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Impact Assessment of Climate Change on Public Health: A Global Perspective †

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Abstract: Climate change is unquestionable and climate disasters are projected to increase in frequency and intensity. The adverse effects of climate change on people's health are significant and depend on the type of climate hazard that threatens vulnerable populations in different regions around the world. The climate change impacts on public health include not only the direct effects on people's physical and mental health, but also the side effects of climate change on critical infrastructure and systems that are involved in assisting healthcare operations. This paper develops a methodology for assessing the impacts of climate extremes based on people's and systems' vulnerabilities and builds a global framework for assessing the public health risk of climate change.

Keywords: climate change; public health; impact assessment; vulnerability; risk assessment; climate extremes

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1. Introduction

Climate change is unequivocal and the associated extremes are projected to increase in frequency and intensity in the future [1]. The increased climate extremes, including extreme heating, sea level rise, intense tropical storms, storm surges, extreme precipitation, permafrost thawing and glacier tsunamis, could significantly affect public health and safety [2].

More precisely, high temperatures could increase respiratory and cardiovascular diseases, thermal stress, premature deaths, allergens and infertility, while extreme drought could enhance infectious diseases and immigration-related diseases, as well as food- and water-borne illnesses [2]. Extreme flooding occurrences could cause injuries and fatalities and increase infectious diseases [2]. In addition to these, climate change could also affect mental health as people feel insecurity or experience mental traumas after disasters due to extreme climate occurrences [2]. In arctic regions, permafrost thawing could release ancient viruses and bacteria that are hazardous for people [3] and cause injuries mainly associated with infrastructure failures [2,4], while glacier tsunamis could be fatal for coastal populations in the surrounding areas, even in those at very high elevations, and also affect people living thousands of kilometers away [5]. Climate change, however, may also have positive effects on populations living in northern latitudes as they would enjoy milder winters [6].

Moreover, climate extremes could cause severe damage to hospitals' and healthcare centers' infrastructure, causing disruptions of operations and thus reducing the level of healthcare services to the people in need [7,8]. Failure of other critical infrastructure, such as airports, roads and communications, could also cause delays and significant disruptions in healthcare operations [8]. The adverse impacts of climate change on systems, networks and infrastructure that contribute to the optimization of the effectiveness of healthcare services should definitely be considered when assessing the impact of climate extremes on public health. More accurate impact assessment could lead to more accurate public health climate change risk assessment.

To summarize, the effects of climate change on public health differ according to the geography and geomorphology of each region and vary according to the regional vulnerabilities. This paper is the first that identifies the vulnerabilities of populations and systems to climate hazards from a geographical perspective, assess the associated impacts and develop a framework for a global health risk assessment framework. Accurate risk assessment is essential for effective decision making, with respect to resilience building towards climate change and prioritization of adaptation and mitigation investments.

2. Materials and Methods

For the purposes of this paper, an extensive literature review has been conducted so as to identify the climate change hazards that threaten the different geographical regions around the world [9]. This step is essential to identify the vulnerabilities of people and systems to each hazard and finally assess the impact and the risk of the specific hazard.

The most integrated formula to assess risk is R = Likelihood × Vulnerability × Impact [1,10]. This is a general formula that can be adapted to the needs of the discipline in which it is implemented. Here, risk refers to public health, so risk is assessed as follows:

$$R(x)_{public\ health} = L(x) \times V(x) \times I(x) \quad (1)$$

where x is the climate hazard discussed, $L(x)$ is the likelihood of occurrence of the climate hazard x, $V(x)$ represents the vulnerability of peoples and systems to hazard x and, finally, $I(x)$ implies the impact of hazard x on people's health, lives and systems. It is important to define that each climate extreme should be separately discussed as they are associated with different vulnerabilities and produce different impacts. Due to the fact that the literature with respect to risk is fuzzy and risk factors show a huge variability in terms of interpretation and comprehension, the definition of these elements is crucial [10].

2.1. Likelihood Assessment

In this paper, the likelihood of climate hazard occurrence is expressed in qualitative terms, as defined in IPCC Reports [11], and takes values from "Virtually certain" to "Exceptionally unlikely", as described in Table 1. In order to quantify the qualitative terms of likelihoods, values on a scale of [1,5] are assigned as described in Table 1. This scale can then be applied to the hazards that threaten each region.

Table 1. Likelihood of climate change hazards description and scales.

	Likelihood Scale (L)				
	5: Very high	4: High	3: Moderate	2: Low	1: Very low
Likelihood expression	Virtually certain (>99%)/Extremely likely (>95%)	Very likely(>90%)/Likely (>66%)	About as likely as not (33–66%)	Unlikely (<33%)/Very unlikely (<10%)	Extremely unlikely (<5%)/Exceptionally unlikely (<1%)

2.2. Geospatial Vulnerability Assessment (Exposure)

The vulnerability of public health to climate hazards varies primarily according to the exposure of the population and the associated healthcare infrastructure and systems to each hazard. In all cases discussed below, vulnerability is assigned with metrics on a [1,5] scale in order to obtain measurable results.

2.2.1. Sea Level Rise, Storm Surges and Extreme Precipitation

A retrospective analysis of past large flooding events has resulted in metrics that assess the vulnerability of people and critical infrastructure to sea level rise (V_{SLR}) and extreme precipitation(V_{PREC}) [1]. Using the elevation (E_i) of any element i, its distance from the coastline (D_{Ci}) and distance from rivers or lakes (D_{Ri}) as exposure factors, the vulnerabilities to SLR (V_{SLR}) and extreme precipitation (V_{PREC}) are described in Table 2. Due to the interconnection between SLR and extreme precipitation hazards, V_{PREC} in coastal and estuarian regions is assigned to the V_{SLR} value when $V_{SLR} > V_{PREC}$ [1] (Table 2).

Table 2. Vulnerability assessment per vulnerability type.

	Vulnerabilty Scale				
Type of Vulnerability	**5**	**4**	**3**	**2**	**1**
Vulnerable populations V_{pop} [2]	Premature babies, infants and children under 4 years old., the elderly, pregnant women, people with severe physical and mental impairments, people with increased blood pressure, people working outdoors, homeless pople, immunodeficient people, cancer patients, extremely poor populations, people living in remote regions, forcibly displaced populations and immigrants, people in areas with high population density	Children over 5 years old., overweight people, drug addicts, immigrants, people working with vulnerable people (military personnel, police, coastguard, migrant workers, health volunteers and healthcare providers), people living in overcrowded housing, collective sites, informal settlements, slums and closed facilities, people with language and knowledge impairments, people with hyperthyroidism	Couples trying to conceive (infertility), people with minor diasbilities	Wealthy people with minor health issues	Young people, athletes and generally healthy adults and people living in areas resilient to climate extremes
S.L.R and storm surges * V_{SLR} [1]	G.L: (a) Ei < 1 m and Dci < 3 km (b) 1 m ≤ Ei < 3 m and Dci < 1 km L.L: (a) Ei < 1 m and Dci < 30 km (b) 1 m ≤ Ei < 3 m and Dci < 15 km	G.L: (a) Ei < 1 m and 3 km ≤ Dci < 6 km (b) 1 m ≤ Ei < 3 m and 1 km ≤ Dci < 3 km (c) 3 m ≤ Ei < 6 m and Dci < 1 km L.L: (a) Ei < 1 m and 30 km ≤ Dci < 40 km (b) 1 m ≤ Ei < 3 m and 15 km ≤ Dci < 30 km (c) 3 m ≤ Ei < 6 m and Dci < 15 km	G.L: (a) Ei < 1 m and 6 km ≤ Dci < 10 km (b) 1 m ≤ Ei < 3 m and 3 km ≤ Dci < 6 km (c) 3 m ≤ Ei < 6 m and 1 km ≤ Dci < 3 km (d) 6 m ≤ Ei < 10 m and Dci < 1 km L.L: (a) Ei < 1 m and 40 km ≤ Dci < 50 km (b) 1 m ≤ Ei < 3 m and 30 km ≤ Dci < 40 km (c) 3 m ≤ Ei < 6 m and 15 km ≤ Dci < 30 km (d) 6 m ≤ Ei < 10 m and Dci < 15 km	G.L: (a) Ei < 1 m and Dci ≥ 10 km (b) 1 m ≤ Ei < 3 m and 6 km ≤ Dci < 10 km (c) 3 m ≤ Ei < 6 m and 3 km ≤ Dci < 10 km (d) 6 m ≤ Ei < 10 m and 3 km ≤ Dci < 6 km (e) Ei ≤ 10 m and Dci < 1 km L.L: (a) Ei < 1 m and Dci ≥ 50 km (b) 1 m ≤ Ei < 3 m and 40 km ≤ Dci < 50 km (c) 3 m ≤ Ei < 6 m and 30 km ≤ Dci < 50 km (d) 6 m ≤ Ei < 10 m and 15 km ≤ Dci < 40 km (e) Ei ≤ 10 m and Dci < 15 km	G.L: (a) Ei ≥ 1 m and Dci ≥ 10 km (b) 1 m ≤ Ei < 3 m and Dci ≥ 10 km (c) 3 m ≤ Ei < 6 m and Dci ≥ 6 km (d) 6 m ≤ Ei < 10 m and Dci ≥ 6 km (e) Ei ≥ 10 m and Dci ≥ 1 km L.L: (a) 1 m ≤ Ei < 3 m and Dci ≥ 50 km (b) 3 m ≤ Ei < 3 m and Dci ≥ 50 km (c) 6 m ≤ Ei < 10 m and Dci ≥ 40 km (d) Ei ≥ 10 m and Dci ≥ 15 km
Extreme precipitation V_{prec} [1]	V_{SLR} = 5 E_i < 1 m, D_{ci} < 1 km	V_{SLR} = 4 $E_i \in [1,3)$ m, $D_{ci} \in [1, 3)$	V_{SLR} = 3, $E_i \in [3,6)$ m $D_{ci} \in [3,6)$	$5.0 \leq D_{Ri} < 8.0$ km	$D_{Ri} \geq 8.0$ km
Extreme heat and drought V_{heat} [9,12]	Alaska, Canada, S. Central America, Greenland, Iceland, all of Europe, Arabic Peninsula, Russian Arctic, W. Central Siberia, E. Central Siberia, Russian Federation, W. Central Asia, E. Central Asia, Tibet, E. Asia	N.W. USA, N. Central USA, N.S. USA, N.E. USA, Caribbean, N.W. South America, N.E. South America, S. W. South America, N. Africa (Mediterranean), Sahara, W. Africa, W. South Africa, E. South Africa, Central Australia, S. Australia, E. Australia, New Zealand, Pacific Islands	Eastern South America, South Asia, Southern East Asia, Northern Australia	Northern East Africa, South East Africa, Madagascar	Central North USA, East Northern USA, South Central America
$V_{permafrost}$ [13,14]	Continuous permafrost regions (>90% coverage)	Discontinuous permafrost regions (50–90% coverage)	Sporadic permafrost (10–50% coverage)	Isolated patches (<10% coverage)	Glacier regions

Table 2. *Cont.*

	Vulnerabilty Scale				
Type of Vulnerability	**5**	**4**	**3**	**2**	**1**
$V_{trop.cyclones}$ [15]	North West Pacific, Japan, East China, Korea, Taiwan, Philippines to suffer from stronger cyclones and be extremely vulnerable to category 5 cyclones	North East Pacific and North West Atlantic, including Hawaii, Central America, Bangladesh, Myanmar, North West Australia and Caribbean	New Zealand, South Pacific Islands, Indian Ocean Islands (Seychelles, Mauritius, Reunion, Port Mathurin, Cocos Islands), East Coast of Northern America and Canada	India, Vietnam, Madagascar, Azores, Comoros islands	All other regions
$V_{glacier\ tsunamis}$ ** [5]	All arctic coastal regions and lakefront areas with large glaciers	-	-	-	-

* G.L: General landscapes; * L.L: Low-lying regions; ** There is no study that reveals data that can be used to define vulnerability zones, so all arctic coastal regions with very high elevations up to 500 m are considered vulnerable to glacier tsunamis.

2.2.2. Extreme Heating and Drought

Extreme heating is projected to have a global impact, as most regions are expected to be significantly exposed to extreme heating occurrences. The recent IPCC Report [9] describes regional projections for extreme heating events based on their frequency trends. These projections could be used to assess the vulnerability of the exposed regions to increased temperatures and the consequent drought, which are described in Table 2. Although drought shows significant seasonal variability (wet–dry), it is clear that drier regions will be mostly affected [12] (Table 2).

2.2.3. Permafrost Thawing

Permafrost regions consist of soil that remains at temperatures lower than 0 °C for at least two years consecutively [13] and are described as continuous, discontinuous, sporadic and isolated [14]. Vulnerability to permafrost thawing ($V_{permafrost}$) can also be measured on a [1,5] scale based on the thickness and continuity of the permafrost (Table 2).

2.2.4. Tropical Storms

Climate change is projected to primarily affect the intensity of tropical cyclones and not their frequency. A regional vulnerability assessment to tropical cyclones ($V_{trop.cyclones}$) by severity and frequency is attempted in Table 2 [15].

2.2.5. Glacier Tsunamis

Glacier tsunamis are the most disastrous climate change hazards as they threaten coastal arctic regions with waves that may exceed 500 m height and inundate extensive regions. Due to the lack of evidence, all arctic coastal and lakefront areas that are covered by large glaciers and populations living on these areas should be considered extremely vulnerable to glacier tsunamis ($V_{glacier\ tsunami} = 5$) (Table 2) [5].

2.3. Population Vulnerability (Sensitivity)

Apart from the exposure factor that actually defines vulnerability to climate hazards, sensitivities related to health conditions, age, physical and mental impairments, homelessness, wealth, etc. [2] shall be considered when discussing vulnerability to climate change. The population vulnerability (V_{pop}) can be assessed as

$$V_{pop} = \frac{\sum_1^n V(xi)}{n} \tag{2}$$

where x_i is population vulnerability factors, as described in Table 2, and n is the number of factors. If 30% of the population has a type of impairment and 80% are displaced people and immigrants, then $V_{pop} = (V_{disability} + V_{immigrants})/2 = (30\% \times 5 + 80\% \times 5)/2 = (1.5 + 4)/2 = 2.73 \approx 3$.

2.4. Climate Change Impact on Public Health

Impact is defined as the "effects on natural and human systems" [2]. The impact of climate change on public health refers initially to the direct impacts on the physical and mental health of people and secondly to the indirect impacts [2], derived from the structural damages and operational disruptions occurring in critical healthcare infrastructure, as well as other critical infrastructure that affects the effectiveness of health operations, such as transport infrastructure [8] (primarily airports, heliports and roads), energy and communication networks. Therefore, the impact of climate change on public health could be assessed as follows:

$$\text{Total impact} = \text{Direct impact on public health } (I_d) + \text{Indirect impact on public health } (I_{ind}) \tag{3}$$

Total impact assessment is also assessed on a [1,5] scale as described in Table 3, where all aspects that define the magnitude of the impact are included. The largest impact is caused by flood-associated hazards in both developed and developing countries, despite the level of adaptation [1,16].

Table 3. Impact assessment by climate hazard on a [1,5] scale.

	Direct Impact Assessment				
Climate Change Hazard	**5**	**4**	**3**	**2**	**1**
SLR and storm surges [2,17]	Fatal injuries, drowning, fatal infectious disease and illnesses, severe violence	Severe injuries and diseases that could potentially threaten human lives, severe mental health issues, violence	Moderate injuries and diseases that do not threaten human lives	Treatable and temporary injuries, illnesses and infections	Negligible impacts on health
Extreme precipitation [2,17]	Fatal injuries, drowning, fatal infections diseases and illnesses, extreme violence	Severe injuries and diseases that could potentially threaten human lives, violence, severe mental health issues	Moderate injuries and diseases that do not threaten human lives	Treatable and temporary injuries, illnesses and infections	Negligible impacts on health
Extreme heating [2,17]	Acute respiratory and cardiovascular diseases, brain stroke, heat stroke, stillbirth, premature deaths, severe malnutrition, extreme violence	Thermal stress, allergens, severe mental health issues, preterm births, malnutrition, violence	Infertility, low blood pressure, moderate hydration	Temporary fever associated with dehydration, fatigue, coughing, muscle aches, mild dehydration	Negligible impacts on health
Drought and wildfires [2,17]	Acute respiratory and cardiovascular diseases, fatal infectious diseases, fatal food- and water-borne illnesses *, severe mental health issues, severe malnutrition, extreme violence	Infectious diseases, immigration-related diseases, food- and water-associated illnesses, mental health issues, malnutrition, violence	Moderate illnesses and diseases associated with drought, moderate malnutrition and dehydration	Drought, fatigue, mild dehydration	Negligible impacts on health
Permafrost thawing [2–4]	Fatal injuries mostly due to structural failures, fatal diseases due to release of ancient viruses and bacteria	Severe injuries, illnesses associated with gas release	Moderate injuries	Minor injuries	Negligible impacts on health
Glacier tsunamis [5,17]	Drowning, fatal injuries due to extremely high waves, fatal infectious disease and illnesses, severe mental health issues, extreme violence	Severe injuries due to high waves and debris, severe infectious diseases, mental health issues (post-traumatic), violence	Moderate injuries and diseases that do not threaten human lives	Treatable and temporary injuries, illnesses and infections	Negligible impacts on health

* water-borne diseases: *E. coli*, cholera and algal bloom; airborne and dust-related disease: silo gas exposure and coccidioidomycosis; vector-borne disease: malaria, dengue and West Nile virus; mental health effects: distress and other emotional consequences.

Table 3. *Cont.*

	Indirect Impact Assessment				
Climate Change Hazard	**5**	**4**	**3**	**2**	**1**
SLR, storm surges, extreme precipitation, tropical cyclones, glacier tsunamis [1,5,15]	(1) Inundation and severe damage to large hospitals with very large capacity (tertiary and quaternary) (2) Severe damage to other critical infrastructure including (i) large airports with large capacity and military airports that could support disaster management procedures with medical and rescue staff, emergency medical evacuations and mass evacuations, (ii) central roads and bridges that connect with the nearest hospitals and facilitate evacuation, (iii) nuclear plant damages that could increase the impact on public health, (iv) severe energy pipelines damage that affect the recovery procedures and healthcare operations, (v) communication system damage that disables coordination between stakeholders and decision makers (3) Severe disruptions of the above infrastructure operations due to (i) severe erosion due to inundation and (ii) flights and other transport delays and cancelations	(1) Inundation and severe damages to medium-size hospitals (tertiary, secondary) with large capacity (2) Severe damage to other involved infrastructure including large- and medium-size airports with medium capacity that could enhance evacuations and provide shelter to people and medical staff, severe structural damage on runways and road pavements, erosion due to flooding, electrical failures	(1) Damage occurring in moderate-capacity health centers (secondary) (2) Moderate structural damage to other related infrastructure, such as smaller and general aviation airports with small capacity and heliports, moderate structural damage to roads and transport network	(1) Small damage to small hospitals, private physicians' offices and local/communal health centers (2) Small damages on roads connecting to hospitals or secondary roads, damage to very small or communal airports that have no facility to provide services during climate disasters	Negligible structural damage to any type of hospital or other infrastructure, such as roads, and negligible operation disruption

Table 3. *Cont.*

	Indirect Impact Assessment				
Climate Change Hazard	**5**	**4**	**3**	**2**	**1**
Extreme heating [9,10]	(1) Severe impact on aviation operations that are vital for emergency management, evacuations, coordination, shelter provision (2) Severe energy disruptions at large hospitals (3) Water supply disruptions at large hospitals (4) Primary highways and road pavements melting	(1) Short energy supply disruptions at large and medium hospitals (2) Short water supply disruptions at large and medium hospitals (3) Disruption of central roads due to melting and pavement failures	(1) Energy and water supply disruption at small-capacity hospitals (2) Disruption of small and general aviation airports (3) Disruption of secondary road operations	(1) Short energy and water supply disruptions at local/communal health centers with very low capacity (2) Disruption of very small muninicipal/local aerodromes and secondary roads with low traffic	Negligible impact on any type of hospital or other infrastructure (i.e., potholes on road pavement) and negligible operation disruption
Permafrost thawing [4]	(1) Severe structural damage and collapse due to extreme erosion at large hospitals with large capacity and to other infrastructure (2) Severe disruption of operations	(1) Severe damages to medium-sized secondary hospitals with large capacity and other medium-size infrastructure with large capacity (2) Disruption of operations	(1) Damage occurring to moderate-capacity health centers (secondary) (2) Moderate structural damage to other related infrastructure, such as smaller and general aviation airports with small capacity and heliports, moderate structural damage on roads and transport network	(1) Small damage that does not threaten the stability of hospitals and other infrastructure (2) Severe damages to very small (local/communal) health centers/offices with very small capacity	Negligible structural damages to any type of hospital or other infrastructure (i.e., potholes on road pavement) and negligible operation disruption

3. Results

The total impact of climate change on public health and the related risk can then be assessed by applying the above likelihood, vulnerability and impact scales. For instance, the risk of sea level rise and storm surges in Potts Point–Woolloomooloo (Table 4), the most dense region of Sydney, Australia, could be assessed by applying the above metrics on selected populations, hospitals, other supportive infrastructure and the selected area. Both L_{SLR} and L_{prec} are assigned 4 as IPCC reports consider that Victoria will very likely face the impacts of SLR and extreme precipitation by the end of the 21st century. This region is at high elevation (>25 m), is very close to the ocean, has high density, a high quality level and a low number of children, with 2% of the population being children ≤4 years old and 4% being children over 5 years old. The majority of people are middle-aged, and elderly people over 65 years old make up 16% of the population. More than half of the population hold university degrees and only 0.2% have knowledge-related disabilities [18]. Therefore, $V_{density} = 5$, $V_{children<4y.o} = 1$ ($5 \times 2\% = 0.1$), $V_{children>5y.o} = 1$, ($5 \times 4\% = 0.2$), $V_{elderly>65y.o} = 1$ ($5 \times 16\% = 0.8$), $V_{low\ quality\ of\ life} = 1$ (satisfactory mean per capita income) and $V_{knowledge\ disability} = 1$ ($5 \times 0.2\% = 0.01$); thus, $V_{pop} = Mean(V) = 1.8 \approx 2$.

Table 4. Public health risk assessment in Sydney.

	L_{SLR}	V_{SLR}	V_{pop}	I_d	I_{nd}	$Risk_{SLR}$
Potts Point–Woolloomooloo [18]	4	2	2	5	-	40
Royal Prince Alfred Hospital	4	1	-	-	5	20
Sydney International Airport	4	5	-	-	5	100
M1 Highway Sydney Int. Airport to Sydney city center	4	4	-	-	5	80

The hospitals' and M1 highway's vulnerability have been assessed based on the spatial criteria discussed above and the impact is assessed based on the fact that the M1 is a primary highway that provides access from the airport to Sydney city and connects Woolloomooloo to major hospitals, so any disruption could cause significant impacts.

4. Discussion and Conclusions

This study provides an integrated public health risk assessment methodology that could be widely used by all decision-makers and stakeholders around the world. The standardization of the criteria that define the vulnerabilities and the impact on public health is crucial to identify the needs for adaptation and risk mitigation. This methodology also enables the risk ranking of hospitals to climate extremes and assesses the coping capacity of a specific health system to manage the adverse impacts of climate change on public health. Finally, this methodology could be used to compare national health systems' preparedness for climate change disasters.

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