Cities in Hazardous Environments Risk Assessment, Resilience, and Sustainability

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Abstract. Cities can concentrate disaster risk from the aggregation of people, infrastructure, assets, expansion, inadequate management, and the surrounding hazardous environments. Many cities are located close to geologic faults and active volcanoes, in coastal areas exposed to tropical cyclones and climate change conditions, and in the vicinities of nuclear, chemical, biological, and hazardous landfill facilities. By the end of this century most of the people will live in cities, which will present enormous exposure problems and invite human catastrophes. In the first part of the paper some cities in hazardous environments are identified where the consequences of hazards can be catastrophic, and the tools used in these cities to address their hazards are examined. To achieve resilience and sustainability of complex socio-technical systems like cities requires an appropriate modeling strategy, and in the second part of the paper a mathematical model is presented for addressing risk, vulnerability, resilience, and sustainability of cities. This model incorporates deductive and inductive logic for defining the sample space of events, consequences, and sustainability attributes, and employs the data base associated with the propositions and their memory information content, including the knowledge base not logically connected with the sample space propositions. This modeling strategy is presently applied to the cities of Naples in Italy and New York City in the United States.

Keywords: Cities, hazards, risk, vulnerability, resilience, sustainability, climate change, earthquakes, floods, landslides, volcanoes, tsunami, probability theory, modeling

1. Introduction

The human population is becoming more numerous, healthier, wealthier, and more concerned for its security and thus aware of its surroundings. Today, more than half of the world's population lives in cities and by the middle of this century an additional two billion people will join the urban dwellers [1]. The cities in the developing countries will experience most rapid urbanization and

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thus be exposed to the fastest rate of increase in the incidents of disasters. On average and in recent decades some 100,000 people have been killed annually by 200 disasters, and 100 million people were affected and $40 billion losses were sustained every year [2]. The cities, and those in hazardous environments in particular, will be confronted with increasing challenges on how to deal with possible consequences of the threats, from both the internal and the external city environments.

The policy makers are being increasingly aware of the global nature of threats and disasters and the United Nations (UN) in 1990 started a process of this awareness with the International Decade for Natural Disaster Reduction (IDNDR) [3]. This was followed in 1994 with the World Conference on Natural Disaster Reduction in Yokohama, Japan, where the significance of human vulnerability to disasters was recognized. In 1992 the United Nations Framework Convention on Climate Change (UNFCCC) [4] recognized the concerns about climate change, and in 1997 with the adoption of Kyoto Protocol [5] and passage into law in 2005 the nations of the world placed legal requirements on developed nations to reduce the emissions of greenhouse gases into the atmosphere. In 2000 the world leaders formalized 18 Millennium Development goals for reducing poverty and improving lives, and expressed the concern that the disasters can undermine these goals [6]. Following up on IDNDR, the UN adopted in 2004 the International Strategy for Disaster Reduction (ISDR) [7], consisting of partnerships comprising governments, intergovernmental and nongovernmental organizations, scientific and technical bodies, financial institutions, private sector, and civil society. The 168 countries that adopted the Hyogo Framework of Action (HFA) during the Hyogo World Conference on Disaster Reduction held in Kobe, Japan in 2005 placed emphasis on building more resilience to disasters and again encouraged collaborative strategies, but this resolution had no legal binding requirements [8]. Building on the HFA, the Sendai Framework for Disaster Risk Reduction 2015-2030 aims to achieve [9]:

> *The substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries. Prevent new and reduce existing disaster risk through the implementation of integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political and institutional measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness for response and recovery, and thus strengthen resilience.*

These objectives should be achieved through the four priority areas: Understanding disaster risk, strengthening disaster risk governance to manage disaster risk, investing in disaster risk reduction for resilience, and enhancing disaster preparedness for effective response. The 100 Resilient City Initiative aims that the cities around the world become more resilient to the physical, social, and economic challenges that are confronting the 21st century [10].

All of these initiatives highlight the importance of identifying threats and their consequences, reducing risk, producing resilience, encouraging sustainable development, and achieving sustainability in the future. But what precisely is meant by the terms "hazards", "consequences", "disasters", "risk", "vulnerability", "resilience", and "sustainability", and how are these terms supposed to be *operationally implemented* for building resilient and sustainable cities in hazardous environments? We will first briefly discuss what is meant by hazards, events, disasters, risk, and vulnerability, and in Section 4 will elaborate on resilience and sustainability and quantify all of these terms.

For humans, *hazards* are interpretations of events and an *event* is an occurrence happening or potentially happening at a determinable time and place, with or without the participations of humans. Hazards are thus the potential threats to humans and their welfare arising from dangerous phenomena and substances [11]. Although certain events can be triggered by one or more natural phenomena (such as the motions of tectonic plates and atmospheric circulations), the resulting consequences associated with earthquakes, tsunami, floods, landslides, pollutants, etc. can be influenced by human actions. The technological hazards originate from commercial and industrial activities of humans, such as accidents, failures of human built environments, etc. Hazards can produce *consequences*, *circumstances*, or something that the humans value, such as life, health, environment, economic assets, careers, power, and is often difficult not only to enumerate all possible consequences but also the potential events when both the nature and human organizations are involved. If the most relevant events and consequences are known, or sufficient information is available for judging their occurrence, it is possible, in principle, to apply the deductive reasoning to define the treatments to prevent the occurrence of undesirable consequences and eliminate a need for making inductive reasoning. For real problems, however, and in particular for those involving human societies, this information is seldom available and we must resort to inductive or plausible reasoning for optimal processing of incomplete information, so that the likelihoods of most significant harms affecting these societies and their surroundings can be established (Section 4).

Risk is used to denote the occurrence of unwanted circumstances that can produce harmful effects, but neither the United Nations [7], the European Union [12], nor countless researchers and practitioners agree on its precise use. Risk is generally determined through the probability theory and used by the decision makers to reduce it, but if it cannot be properly defined and quantified it cannot be properly used. This presents an enormous problem for cities in hazardous environment where there are many different hazards, consequences, stakeholders, and insufficient information to produce all the data necessary for proper risk evaluation. Under these circumstances a proper "risk control" can be highly uncertain and a proper risk analysis should be able to account for this *uncertainty* [13], which has not yet been clearly incorporated into risk analyses. The generation of more knowledge will lead to the reduction of uncertainty, but not to its elimination, because of the ontological and epistemological issues associated with this word [14].

The degree of severity of consequences depends on *vulnerability* of values that we place on things relative to the financial, ethical, cultural, ecosystem, or other measures expressed through some sort of measurable quantities or *indicators*. Like risk, vulnerability can also be expressed by the probability that a damage and loss can or cannot occur, and as such vulnerable are the social systems, ecosystems, infrastructure, habitats, industrial facilities, etc. Both risk and vulnerability depend on the background knowledge or information that is available and that is not available but must be consistent with the available data. Without a proper inference procedure that requires a model, all possible outcomes, and some other structure discussed in Section 4, we cannot properly use the probability theory to determine for whom or for what, where, and for how long risk and vulnerability assessments will be valid.

The specification of a *system* is a fundamental attribute of this assessment, since this is simply a region in space set aside for investigation whose size and properties can change with time. The choice of this region is arbitrary, but we should select it in a such a way that the specification by its properties which define the *system state* becomes as simple as possible for the solutions of real problems. Once a system is defined, everything else outside of the system becomes the *surroundings* and the interaction between the system and its surroundings is through the system *boundary* or boundaries that can change with time. We will see later on that without this clarity there is a great deal of confusion when confronting the concepts of communities, cities, resilience, sustainability, and other buzzwords (defined bellow) that are widely used in professional literature but seldom clearly defined. The threats to a community, region, or system can, therefore, be *internal* or coming from within the system and *external* or coming from the system's surroundings. The more vulnerable are the properties of a system exposed to (internal and/or external) hazards, the higher is the risk that these properties will change to those that are unsuitable for living beings.

By *disasters* we mean that the losses from hazards are sufficiently large to disrupt the functioning of a community or a society beyond its ability to cope. The loss of life is the principal indicator of a disaster [11], and since 1900 the most deadliest disasters caused by nature are the 1931 China floods (1-4 million deaths), 1970 Bhola cyclone in Bangladesh ($\geq$ 0.5 million deaths), 1920 Haiyuan earthquake in China ($\sim$ 0.3 million deaths), and 1976 Great Tangshan earthquake in China (0.2-0.7 million deaths) where the city of Tangshan of one million people ceased to exist [15, 16]. More recently, in 2005 Hurricane Katrina struck the Golf Coast of the United States and in New Orleans and surroundings caused some 2000 deaths and $125 billion in damage, in 1992 Hurricane Andrew made the landfall in Florida and Louisiana and caused 50 deaths and $30 billion in damage, in 1995 the Great Hanshin earthquake caused some 6000 deaths and $100 billion in damage in Kobe, Japan, and in 1985 the Mexico City earthquake caused 5000-10,000 deaths [17]. The rise of large urban agglomerates or megacities[1] underscores the increasing potential for much larger disasters.

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[1] A *city* consists of at least 50,000-100,000 inhabitants, whereas a *megacity* is usually considered a city with greater than one million inhabitants.

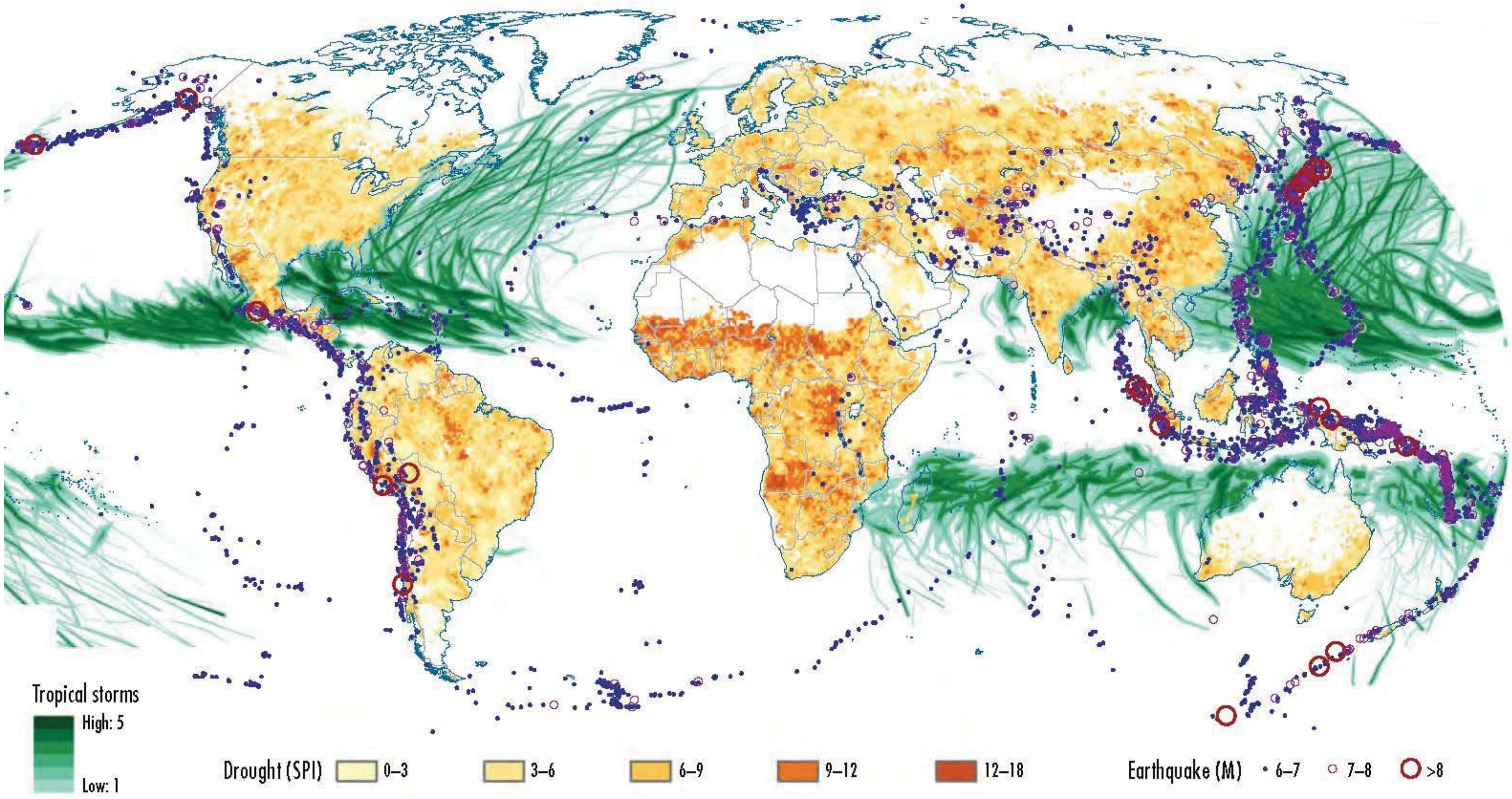


Figure 1. Distribution of storms and earthqakes worldwide [18]. Many earthquake locations are also associated with the locations of volcanoes, such as around the "ring of fire" in the Pacific, Central America, Mediterranean, and West Africa.

Cities can, therefore, concentrate the *disaster risk*, not only due to the aggregation of people, infrastructure, assets, expansion, and inadequate management, but also from the surrounding hazardous environments. Cities on volcanoes and on geologic faults, cities exposed to meteorological and climatological conditions, cities in the vicinity of nuclear, chemical and biological facilities, and cities neighboring hazardous landfills containing industrial and medical waste and stockpiles of spent fuel from nuclear reactors can be found all over the world. San Francisco, Naples, Istanbul, Tokyo, Rabaul, Mexico City, Lima, and many others are all situated in active geologic areas, whereas the coastal cities of North and South America, West Africa, Mediterranean, Bay of Bengal, and South China Sea, such as Dhaka, Sidney, Miami, Seoul, and Rio de Janeiro, are exposed to tropical cyclones (storms, hurricanes, typhoons), inundations, and tsunami (Fig. 1) [18]. The global warming will increase the potential hazards from the sea-level rise and changes in atmospheric and oceanic circulations [19]. Many nuclear power stations and chemical and biological facilities are today located close to large metropolitan areas (Los Angeles, New York, Paris, and others) with questionable safety nets and this problem will proliferate with the need to double the energy supply for humanity by the middle of this century and development of the African Continent [20].

Urban areas both affect and are affected by the hazards, because of both the natural and anthropogenic threats. Cities demand materials for production and consumption, alter ecosystems, and their waste products affect biogeochemical cycles and climate [21]. Throughout the human history the concentrations of individuals have made ideal settings for innovations and agglomerations of economies that resulted in higher standards of living [22], and given the advantages that the cites are providing it is thus not surprising that more and more people have been moving to urban areas on the expense of creating different risks for themselves and their offspring. For cities in hazardous environments this risk becomes especially elevated when the urban dwellers are ignorant of the consequences of cities' hazards or fail to prioritize security over emergency. Building security with preemptive prevention strategies instead on relaying on dealing with emergencies or promoting emergency culture should be the key pursuits of civil societies, but, unfortunately, managing the disasters instead of preventing disasters takes precedence, because managing the long-term preventive strategies are apparently more "risky" than managing the short-term risks. It should be, therefore, of no surprise that the people in hazardous environments thrive in the *apparent security* just because they have no personal experiences with the possible consequences of their hazards and allow their representatives to behave as the catastrophic consequences of these hazards will not occur during their lifetimes [23].

Most city habitats have been built without adequate urban plans and their key structures and infrastructures have been designed only on the basis of the *most probable* levels of natural and anthropogenic hazards, where the severe consequences for the populations and built environments from low probability events (large earthquakes, nuclear reactor accidents, large volcanic eruptions) have been marginalized. Such practices for cities in hazardous environments are inviting disasters and should change, because *the consequences of small probability events are often catastrophic* for large urban centers.

Every city in a hazardous environment has specific issues, and what may be acceptable to one socio-economic and cultural group does not necessarily imply that it will be acceptable to another group. One of the central pillars of sustainability is the *sense of belonging* [24], where the people prefer to cohabit whenever possible with the environment where they have been raised and where they built their culture, instead of relocating to potentially more secure environments but have to face socio-economic and cultural uncertainties. The populations of many cities in hazardous environments have thrived and will therefore continue thriving in apparent security as long as the advantages of sense of belonging and apparent security outweigh the apparent disadvantages of natural and anthropogenic threats.

Some key natural and anthropogenic hazards that many cities are confronted with are discussed in Section 2. Section 3 presents some examples of cities where these hazards pose great dangers to populations and what is being done to confront these hazards seriously. Risk assessment, vulnerability, resilience, and sustainability for cities in hazardous environments are elaborated in Section 4 where a probability theory model for quantifying these terms is presented. The agglomeration of people in cities offers extraordinary opportunities for innovations leading to the creation of security culture, but these collaborative interdisciplinary and transdisciplinary opportunities are often suffocated by too many special interests.

2. Natural and Anthropogenic Hazards

According to UNISDR [25], a *hazard* is “a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage” and can be of *natural* or *anthropogenic* origin, and often appearing in combination. A hazardous thing or event can cause other hazardous events, and when defining the hazards for cities it is necessary to consult carefully the historic sources to ascertain the nature of past events and their consequences. The knowledge base of past and projected future events and consequences is an integral part of the definition of risk and may thus make its assessment subjective or produce only an illusion of risk control, and especially for large cities where there are complex perceptions of risks and decision makers can easily marginalize all those risks that for them are little relevant during their short-term of governance.

Earthquakes are ubiquitous (Fig. 1) and often cause catastrophic losses of lives on the Earth’s surface. They are produced from the fracturing of rocks produced by the movements of tectonic plates, by the rising of magma or molten rock from the mantle through the crust and producing volcanic eruptions, or from the man-made explosions in mines, wars, and explorations for fossil fuel resources.

Some volcanic eruptions produce slowly moving lava flows which are not very hazardous for humans but can cause large property damage, whereas the more explosive volcanic eruptions producing high rising and collapsing plumes cannot only greatly affect the local environments, but also the entire climate system of the Earth and cause the extinctions of most life forms [26]. Tsunami are produced from the relative motions of tectonic plates and landslides from underwater volcanoes and land-based mountain ranges. *Technological hazards* form a subset of anthropogenic hazards that are associated with failures of human built environments, such as human habitats, infrastructures, and industrial structures. Industrial facilities can release potent chemical and radioactive materials into the atmosphere and into the ground, and possibly contaminate large areas for hundreds and millions of years and change global atmospheric and oceanic circulation patters that change the Earth's climate. Global warming drives sea-level rise which leads to coastal flooding that can affect socio economic development by affecting the supply of food and water resources and global trade patterns. As shown in Fig. 1, hurricanes and typhoons pose great problems to humanity and depend on atmospheric and oceanic circulations. Human settlements and resettlements can produce fatal diseases, and the wars produce devastations of food supply chains by dismantling the often fragile human collaborations [17, 27, 28].

A single hazardous event, such as an earthquake, can produce a variety of consequences, depending on the surrounding environment. A fracture in a building produced from the lateral and vertical motions of the building can lead to the collapse of the entire building, which may produce fires, loss of electricity, and block city traffic. This in turn causes economic hardships and may produce loss of life. The built environments of cities on volcanoes can be especially vulnerable from the construction practices that may or may not have been properly implemented to account for earthquakes of different strengths, ash fall from volcanic eruptions accumulating on rooftops, pyroclastic flows from collapsing volcanic columns rushing down the volcanoes at several hundred kilometers per hour and at temperatures exceeding 1000 K, large chunks of rocks being ejected from the decapitation of volcanic cones as the ascending magmas in volcanic conduits violently interact with underground aquifers, and lahars produced from the condensing water vapor in the volcanic plumes. All of these volcanic events can occur during a single eruption, and often simultaneously [29]. Nuclear reactor accidents, such as at Chernobyl, Ukraine in 1985 [30] and Fukushima, Japan in 2011 [31], can release radionuclides that make the local areas uninhabitable for hundreds of years and contaminate large surrounding areas, whereas the releases of toxic gases from industrial facilities can cause thousands of deaths in very short time, such as that at Bhopal, India, which in 1984 produced some 6000 deaths and over half a million injuries [32]. Combinations of two or more hazards can also produce unforeseen consequences that are dependent on the local conditions of the environment.

In a complex system, such as city and an ecosystem, there are many events taking place in different parts and at different times, and it may happen that a small event in such a system can cause its state to be defined by completely different properties that may or may not be suitable for living beings. The Earth's atmosphere is such a system, where the global warming and the non-linear behavior of the atmosphere and oceans may trigger abrupt changes with different atmospheric and oceanic circulation patterns that could not only greatly affect the adaptation of humanity, but also produce mass extinctions, as happened several times during the Earth's history [26]. Cities are human-constructed environments that shield their inhabitants from many threats, but when these environments become inadequate for human well-being they can become very unpleasant. High cost of land in cities encourages crowding that exacerbates both the internal and the external threats, and the changing population densities and their economic and cultural functions affect the cities' intellectual and innovative activities. Urban planning and security management become interactive in megacities and the cities have different susceptibilities to disasters.

Urban areas are, therefore, the places where many disasters can occur: Natural, technological, biological, chemical, and societal. Floods can dispense toxic materials and earthquakes can rupture fuel distribution and unbalance information systems. Cities on volcanoes can become uninhabitable for centuries by large volcanic eruptions. Nuclear reactor accidents can produce local and surrounding areas uninhabitable for thousands of years, and the droughts, tsunami, and tropical cyclones can uncover waste disposal sites, disrupt city services, and even terminate their existence. Social inequality can produce unrests and crime can take control of cities innovative capacities. These and other *multihazards* are difficult to assess for any large city, because our knowledge on how the complex systems function are rudimentary [33]. But hazards can also produce *hazard opportunities* for producing higher levels of safety and human development, as the great cultures of the past (in the Middle East, Asia, and Central America) demonstrated by their central preoccupation with avoidance, prevention, and mitigation of hazards and disasters. The megacities of tomorrow have a great potential of becoming not only the key places of unprecedented disasters, but also the places of extraordinary growth of humanity.

3. Cities Exposed to Natural and Anthropogenic Hazards

By the middle of this century 70% of world's population will live in cities and almost two billion people will be exposed to tropical cyclones and earthquakes, and the urban management will have to perform better in generating and disseminating credible information on city hazards and their associated risks [34, 35]. The economics of cities is related to favorable geographical locations that are often exposed to the increased likelihoods of hazard events, such as floods, cyclones, and volcanoes. The agriculture in particular is beneficial in the proximities of volcanoes and about 10% of population lives within 100 km of historically active volcanoes, with high concentrations in Southeast Asia (Indonesia, Philippines) and Central America (Mexico) [36]. Low elevation coastal zones cover some 2% of the world's land area and contain more than 10% of the world's population

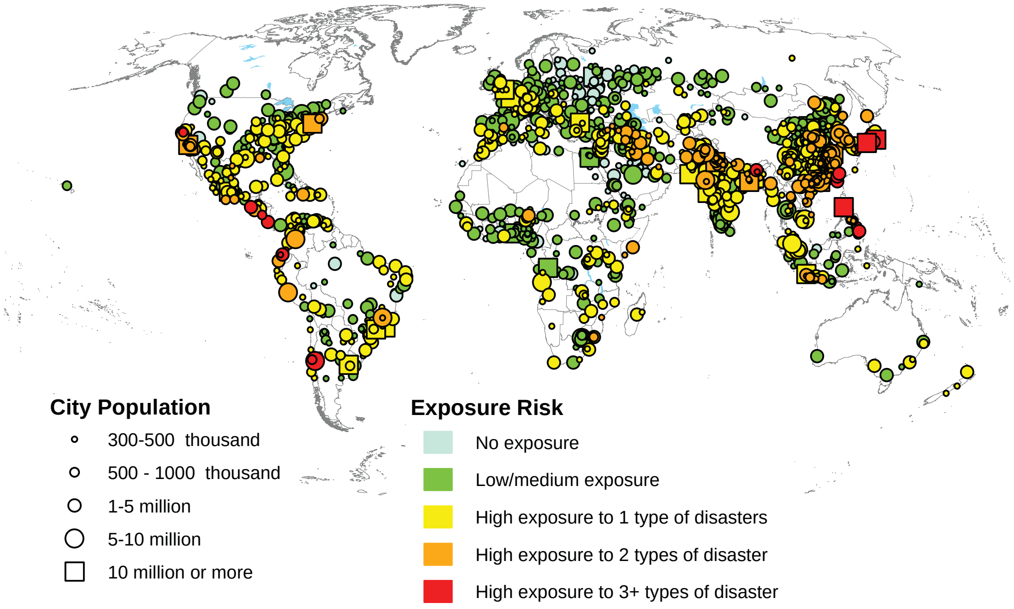


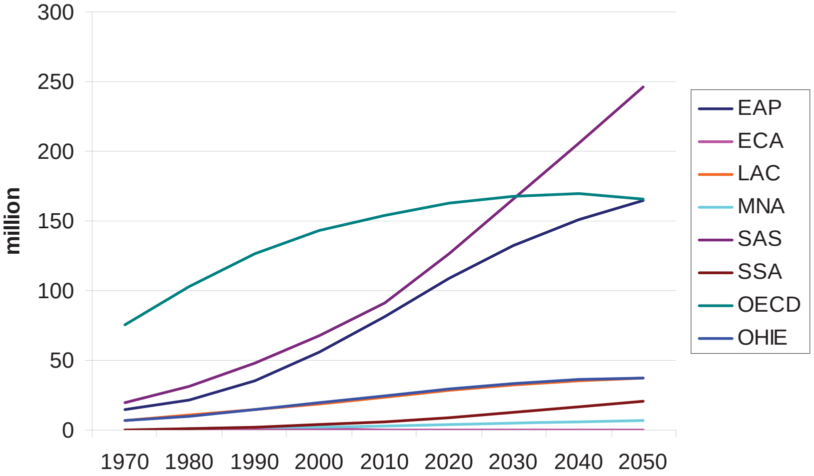
Figure 2. World cities at risk [38].

and 15% of the world's urban population [37]. The intense competition for land in urban areas not only leads to higher population densities but also to the increasing risk from the rise in exposure. Figure 2 shows the world's cities exposed to different levels of risk and Fig. 3 the projected population increases in large cities exposed to cyclones and earthquakes for different regions of the world defined by the World Bank Organization. Nuclear reactor accidents at Chernobyl in 1986 and Fukushima in 2011 produced large exclusion areas for hundreds of years and contaminated hundreds of square kilometers of fertile soils [30, 31], and only in imagination can we perceive what could happen if such accidents occurred in the close proximities of cities with millions of people. In 1984 the Union Carbide pesticide plant in India released some 30 tons of a highly toxic gas and some 600,000 people were exposed and several thousand people died from the release of methyl isocyanate gas [32].

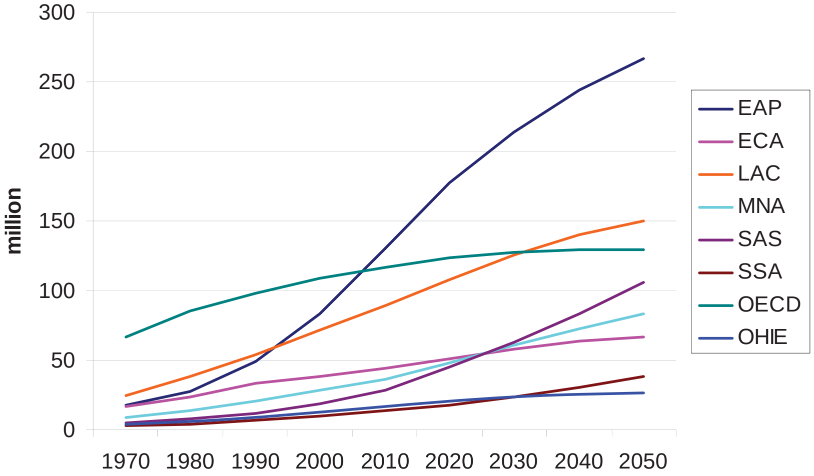
The following brief tour of some of the cities on geologic faults, cities on volcanoes, cities exposed to tropical cyclones and climate change, and cities exposed to hazardous industrial facilities attest to the challenges imposed on the technical and governance organizations to ensure that these cities thrive in security and prosperity in spite of their surrounding hazardous environments.

3.1 Cities on Geologic Faults

Figure 4 presents a sample of some cities of the world that are exposed to earthquakes by their virtues of being situated on or close to the *geologic faults*. The faults are ruptures on the Earth's crust or *lithosphere* consisting of six large

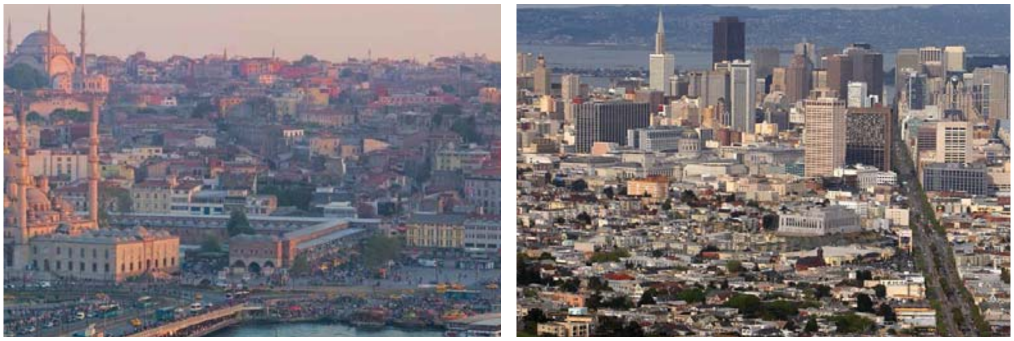


(a) Populations in large cities exposed to cyclones will increase from 310 million in 2000 to 680 million in 2050.



(b) Populations in large cities exposed to earthquakes will increase from 370 million in 2000 to 870 million in 2050.

Figure 3. Exposures of populations to cyclones and earthquakes [35]. EAP (East Asia Pacific), ECA (Europe and Central Asia), LAC (Latin America and Caribbean), MNA (Middle East and North Africa), OECD (Organization for Economic Cooperation and Development, 34 democracies with market economies).



(a) Istanbul (left). San Francisco (right).

(b) Mexico City (left). Wellington (right).

(c) Tokyo (left). Amatrice after 2016 earthquake (right).

Figure 4. Cities on geologic faults: Istanbul (Turkey), San Francisco (United States), Mexico City (Mexico), Wellington (New Zealand), Tokyo (Japan), Amatrice (Italy).

(African, Eurasian, Indo-Australian, North American, Pacific, and South American) and many small *tectonic plates*, each 50-150 km thick [29].

Istanbul is the oldest and the largest city in Turkey with a population of about 15 million people and growing at an estimated 400,000 a year and containing close to 2 million buildings located on the two continents of Europe and Asia. The European side of Istanbul in built on soft rock and the Asian side sits on hard old rock. The North Anatolian Fault Zone with two tectonic plates (Eurasian and Anatolian) sliding past each other is only a few kilometers away from the city's center and passing through the Sea of Marmara along which the earthquakes occur and affect Istanbul. The 1999 Izmit or Marmara earthquake on this fault had a moment magnitude of 7.6 and killed some 20,000 people, left half million homeless, and the city of Izmit, some 110 km east of Istanbul, was severely damaged. This raised a concern for Istanbul where the probability of a major earthquake affecting this city by 2030 exceeds 60%. The World Bank is investing significantly in the city's quake readiness measures and the building regulations have been tightened, but an estimated 65% of buildings in Istanbul still don't meet building regulations and many people are fatalistic [39, 40].

San Andreas Fault is the 1200 km long sliding boundary between the Pacific Plate and the North American Plate, and slices California in two, with San Diego and Los Angeles on the Pacific Plate and San Francisco on the North American Plate [41]. A scientific study [41] projects that this fault has reached a sufficient stress level for an earthquake of greater than 7 on the moment magnitude scale, and a U.S. Geological Survey report [42] states that a magnitude 7.8 earthquake could cause several thousand deaths and over $200 billion in economic losses, in spite of aggressive retrofitting programs that have increased the seismic resistance to buildings and infrastructure.

Mexico lies on top of three great tectonic plates: North American Plate, Cocos Plate, and Pacific Plate, and when these plates move the vibrations felt by the soft soil of a former lake bed on which Mexico City is built can be trapped in the bed and amplified, causing large movements of the buildings in the city. When in the morning of 19 September 1985 a moment magnitude 8 struck this city from the 500% amplification of vibrations it seriously damaged the greater part of the city and caused over 5000 deaths. This and the subsequent aftershocks, produced from the earthquakes some 350 km away, caused several billion USD in damage, over 400 building collapses, and several thousand seriously damaged structures [43]. More recent 7.1 magnitude earthquake that struck the coast of Mexico in 2017 topped some 40 buildings and killed over 100 in Mexico City [44]. The highlands plateau on which Mexico City is built is also populated by volcanoes, and the active volcano Popocatépetl, at 70 km southeast of the city, majestically overlooks this metropolis and may one day cause large population movements from the valleys below the volcano. After the 1985 disaster, Mexico changed its building regulations and pushed for better design and materials [45]. Today there are dedicated warning receivers in schools and public places of Mexico City and warnings issued through radio and television broadcasts [46].

Wellington Fault is an active seismic fault in the southern part of the North Island of New Zealand and is associated with the boundary of Indo-Australian Plate and Pacific Plate. This fault runs right through the New Zealand's capital Wellington City whose major hazards are earthquakes and tsunami generated from the earthquakes. Although no historic earthquake has been recorded for this fault, the potential impact of rupture along the Wellington-Hutt Valley section in the Wellington area makes it one of the greatest natural hazards in New

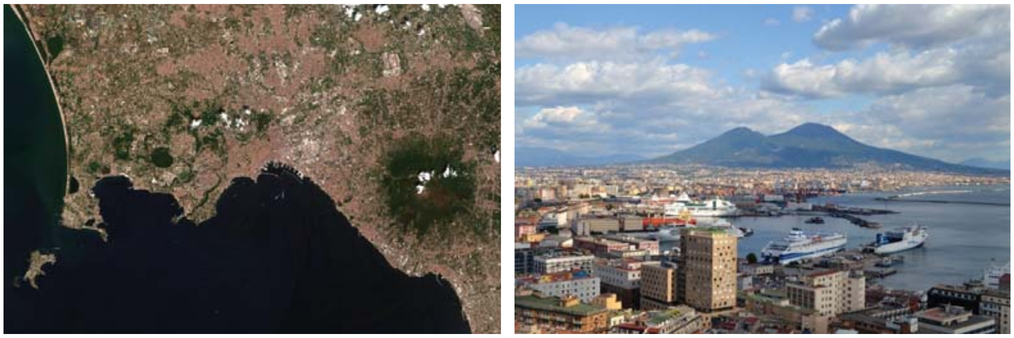
Zealand. The last time that Wellington Fault ruptured through the Wellington region and caused a major earthquake was 300-500 years ago and is capable of producing earthquakes of up to magnitude 8 [47, 48].

Another majestic volcano Mt. Fuji overlooks the megacity of Tokyo some 100 km away, but it is the earthquakes that this city is most concerned with. Tokyo is located on the three layers of tectonic plates: North American Plate on the top, Philippine Sea Plate under it, and Pacific Plate underneath both of them. These plates move regularly and the probabilities of major earthquakes occurring in the Tokyo Metropolitan Area range from 50-85% in different areas [49]. Eastern Tokyo is at the highest risk of major earthquake damage and as a result of redevelopment in densely populated residential areas (wider roads, quake-resistant houses) the updated 2018 map shows 20% reduction for building collapses and 40% reduction of fires since 2013. The risk levels were analyzed based on ground stability, building structures, road conditions, and oil stoves of households. The Japanese government estimates, however, that a 7.3 earthquake in the city could cause over 5600 deaths, 160,000 injured, and destroy 850,000 buildings. The Great Kanto earthquake of magnitude 7.9 that struck the Tokyo-Yokohama Metropolitan Area in 1923 produced an estimated 140,000 fatalities and $1 trillion in damage [50]. A disaster prevention guidebook prepared by the government of Tokyo describes in great deal how the population needs to be prepared to confront earthquakes and associated tsunami, typhoons, and other natural and anthropogenic hazards [51].

The 24 August 2016 Central Italy earthquake, with the epicenter near the town of Amatrice and measuring 6.2 on the moment magnitude scale, almost raised to the ground this small town with a population of 2650 inhabitants. Over 300 people lost their lives, several thousand had to find shelter in emergency camps, and an estimated $1-10 billion in damage was sustained. The loss of cultural heritage was widespread, since many constructions and renovations did not follow the antiseismic law [52]. Amatrice is today on the list of the world's most endangered heritage sites, empty, and strewn with rubble, and waiting to be resurrected from the disaster.

3.2 Cities on Volcanoes

Volcanoes are openings in the Earth's crust that allow the escape of molten rocks or magma from the Earth's interior onto the surface. There are about 500 volcanoes that have erupted during historic time and the larger the repose time of a volcano, the more energetic its resumption becomes. Most volcanoes are situated along the edges of tectonic plates: Andes in South America; Central American Mountain Range; Cascades Range in North America; Aleutian Islands in Alaska; western Pacific Ocean from New Zealand, through the Indonesia, Philippines, Japan, and Kamchatka; northern Mediterranean; and west of Africa [29]. Most of the Earth's volcanoes are, however, hidden beneath the oceans along the mid-ocean ridges and some pierce the tectonic plates, but these do not concern us in this paper. Figure 5 illustrates some examples of large cities



(a) Aereal view of volcanoes Vesuvius to the east and Campi Flegrei to the west of Naples (left). Naples with Vesuvius in the background (right).

(b) Arequipa with Misti (Putina) volcano in the background (left). Kagoshima City with Sakurajima volcano in the background (right) .

(c) Legazpi City with Mayon volcano in the background (left). City of Puebla with Popocatépetl volcano in the background (right).

Figure 5. Cities on volcanoes: Naples (Italy), Arequipa (Peru), Kagoshima City (Japan), Legazpi City (Philippines), City of Puebla (Mexico).

(Naples, Arequipa, Kagoshima, Legazpi, and Puebla) too close to the volcanoes Vesuvius, Campi Flegrei, Misti, Sakurajima, Mayon, and Popocatépetl.

Naples in Italy is situated between two explosive volcanoes: Vesuvius to the east and at 14 km from the center of the city, and Campi Flegrei to the west whose 12 km wide caldera is only 5 km from Naples. Vesuvius produces large plinian eruptions every few thousand years and an order of magnitude less powerful sub-plinian eruptions every 3-6 centuries in between the plinian eruptions. The Campi Flegrei volcanic complex has been active for at least 60,000 years and during this time produced two super eruptions, with each erupting 10-100 times more material than the largest eruptions of Vesuvius and on which the city of Naples is built [53, 54]. The official plan is to relocate one million people surrounding the volcanoes all over Italy in the event of impending eruptions, but these plans are unreliable from the technical, social, and cultural perspectives [55]. The alternative resilience and sustainability framework for the Neapolitan area proposed more than 20 years ago does not require such a dispersion of population and requires territorial intervention for the people being able to cohabit with the volcanoes in security and prosperity [23]. Naples and its surroundings have an inestimable cultural value and the nearby ancient cities of Pompeii and Herculaneum that were buried by the eruption of Vesuvius in A.D. 79 attract millions of visitors each year.

The volcano El Misti (also known as Putina) stands at 5,822 m above the sea level and last erupted in 1985. The world heritage city of Arequipa with 1.5 million inhabitants is the second largest in Peru and the city center is only 17 km from the craters of El Misti, with new settlements only 13 km away. In the event of a major eruption like that of 2000 years ago, the city faces being inundated with ash fall, pyroclastic flows, and lahars [56, 57]. Although the hazard maps of the city are shared with public and nonpublic institutions, much of the city remains at high risk levels [58].

On the south-western tip of the island of Kyushu in Japan, Kagoshima City with about 600,000 inhabitants stands in the Kinko Bay, with the volcano Sakurajima situated at 4 km across the bay where 7000 close by residents are being exposed to frequent eruptions of this volcano. A major lava flow eruption in 1914 connected the Sakurajima volcanic island with the mainland. The Sakurajima Volcano Hazard Map [59] instructs the people living close to the volcano of the precursory phenomena of the eruption, dissemination of volcanic warnings, and evacuation procedures. The authorities of Kagoshima City also instruct the citizens of the impending dangers of the volcano and confront resilience and sustainability with an evacuation plan [60].

In January 2018 steam and ash plumes rose above the volcano Mayon on the large island of Luzon in the Philippines and warned the 200,000 inhabitants of Legazpi City which is only 15 km away of the impending danger of ash fall, lava and pyroclastic flows, and lahars [61]. The 2018 eruption caused the evacuation of people from the permanent danger zone (6 km radius of the volcano) and preparation was underway to relocate people from more distant areas if the volcano alert levels increase [62]. The government of Albay Province has a general resilience strategy for the cities surrounding Mayon [63].

As one of the most active volcanoes in Mexico, Popocatépetl (El Popo) is situated 70 km southeast of Mexico City and 40 km west of the City of Puebla with a population that exceeds 3.2 million. Its major eruption 23,000 years ago produced an avalanche that reached up to 70 km from the summit [64] and a major pyroclastic flow eruption can, therefore, reach Puebla. During the active periods of the volcano this city is frequently exposed to the ash fall [65].

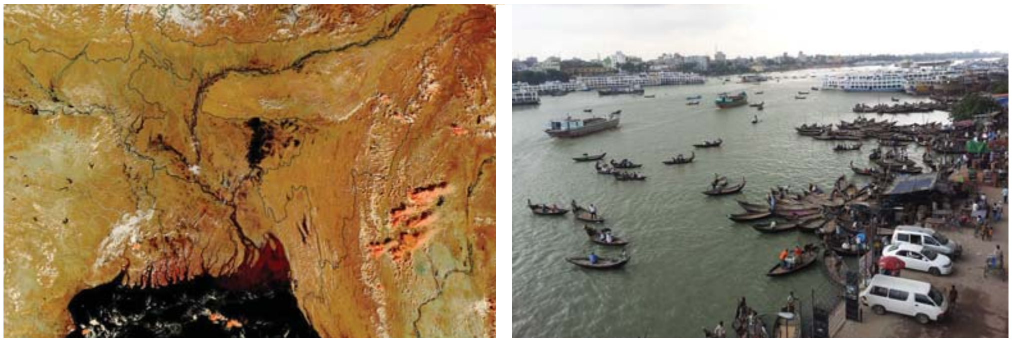
3.3 Cities Exposed to Tropical Cyclones and Climate Change

Tropical cyclones (also called hurricanes and typhoons) are rotating and organized systems of clouds and thunderstorms that originate over tropical or subtropical waters in Atlantic, Pacific, and Indian Oceans. They can produce sustained winds as high as 250 km/hr with gusts exceeding 300 km/hr and heavy rains, high waves, storm surges up to 10 m, and have the potential of spawning tornadoes when making landfall. Flooding caused by the storm surge is responsible for most of the deaths and is particularly severe in low-lying areas such as in Bangladesh and the Gulf Coast of the United States. Mountains and canyons can concentrate the rainfall from tropical storms that can then cause landslides and wash away entire towns and far away from the coasts as in Himalayas [66].

Processing and combustion of fossil fuels from industrial operations, such as materials processing and energy generation, produce *greenhouse gases* (carbon dioxide, methane, water vapor, nitrous oxides, and synthetic compounds made of carbon, fluorine, hydrogen, phosphorus, sulfur) which trap the radiation emitted from the surface of the Earth and warm the atmosphere. *Global warming* [67, 68] causes the melting of glaciers that can greatly affect the Earth's atmospheric and oceanic circulations [69] and thus exacerbate the already large problems of many cities caused by tropical cyclones and produce new problems for those cities not yet affected by the cyclones. New York City, Venice, Dhaka, Jakarta, and Manilla (Fig. 6) are only a few of such cities that can be affected by tropical cyclones and/or climate change.

New York City is almost completely surrounded by water from the Atlantic Ocean on the east and Hudson River on the west, and is subjected to storm surges from hurricanes and sea-level rise from global warming, tsunami arriving from the landslides at volcanic Canary Islands off the coast of west Africa, and releases of long/acting radionuclides from a nuclear power station located 60 km from Midtown Manhattan. When the Hurricane Sandy swept up the East Coast of the United States and made a landing near New York City on 29 October 2012 with 140 km/hr winds it flooded a large part of the city's subway system and some tunnels, closed Lower Manhattan services, caused large damage to the houses and businesses along the Atlantic coast of Long Island, over 2 million people lost electricity services, and many locations required emergency services. From Caribbean to New York, Sandy caused 159 deaths, damaged or destroyed some one million homes, 10 million customers lost electricity, produced 10 m high storm surges, and incurred $65 billion in damage [70–72]. Following the Sandy disaster, the New York City government produced a resilience plan for providing additional protection for New York's infrastructure, buildings, and communities from the impacts of cyclones and climate change, so that the water can find it more difficult to enter the city and thus reduce future economic losses [73].

(a) New York City (left). Venice (right) .



(b) Bangladesh (left). Dhaka (right), capital city of Bangladesh.

(c) Jakarta (left). Manilla (right).

Figure 6. Cities exposed to tropical cyclones and climate change: New York City (United States), Venice (Italy), Dhaka (Bangladesh), Jakarta (Indonesia), Manilla (Philippines)

The sea-level rise and human interventions of deep-water extraction causing the subsidence of soil risk permanent flooding of Venice by the end of this century. The Venice Lagoon is supplied with water from the Adriatic Sea through three inlets and the water circulation in the lagoon is essential for maintaining Venice a habitable environment. About two thirds of city's population lives on mainland and one third is spread over 100 islands in the lagoon. Many of city's historic buildings and walkways are compromised from the corrosive effects of sea water, soil erosion, boat wakes, etc. The 1966 storm surge flooded the city and the Save Venice effort was launched to start protecting this former republic [74]. The project adopted to save Venice from floods is knows as MOSE (MOdulo Sperimentale Elettromeccanico) and consists of a set of mobile gates to be built across the three inlets to the lagoon and closed only during high water events [75]. The construction of this project is expected to be completed in 2022 [76].

Eighty percent of Bangladesh is floodplain and can be flooded from severe tropical storms [77]. Thousands of people perish and millions of homes are destroyed every year in this country from flooding and the capital city Dhaka with 10 million inhabitants is paved with water during the monsoon season. The largest slum Korail in Dhaka is raised on sticks above the water level and is especially vulnerable to floods, and most of the country will be flooded if the sea-level rises more than 1 m during this century. The floods in Bangladesh have caused devastations in 1966, 1987, 1988, and 1998.

While India is the most exposed country in the world to natural disasters and Bangladesh has the highest exposure rate, Manilla, Tokyo, and Jakarta are the most exposed cities [78]. Jakarta with 10 million inhabitants is projected to double its population in the following decade and its thirst for drinking water is causing severe subsidence in many areas of the city. Jakarta is situated on the north coast of the island of Java in the Indonesian archipelago and in a deltaic plain crisscrossed by rivers. Some 40% of Jakarta is below sea-level and prone to flooding from water draining through the city from the hills in the south and from tidal flooding and climate change. There is no comprehensive risk management program for Jakarta [79, 80].

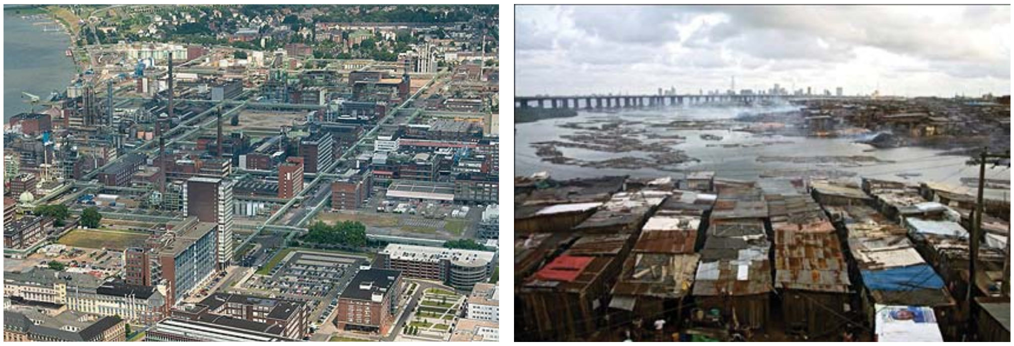
Manilla is one the most densely populated cities in the world and its two million inhabitants are not only exposed to the hazards from earthquakes, volcanic eruptions, and tsunami, but also from half a dozen typhoons that each year cause extensive flooding of the city. In 2009 the typhoon Ketsana claimed over 700 lives and produced 1$ billion in damages [81]. The informal settlements in this city are especially vulnerable to typhoon hazards [82] and the Philippine Development Plan 2017-2022 [83] aims to build resilience to hazards through the geohazards maps and economic investments [84].

3.4 Cities Exposed to Hazardous Industrial Facilities

The Chernobyl Power Complex included four nuclear fission reactors prior to the accident on 26 April 1996 when one of the reactors suffered a core meltdown and produced a release of radionuclides into the atmosphere and surrounding soils. Within few weeks 28 people died and 600 emergency workers were exposed to high levels of radiation, and some 120,000 people from the 30 km radius of the plant were evacuated, including the 49,000 residents from the city of Pripyat that was only 3 km away from the plant [85] (Fig. 7a,left). The exact degree of radioactive contamination in the vicinity and beyond the nuclear power plant is still being debated, and today this facility is covered with a sarcophagus and the people are prohibited to enter into the 10 km radius exclusion area of the plant.

(a) Chernobyl with the former city Pripyat in the foreground (left). Fukushima Daiichi (right).

(b) Indian Point (left). Diablo Canyon (right).



(c) Leverkusen (left). Lagos (right).

Figure 7. Cities and towns exposed to hazardous industrial facilities: Chernobyl (Ukraine), Fukushima (Japan), New York City (United States), Los Angeles (United States), Leverkusen (Germany), and Lagos (Nigeria).

The Chernobyl disaster occurred from operator errors and poor safety measures, and when in 2011 a similar accident occurred at the Fukushima Daiichi nuclear power plant in Japan, new questions were raised as to the safety and security of such facilities [31, 86].

The Fukushima Daiichi disaster (Fig. 7a,right) was triggered by the magnitude 9 earthquake off the coast of the largest and most populous island Honshu of Japan, where the Pacific Plate subducts the North American Plate. The energy accumulated from the movements of these plates was released through a slip that raised the top plate which produced a tsunami 40 m high. This wave then overflowed the protective barrier of the Fukushima Daiichi nuclear power plant and immobilized the plant's cooling and safety systems. The meltdown of two of four reactor cores followed and large quantities of radionuclides were released and dispersed over the mainland Japan and Pacific Ocean. Some 13% of Japanese mainland was contaminated with radioactive cesium-137, and from 1000 km^2 exclusion area adjacent to the plant more than 150,000 people have been evacuated [87]. The Fukushima Daiichi disaster occurred because the power company TEPCO managing the plant also managed to control the government's regulatory process that did not require building the plant to withstand the historical tsunami intensities in the region of the plant, and once the accident occurred the authorities failed to properly manage some 10 million people in the contaminated area [86, 88].

The Indian Point Energy Center (Fig. 7b,left) is a nuclear power plant station on the Hudson River, 60 km from the Midtown Manhattan in New York City, and its 40-year operating license expired in 2013, but was extended for another 8 years [89]. The plant contains some 2 tons of cesium-137 in its spent fuel pools, and any release of radionuclides is easily transported downstream to New York City with 20 million people. The Indian Point plant also sits 2 km from a fault whose activity is disputed. But this is not the case with the Diablo Canyon nuclear power plant (Fig. 7b,right) in California with several small cities close by and megacity Los Angeles 300 km away. This plant is located in the earthquake red zone containing several faults, including the major San Andreas fault 80 km away [90]. Diablo Canyon is, however, under intense pressures to shut it down.

In France, about 75% of electricity is produced from nuclear energy and a dozen of nuclear fission power reactors are located within 50 km radius of large cities [91]. Bordeaux, Lyon, Marseille, and Paris, among others, would all be exposed to radionuclides in the event of severe accidents, triggered by either operator errors, terrorist acts, or possibly earthquakes produced from the nearby geologic faults.

The cities of Leverkusen in Germany and Lagos in Nigeria have, however, the problems of being close to the processing of chemical materials and decomposition of hazardous waste. More than 5,000 chemicals are manufactured in CHEMAPARK of Leverkusen (Fig. 7c,left) where over 30,000 people work and live [92]. The production of these chemicals produces emissions into the air and waste products, and it is claimed that their disposal in the huge landfill next to CHEMPARK is safe. Olusosun landfill in Lagos, Nigeria is the largest in Africa and one of the largest in the world, where over 1000 families live on the site and scavenge for scrap being delivered from all over the world (Fig. 7c,right) [93]. This 100 acres landfill receives about 7000 tons of trash a day, is surrounded by commercial and residential areas, and is not subjected to regulations.

For many cities in hazardous environments the future does not appear very promising, unless large resources are employed to make these cities safe and prosperous. This requires producing *professional feasibility studies* that detail how, what, and for whom should the cities be reorganized, so that the perturbing effects of natural and anthropogenic hazards do not produce disastrous consequences, nor make the cities uninhabitable for future generations. To produce such feasibility studies and make optimum decisions we must be able to quantify vulnerability, risk, resilience, and sustainability for cities, which we address in the following section.

4. Risk Assessment, Resilience, and Sustainability

4.1 Complex System Modeling

Can the risks and vulnerabilities of cities in hazardous environments be properly assessed and can effective decisions be taken for making these cities more resilient and sustainable so that their inhabitants can live in security and prosperity without compromising similar aspirations of populations elsewhere? In order to answer the first part of this question requires appropriate models for quantifying risks, vulnerability, and other related quantities, such as resilience and sustainability which we will discuss shortly. Without this quantification proper decisions cannot be made reliably and instead of making concrete progress we will continue producing subjective judgements on how to achieve this goal, as the vast literature on this subject is attesting. But what kind modeling approaches could serve our purpose when dealing with a complex system such as a city?

Transformation, reorganization, and adaptation to the surroundings in central for the survival of a complex system, and an effective model of this system should account for these attributes. A model of such a system should deal with all the relevant information of past events and consequences and be able to quantify all relevant future events and consequences that *may* affect the functioning of the system. Given the system complexity and uncertainty about its future state, such as model should be defined by the *plausibility* (degree to which the statements about the system can be believed) of propositions or hypotheses regarding its functioning, evidence or data pertaining to these propositions, and any additional knowledge pertaining to the system but not connected with the propositions. We then need to express this information in a mathematical form that includes both the *physical causality* or determinism, where the past determines the future, and *logic* which mimics the human brain through its memory content. The incorporation of this *memory information* into the model is necessary for allowing system transformation, reorganization, and adaptation.

The model that we are proposing is based on the "logical" interpretation of *probability theory* and requires only finite number of propositions, common sense correspondence, and consistency [94, among others]. Consider, therefore, the plausibility of assigning a space of propositions or hypotheses $H = \{H_1 \ldots H_h\}$ by knowing that some other space of propositions $B = \{B_1 \ldots B_b\}$ is true,

$$H \mid B \tag{1}$$

and seek a real number between 0 and 1 that measures this possibility through the definition of *probability* of $H \mid B$ (probability of H, given B), i.e.

$$0 \leq P(H \mid B) \leq 1 \tag{2}$$

where B may or may not include some knowledge of the propositions H of causual (deterministic) and logical nature. In addition, we need some structural elements of probability theory, the *product rule* and the *sum rule*,

$$P(AB \mid C) = P(A \mid BC)P(B \mid C) = P(B \mid AC)P(A \mid C) \tag{3}$$

$$P(A \mid B) + P(\bar{A} \mid B) = 1 \tag{4}$$

where $A = \{A_1 \dots A_a\}$ and $C = \{C_1 \dots C_a\}$. $AB \mid C$ is the plausibility that A and B are true, given that C is true, $A \mid BC$ is the plausibility that A is true, given that B and C are true, and $\bar{A} \equiv A$ is false.

The fundamental principle of probabilistic inference is that of forming a judgement about the likely truth or falsity (probability) of any proposition, or which one of a given a set of hypotheses is most likely to be true, conditioned on *all* the available evidence and not only on partial evidence. For practical purposes, there is no such thing as the absolute probability. We can decompose the evidence (information or knowledge base) B into three types of knowledge: (1) data $D = \{D_1 \dots D_d\}$ about the propositions or hypotheses, (2) data $M = \{M_1 \dots M_m\}$ about some key attributes of H stored in system's memory, and (3) *prior information* X of the system with no logical connection with the hypotheses. The division of evidence into data and prior evidence serves only to organize the chain of inferences and X should not contain any major premise such as a physical law. The data M or the *memory data* can be interpreted as the data pertaining to the uncertainties of probabilities of hypotheses through which the system draws certain information about the propositions (like their social values) without remembering all historical details about their relevance.

Using Eq. (3) we can then compute the *posterior probability* $P(H \mid DMX)$ of inferring the likelihood of hypotheses H, given the data DM and prior information $X = \{X_1 \dots X_x\}$,

$$P(H \mid DMX) = P(H \mid X)\frac{P(DM \mid HX)}{P(DM \mid X)} \tag{5}$$

Borrowing the language from statistics, $P(H \mid X)$ and $P(DM/X)$ are the *prior probabilities* (or priors, since they are conditions on X alone), $P(DM \mid HX)$ is the *sampling probability*, and the last factor is the *likelihood* (not a probability) and can be represented by $L(H)$. If $P(H \mid DMX)$ turns out to be close to one (zero), we may conclude that H is very likely to be true (false), but if $P(H \mid DMX)$ is close to 0.5 the available evidence is not sufficient for confident decision making and we need more evidence for obtaining higher confidence. So far our theory does not allow assigning prior and sampling probabilities and in the literature they are often confused and require the utilization of some guiding principles involving maximum entropy, group invariance, coding theory, etc. [95].

The determination of priors is an important issue when employing probabilistic methods and we should keep this in mind as we proceed with the probabilistic definitions of risk and other relevant variables. The use of uncertainty in probability theory has been addressed in some recent works without operationalizing it [96]. In this work we interpret the uncertainty of propositions as the loss of their detailed histories and remembering only their overall characteristics, such as mean values, stabilities, values, etc. Our brain works in this manner and serves us to build new knowledge from the knowledge retained in its memory [97].

4.2 Risk, Vulnerability, and Risk Assessment

Equation (5) is our *fundamental principle* and we can apply it to quantify risk and vulnerability. If we denote risk by R, events by $E = \{E_1 \ldots E_e\}$, consequences by $C = \{C_1 \ldots C_c\}$, and knowledge base by DMX, we should be able to quantify the risk (likelihood) of any hypothesis on the occurrences of E and C, given the evidence DMX, i.e.

$$R(EC, DMX) \equiv P(EC \mid DMX) = P(EC \mid X)\frac{P(DM \mid ECX)}{P(DM \mid X)} \tag{6}$$

To evaluate this probability requires the specification of relevant hazard events and consequences (hypotheses or propositions) that often cannot be clearly separated, because: (1) some events can produce other unforeseen events and consequences, and (2) some consequences can produce both foreseen and unforeseen events. In addition, the data associated with hypotheses and any other knowledge not logically connected to hypotheses must also be made available, which, as we will see below, requires an interdisciplinary and transdisciplinary team of experts for their specification. Knowledge may come from various types of (deterministic and probabilistic) simulations of hazards and consequences or scenarios, historical records, geological and archeological studies, etc.

When evaluating risk for a city one should be able to determine if the current risk is acceptable (close to 0) and if not what needs to be done to bring it to this level. Most if not all of the cities in hazardous environments have not undergone such a scrutiny and "risk" facing severe consequences. They do not even have credible emergency plans to confront the hazards, and Naples in Italy is a good example of this deficiency [98].

Consequences are sometimes identified as *objectives* and the risk description is made in terms of objectives, uncertainties of objectives, and "background knowledge on which consequences and the assignment of uncertainties are made" [99], but no operational model is provided on how to systematically conduct such a risk analysis. In our probabilistic definition of risk, both the events and consequences[2] enter into the definition of risk, and the uncertainties of their probabilities (variances and higher moments) are automatically determined from

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[2] Events and consequences are treated as independent because we want to assess the probabilities of one or more events producing one or more consequences, and vice versa.

these probabilities and stored in memory data M for subsequent updating of risk probabilities. This allows for two or more states of knowledge to have the same mean values (equalities of first order moments of probability density functions), but representing different knowledge, because of the difference in higher order moments (variances and cross correlations).

Risk assessment is a process for evaluating hazards, deciding who or what might be harmed (defining a system) and how, evaluating risks and deciding on precautions, implementing the findings through the appropriate control measures that reduce the risks, and periodic evaluations of risks based on updated knowledge. The complexity of a system such as a city requires that the risk assessment team consists of the right mix of experiences and responsibilities, and that the team's goal is to reduce risk to tolerable levels. Central to the risk assessment is *risk perception*, since different individuals or groups, with different experiences and knowledge, interpret differently the potential for negative consequences. Some well-known tools used in risk assessments are: Interviewing; historical records; scenario hazards analysis; expert judgement; failure mode and effects analysis; event, fault, and decision tree analysis; probabilistic risk assessment; human reliability analysis; critical function analysis; etc. This risk assessment tool box and the more fundamental one noted above and associated with the determinations of prior and sampling probabilities, provide no absolute rule as to how and to what depth a risk assessment should be performed, but it must be systematic to be most effective and begin early in the life cycle of complex systems and include all relevant hazard scenarios and consequences [100]. The complexity of a city and its exposure to threats, and the resulting consequences that may ensue, places a severe burden on the risk assessment team, and especially when the city must reorganize its built environment, and likely that of its surroundings, to resist the threats that have the potential of producing great human catastrophes [23, 101].

We noted above that the degree of severity of consequences depend on the *vulnerability* V of values that we place on things relative to the financial, ethical, cultural, ecosystem, or other measures. Vulnerability should, therefore, represent the likelihood or probability that damage and loss can or cannot occur, following the initiation of *one or more* given events E', data $D'M'$ pertaining to C', and knowledge X' not connected with C'. Using Eq. (5), vulnerability or the likelihood of consequences V can then be expressed as

$$V(C', D'M'X'E') \equiv P(C' \mid D'M'X'E') = P(C' \mid X'E')\frac{P(D'M' \mid CX'E')}{P(D'M' \mid X'E')} \tag{7}$$

from where we have that the prior probabilities $P(C' \mid X'E')$ and $P(D'M' \mid X'E')$ are now conditioned on the knowledge $X'E'$. Note also that the set of vulnerability consequences is smaller than the set of risk consequences and that the knowledge base of vulnerabilities is greater, which implies that it is easier to assess vulnerabilities than risks.

4.3 Resilience

The word “resilience” comes from “being able to resist” *one or more* consequences and as such is applicable to social and non-social systems (individuals, families, businesses, communities, economies, governments, ecosystems, facilities, objects). Systems can be resilient to internal and external impacts if they resist loosing their functional capacities, and, failing this, are able to overcome, adapt, and recover from these impacts. Our probability theory can be employed to operationalize resilience by performing two separate analyses. In the first analysis we compute resilience by searching for very high (almost 1) likelihoods of those consequences that lead to the loss of functional capacity of the system, and in the second analysis we determine the likelihood of reducing these consequences to acceptable low values (almost 0) by mitigating these consequences trough a *reorganization* of the system. As an example, if flooding is threatening a community we can construct barriers, move the communities to higher grounds, protect better the infrastructure from flooding, etc. To produce a non-resilient system resilient requires, therefore, intervening or rearranging the system, which generally requires adopting long-term preventive actions. The two analyses above can be combined by including in the hypotheses of events, consequences, and knowledge base also those events, consequences, and knowledge base associated with the reorganized system and then computing the probabilities of all consequences.

Thus, if we denote resilience by Res, consequences from both non-reorganized and reorganized system by C'', all events by E'', and data and prior information pertaining to the hypotheses C'' by $D''M''$ and X'', respectively, our resilience probability problem becomes,

$$Res(C'', D''M''X''E'') \equiv$$
$$P(C'' \mid D''M''X''E'') = P(C'' \mid X''E'')\frac{P(D''M'' \mid C''X''E'')}{P(D''M'' \mid X''E'')} \tag{8}$$

where X'' is the prior information not logically connected with C''. The priors depend on $X''E''$, where E'' includes the events from the non-reorganized and reorganized system and not only a subset of these events as in the vulnerability. Another difference between vulnerability and resilience is that the former operates on a smaller set of consequences than the latter, because a *resilient system should resist all the consequences from all the events.* Looking in a different manner, the knowledge base used to determine resilience must be larger than that involved in determining vulnerability.

Like risk and vulnerability, resilience is also a product of social and non-social order, and thus a system exposed to a threat or threats has the power to become less vulnerable and more resilient. Resilience requires change, internal reorganization, and transformation to a new set of operating parameters which can be stable or meta-stable. Metastable systems operate at higher energies than stable systems, and one can argue that *all desirable and evolving systems* (like cities) must belong to the former category, because they can more easily adapt to the circumstances of their changing surroundings. If sufficiently large, the internal and external perturbations on a metastable system can render it stable, metastable, or unstable in terms of its energy content, which for a socio-technical system can lead to a disaster, since the transition of system properties to new properties may not be suitable anymore for the survival for system inhabitants. The lack of water supply to cities, exposure to disease-prone environments, loss of business opportunities, etc. has in the past led the people to desert many great urban centers in different parts of the world [102].

4.4 Sustainability

The word "sustainability" appears in many publications of United Nations and national and local governments attempting to improve the socio-economic status of the people. That what can be maintained under the existing conditions can be considered sustainable, but both the natural systems and the societies are self-organizing systems that are in general in non-equilibrium and thus dynamical entities that can change gradually and abruptly and coexist at best in local or metastable equilibrium [103].

According to the report Our Common Future of World Commission on Environment and Development of the United Nations, sustainable development points to a directional and progressive change of humanity [104, 105]. This report defines *sustainable development* as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs and aspirations". Sustainability in this form is an anthropocentric concept where the human-induced changes of the environment do not threaten the exchange processes between the humanity and the natural environment in which the society is expected to survive for an indefinite time. But how is sustainable development to be achieved and what exactly are the needs and aspirations that we should be aiming at and over what space and time frames remains unclear. To achieve sustainability we should sustain economy, protect the environment, achieve social goals, and maintain institutions that are able to safeguard such visions into the distant future. Sustainability is, therefore, influenced by value judgments and ethics, and Agenda 21 Program of Action, and more recent elaboration of the principles in this document, suggest 10 sustainability principles [106]. These principles require clear definition, focus on holism or self-contained systems, underline the importance of time and spatial scales in the assessment of sustainability, and emphasize the use of a limited number of indicators or attributes and how they should be developed and employed. United Nations, International Atomic Energy Agency, and many other national and international agencies and organizations made noble attempts to compile extensive lists of sustainability indicators, but some of the problems with these compilations are that they are general, voluminous, and left as guides to the nations, organizations, and businesses to develop their own strategies of sustainability and place their own specific weights on them [103].

Sustainability is thus more difficult to operationalize than risk, vulnerability, or resilience, because of a much larger *sampling space* (all possible outcomes). Returning to our fundamental principle of probability theory as expressed by

Eq. (5), we can include into the hypotheses a wishful list of sustainability hypotheses or *sustainability indicators and consequences* and seek to determine their likelihoods, conditioned on the data connected with the hypotheses and prior information not logically connected with these hypotheses. Operationally, we can express the *sustainability probability* S as,

$$\begin{aligned} &S(H''', D'''M'''X''') \equiv \\ &P(H''' \mid D'''M'''X''') = P(H''' \mid X''')\frac{P(D'''M''' \mid H'''X''')}{P(D'''M''' \mid X''')} \end{aligned} \tag{9}$$

where H''' are the sustainability indicators and consequences, $D'''M'''$ are the data pertaining to H''', and X''' is the prior information of sustainability propositions that does not have logical connection with H'''. Note now that the priors depend on X''', unless we also condition sustainability on some particular sustainability attributes or indicators.

Sustainability hypotheses or sustainability propositions should be defined for each city by a team of individuals possessing multidisciplinary and transdisciplinary knowledge and grouped into 3 categories: (1) Technical system propositions, (2) environmental system propositions, and (3) human system propositions. The technical system propositions can include subpropositions of mass and energy flows, built environment characteristics, telecommunication services, etc. The environmental system propositions should involve the consumption of natural resources, emissions, ecosystems degradation, etc., and the human system propositions should specify the economic, social, and cultural metrics of the city [103, 107]. Once a model, sample space of propositions of the system, data associated with these propositions, and information relative to the system but not logically connected with propositions are specified, the analysis proceeds as in the risk, vulnerability, and resilience analyses, with the aim of determining the likelihoods of sustainability propositions. Further details of this analysis are available elsewhere [107].

4.5 Decision Making

There is nothing in our probability theory by which a decision can be made to either accept or reject probability assignments to different hypotheses. The orthodox decision theory suggests that we first complete the inference problem by assigning probabilities to the "states of nature" Θ_p, given the evidence data of these states and prior information not connected with such states. To solve the problem of decision we have to first enumerate the possible decisions Δ_q and associate a *loss function* $\Lambda(\Delta_p, \Theta_q)$ that specifies what needs to be accomplished, and make the decision Δ_q which minimizes the expected loss over the posterior probabilities for Θ_p. As we noted earlier, there are some general formal principles (maximum entropy, transformation groups, etc.) to remove the arbitrariness of prior probabilities, but there are no such principles for determining loss or utility functions. This then places a severe limit of using the orthodox decision theory for making decisions and inviting the development of new strategies.

One possibility may be to express the propositions not only with their plausibility but also how valuable they are. For each proposition we would then have a two dimensional function and could then make decisions on the basis of those propopositions that are both very likely and valuable. Another possibility is to incorporate *values of propositions* into the memory data M in Eq. (5) and then choose those propositions with largest probabilities. But all of this needs to be tested with concrete examples to see how far our probability model can be generalized and validated.

The probability theory model discussed in this section is currently employed to assess resilience and sustainability of Naples in Italy and New York City in the United States. Naples is a city with one million people and is bordered by two active volcanoes Vesuvius and Campi Flegrei on whose slopes live another two million people. The proposed resilience and sustainability framework is called VESUVIUS–CAMPIFLEGREI PENTALOGUE [101] and requires that around each volcano be defined an *exclusion nucleus* where all human settlements are prohibited, a *resilience belt* surrounding the exclusion nucleus where the population can live in security and from where it can be evacuated temporarily if necessary until the volcanic crises subside. The area surrounding the resilience belt is the *sustainability area* which would also serve as the temporary area for housing the evacuees from the resilience belt. The exact boundaries of these three areas are being determined through the five key objectives of the pentalogue and use of the above probability theory model for assessing resilience and sustainability, without and with territorial reorganizations. The knowledge base of propositions is determined through the simulations of relevant eruption, seismic, economic, environmental, and urban planning scenarios [23, 108]. The Metropolitan Area of New York City includes more than 20 million people and is exposed to tropical storms, tsunami, climate change, and nuclear reactor hazards. Here we have a different set of propositions and methods for obtaining the knowledge base of these propositions, but the resilience and sustainability modeling approach is similar to that of Naples.

5. Summary and Conclusions

The majority of people on Earth will reside in cities by the end of this century and many of these cities are situated on/or close to dangerous geologic faults, volcanoes, and industrial facilities. Many cities, and in particular those along the coasts, are subjected to severe flooding caused by tropical storms and cyclones. With climate change the flooding risk will increase because of the sea-level rise and changes of atmospheric and oceanic circulations. The high concentrations of people in large cities present great exposure problems and these cities must begin confronting these problems much more seriously than is currently being practiced through rudimentary warning systems, plans, and evacuation plans, if they intend to function without disruptions or face the consequences of being depopulated and the humanity losing another great achievement.

Cities are complex socio-technical systems involving many stakeholders with different socio-economic and cultural values, and the built environments are composed of many poorly constructed habitats and infrastructure systems. All of this information should be included in the reliable assessments of risk, resilience, and sustainability based on the models that can quantify these variables. Such models should be able to deal with all plausible propositions of hazard events, consequences and attributes associated with sustainability, and process all relevant data pertaining and not pertaining to propositions.

The terms risk, vulnerability, resilience, and sustainability are currently poorly defined operationally for complex socio-technical systems such as the cities and in this work we presented a mathematical model that involves sufficient structure for better quantifying these parameters. The sample space of this probability theory model involves plausible propositions consisting of events, consequences, and sustainability indicators, and the model incorporates memory and other data associated and not associated with these propositions. Based on the sampling and prior probabilities computed from simulations of all relevant scenarios of events, consequences, and sustainability attributes, and some generalized principles that are useful for better defining these probabilities, the model can evaluate the likelihoods of sample space propositions and thus serve for making decisions for producing more resilient and sustainable cities in hazardous environments. This approach is currently being used for assessing the resilience and sustainability of Naples in Italy and New York City in the United States.

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