities and vulnerabilities in relation to disaster management, developing mitigation strategies and building resilience to cope with future hazards. Data collected through these exercises can and should become more comparable, adding to a greater store of understanding and analysis of vulnerable populations. Through sustainably pooling assessments by different organizations, vulnerability analysis can expand operational response and coverage for those left behind as coordinated data collection and communication of findings among different actors on the ground becomes more integrated into DRR strategies and provides a more coherent picture and finer detail into vulnerability assessments.

Conclusions

Vulnerability assessments have repeatedly proven that disasters discriminate on the same lines that societies discriminate against people. Just as risk is generally systemic and interconnected, so too are the drivers of risk. This is also true when it comes to vulnerability. Even children can recognize the interlinked effects of poverty, ill-health, poor employment prospects and social exclusion, but the ability to quantify and measure that multidimensional vulnerability is still immature. The use of quantitative markers, proxy indicators and extrapolated data shows the way forward.

"Vulnerable populations" are often identified with high risk. However, risk is not a defining characteristic of the situation. The simple characteristic of being a child or disabled or of a particular caste or economic group does not define the vulnerability. Vulnerability must be thought of in terms of vulnerability to something. It is true that in many cases, realized risks may have contributed to their destitution as their opportunities to cope with those risks were limited. In other words, personal characteristics can be linked to vulnerability, but not define it; it is precisely the correlations among vulnerability profiles and risks that vulnerability assessments can help determine.

Vulnerability assessments are conducted in an isolated manner, usually with the objective of supporting the targeting of a specific policy question or beneficiary population in development planning and in emergency contexts. Through pooling assessments by different organizations/actors, vulnerability analysis can enrich operational response and coverage for those left behind as coordinated data collection and communication of findings among different actors becomes more integrated into DRR strategies and provides a more coherent picture of the entire society in finer detail.

Systematic collection of rich survey and census data at a global level would propel the accuracy of targeting social safety net projects and emergency measures ahead by decades, in pursuit of SDGs and with the objective of enabling better interventions to build social and economic resilience. Having good data on the coping mechanisms at the disposition of different classes of vulnerable people can help governments to better arrange for a more equitable repartition of public resources for social safety programming or to target development partner programming. The mutual and compounding value of fulfilling this simple act of governance in a systematic and thorough way unlocks resilience.

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201 (Oulahen et al. 2015)
202 (Park et al. 2016)
203 (IFRC 2018b)