[WORKING DRAFT]
Hazards, Impacts, and Risk in Urban Climate Resilience Planning: A Taxonomic Approach

11/13/25

Julius Stroock
Mark Fox
Daniela Rosu

Introduction

Research Questions:

1. Which natural hazards are driven by climate change and pose a risk to housing and critical infrastructure?
2. What are the potential negative impacts of these hazards on housing and critical infrastructure?
3. How is the risk posed by these hazards to housing and critical infrastructure represented?
4. In the context of housing and critical infrastructure, how can these hazards, their impacts, and the representation of their risk be represented in the form of taxonomies?

Definition of Climate Change Driven Natural Hazard:

The term Climate Change Driven Natural Hazard, henceforth CCDNH, is used throughout this survey to describe the drivers of climate change risk with which the survey concerns itself. The term itself is a combination of two adjectives, *climate change driven* and *natural*, applied to the noun *hazard*:

> *hazard* - a physical event with the potential to cause negative effects on human and natural systems (Alexander 1993, 4)(Argyroudis et al. 2019, 4)(Espada, Apan, and McDougall 2017, 377)(Hoque et al. 2018, 23)(Public Safety Canada 2024, 151). This definition fits with the conception of hazards as drivers of risk. However, this is only one of a few distinct interpretations of *hazard* present in the reviewed literature. A tabulation and categorization of the definitions present in the reviewed literature is found in Appendix A.
>
> *climate change driven* - in relation to a hazard, being *climate change driven* is understood to imply that the frequency and/or magnitude of the hazard is in some way increased by extended-term changes of the state of the climate, both anthropogenic and natural (Public Safety Canada 2024, 13)(IPCC AR6 2022, "Climate change").
>
> *natural* - in relation to a hazard, implies that the hazard involves a physical event in the natural environment, as distinct from a physical event in a man-made environment (Alexander 1993, 4). A natural hazard may be driven by human activity and impact human systems, but it must involve a set of mechanisms possible in the absence of humans and their activities.

Taken together, CCDNH refers to,

a physical event in the natural environment with the potential to cause negative effects on human and natural systems, whose frequency and/or magnitude increase(s) as a result of climate change.

Housing and Critical Infrastructure:

Housing and critical infrastructure are the two asset classes of concern in this survey. Every hazard, impact, and risk in the taxonomies that follow is included on the condition that it may be considered relevant to the functionality of housing and critical infrastructure. For the purposes of this survey, these assets are defined as such:

housing - buildings actively providing shelter and living space for humans.

critical infrastructure - structures or networks of structures constructed and maintained by humans which are necessary for the full functionality of housing. These structures and networks provide services including electrical services, natural gas transportation and distribution services, water services (supply and waste), solid waste services, information and communication technology (ICT) services, emergency services, and transportation services (Dawson et al. 2018, 11)(Pitlakis et al. 2014, 9-10)(Joint Research Centre 2013, 1).

The importance of these two asset classes stems from their role in the human-oriented, immediate-term response to natural hazards. A human-oriented, immediate-term response to natural hazards is one that prioritizes the core needs of people in the immediate aftermath of a CCDNH. Housing provides both shelter and safety. The structures and networks providing the list of services included in the definition of *critical infrastructure* help satisfy other needs like warmth, health, water, and food.

Notably absent from the scope of the term *critical infrastructure* are a number of significant infrastructure networks and structures including oil networks (production, transportation, refining, and distribution), natural gas networks (production and refining), waterways networks, manufacturing infrastructure, and port infrastructure. While all of this infrastructure provides important services, none of it is deemed by this survey to be critical in a human-oriented, immediate-term response to a CCDNH.

Methods

Taxonomy Construction:

In the construction of its own taxonomies, this survey abides by the rules of best practice presented in Table 1. In addition to those rules, most of the proposed taxonomies are constructed in accordance with two additional, optional, guidelines shown in Table 2. At the core of the rules and guidelines below and of the taxonomies that follow are the terms *class*, *subject*, *description*, and *member*:

class - a prototypical description of a set of things which are members of the class. Classes may be interconnected by one of only two types of relationships: subClassOf and its converse, superClassOf. Classes are the primary unit of analysis used throughout this survey. The use of the term *class* in the context of this survey's taxonomies should not be conflated with the meaning of *class* as it is used in biological taxonomy.

subject - the core of a class to which attributes, characteristics, or behaviours are ascribed. The subject of a class provides precise information about the position of the class within the taxonomy by referencing the superclass(es) of the class. For example, in the definition of the class "Flood" from Table 3, the subject is *hydrospheric hazard*, indicating that "Flood" is positioned below the class "Hydrospheric Hazard".

description - details the attributes, characteristics, or behaviours of a class. In Table 3's definition of "Flood", the description is "resulting from the accumulation of water on land that is normally dry." Descriptions are crucial to establishing a thing's membership within a class and also to determining the relationships between classes. A description is the natural language statement of certain formal properties of a class.

member - a thing possessing characteristics which allow it to be correctly described with the description of a class.

Table 1: Taxonomic Rules of Best Practice

Rule	Description
Class Definition	Every class included in the taxonomy is clearly defined using terminology relevant to the purpose of the taxonomy.
subClassOf/superClassOf Relationships	The taxonomy's class structure relies exclusively on the subClassOf relationship and its converse, superClassOf.

Table 2: Additional Taxonomic Guidelines

Guidelines/Desiderata	Description
Multiple Inheritance	A single class may maintain multiple superClassOf relationships.
Truncation	Eligible classes may be excluded from the taxonomy. Elements of the descriptions of included classes may be omitted.

Class Definition:

Class definition is one of the base requirements of taxonomy construction. This rule requires that all classes within the taxonomy be defined such that they are unambiguous and mutually exclusive (Taxonomic Oversight Group 2022). Ian McCarthy defines taxonomy as the, "theory and practice of delimiting and classifying different kinds of entities"(McCarthy 1995, 3). Delimiting and classifying classes requires an understanding of how those classes are interrelated which, in turn, requires a stated subject with clear attributes, characteristics, or behaviours. As such, class definition is inherent to the exercise of taxonomy construction.

For the purposes of this survey, the definition of a class comprises two parts: a subject and a description. Throughout the taxonomies that follow, every included class is clearly defined with both a subject and description. The definitions of these classes are directly sourced or synthesized from the relevant reviewed literature. Supplementing the definitions provided in the taxonomies is a terms analysis and glossary found in Appendix A.

subClassOf/superClassOf Relationships:

Every pair of immediately connected classes in the taxonomy is related by a subClassOf/superClassOf relationship. Under this relationship, one of the classes is designated as the subclass of the second, and the second is designated as the superclass of the first. A set of classes S which is interrelated by subClassOf relationships must satisfy four criteria (Brachman 1983)[Another Citation Needed]:

1. for any two classes C and D, subClassOf(C, D) holds if and only if every member of C is also a member of D;
2. subClassOf is transitive, i.e. if subClassOf(C, D) and subClassOf(D, E), then subClassOf(C, E);
3. subClassOf is antisymmetric, i.e. if subClassOf(C, D) and subClassOf(D, C), then C and D are considered equivalent classes;
4. subClassOf is reflexive, i.e. subClassOf(C, C) holds (C is a subclass of itself).

subClassOf is used to define the downwards relationship between two classes. Conversely, the upwards relationship between those same two classes is a superClassOf relationship. For the purposes of this survey, superClassOf relationships can be regarded as needing to satisfy just one criterion:

1. if subClassOf(C, D) holds, superClassOf(D, C) holds;

When considered in the context of a taxonomy containing many subClassOf and superClassOf relationships, broader characteristics emerge:

- Top-down characteristics - As a result of its position at the top, the root class of the taxonomy shares its description with every class in the taxonomy since every class is a member of the root class. This allows the root class to determine the overarching subject and character of the taxonomy. Importantly, this role and influence is not unique to the root class. Any given non-leaf class is able to be treated as the root-class of its own taxonomy composed of itself and all of the classes under it. In the resulting sub-taxonomy, every class is a member of the new root class, sharing its description.
- Bottom-up characteristics - Any non-root class of the taxonomy represents a subclass of every superclass in the direct lineage between it and the root class of the taxonomy, including the root class, and can be described using the description of each of those superclasses. For example, a leaf class of the taxonomy conforms to the description of every superclass in its direct lineage and is a member of each. Testing the truth of this statement can be done by comparing the definition of a leaf class against the definition of each superclass in its direct lineage. If every relationship in the lineage is a superClassOf relationship, the leaf class should be describable, without conflict, by the definition of every class above it. This test is not restricted to leaf classes and holds true for any class in the taxonomy. Note that the creation of multi-lineage classes, which occurs as a result of the introduction of multiple inheritance, complicates this test but does not render it obsolete.

Multiple Inheritance:

Multiple Inheritance is a taxonomic rule that permits a single class to maintain multiple superClassOf relationships. This requires that the class simultaneously be a subclass of each of its superclasses. Thus, the class must inherit the description of each of its direct superclasses in addition to all of the descriptions from their respective lineages.

For the construction of taxonomies, multiple inheritance is not a strictly necessary rule. However, it is a rule that greatly facilitates the modelling of highly interconnected classes. Without it, such sets of classes might require the omission or oversimplification of those among them which cannot accurately be designated as the subclass of just one other class in the taxonomy. The classes involved in modelling CCDNHs, their impacts, and their risk representations are such sets.

Exclusion and Truncation:

The taxonomies that follow contain only classes which are *eligible* to be included in their respective taxonomy in addition to being *meaningfully present* in the reviewed literature. These requirements are defined individually for each taxonomy and lead to the omission of classes which are either ineligible or not meaningfully present. Eligibility-based omission is referred to as *exclusion* while presence-based omission is referred to as *truncation*.

Exclusion:

Potential classes are excluded from this survey's taxonomies on the basis that they are ineligible for inclusion. A class eligible for inclusion in a taxonomy is one that meets the requirements set out by both the "Class Definition" and "subClassOf/superClassOf Relationships" sections. "Class Definition" requires that a specific subject and description may be assigned to the class based on the reviewed literature. Meanwhile, "subClassOf/superClassOf Relationships" demands that the class be able to be included within the structure of the taxonomy such that it meets the all of criteria for proper subClassOf/superClassOf relationships with the other classes in the taxonomy. This requirement is most easily evaluated by checking whether a potential class can be a member of the taxonomy's root class. Classes that fail to abide by one or both of these requirements are excluded.

Truncation:

Truncation, as defined in Table 2, is a taxonomic guideline which, while used in the construction of this survey's taxonomies, is not universally applied. Applying truncation permits a taxonomy to set boundaries on the inclusion of eligible classes. This relieves it of a requirement to be exhaustive in the coverage of its subject matter [Citation Needed].

The truncation used by the taxonomies that follow manifests itself in two ways: the omission of classes as a result of their absence from the reviewed literature, and the omission of classes despite their presence in the reviewed literature. The first occurs because the reviewed literature itself is non-exhaustive. Undoubtedly, there are important concepts documented in the existing literature but that do not appear in the taxonomies that follow because the parts of the literature containing them have not been reviewed. The second occurs because of taxonomy-specific inclusion criteria. These criteria are instituted in order to ensure that all of the included classes are relevant to the purpose of the taxonomy in addition to the survey's broader perspective of urban planning and climate resiliency.

Results

Taxonomy of Hazards

Table 3 contains a taxonomy of the hazards that are driven by climate change and have the potential to cause significant negative effects on housing and/or critical infrastructure. The exclusion and truncation of potential hazard classes in Table 3 is conditional on three criteria:

1. Eligibility: Is eligible to be included in Table 3 (as clarified in the Methods section). Eligibility in Table 3 requires that a hazard class possess a magnitude or frequency that can be reasonably expected to increase as a result of climate change. The class is additionally capable of causing significant negative impacts to housing or critical infrastructure.

2. Traceability: Has at least one traceable potential negative impact on housing or critical infrastructure. Traceability implies that the hazard class has been connected with a specific impact on housing or critical infrastructure by the reviewed literature. Every hazard with traceable impacts is cited at least once as a driving hazard of an impact in Table 12.

3. Differentiability: Has at least one differentiable potential negative impact on housing or critical infrastructure. Differentiability implies that the impact arising from the class is distinct from the impacts of other classes on the basis of the mechanisms giving rise to the impact (pendant column of high winds, abnormally elevated air temperature, salination of normally fresh groundwater, etc…), the unique spatial characteristics of the impact (only occurs in coastal areas, only occurs in between the latitudes of 30° N and 30° S, only occurs in areas with limestone bedrock, etc…), or the temporal characteristics of the impact (most likely to occur during periods of thaw, most likely to occur between the June 1st and November 30th, etc…). A hazard class does not need to have differentiable impacts from its superclasses.

<u>Table 3</u>: Taxonomy of CCDNHs Posing a Risk to Housing and Critical Infrastructure

ROOT CLASS **CCDNH Posing a Risk to Housing and/or Critical Infrastructure:** A natural hazard with a frequency and/or magnitude that is increased as a result of climate change which has the potential to cause significant negative effects on housing and/or critical infrastructure.
Hydrospheric Hazard: A CCDNH posing a risk to housing and/or critical infrastructure resulting from the presence or absence of liquid water. [78]

- Flood**:** A hydrospheric hazard resulting from the accumulation of water on land that is normally dry. [63] [1] [85] [47]
    - Fluvial Flood: A flood in and around a water channel resulting from the surpassment of the flow capacity of the channel. [37] [74] [70]
        - Flash/Dynamic/Torrential Flood: A fluvial flood and flowing mass movement resulting from a rapid increase in flow rate and sediment concentration of a water channel typically located in a narrow and steep catchment. [65] [82] [37] [56] [36] [70]
            - Dam Break/Glacial Lake Outburst Flood: A flash/dynamic/torrential flood, coastal flood, and cryospheric hazard resulting from the rapid discharge of water from a dammed lake following the collapse of the dam or glacier. [37] [44] [1] [26] [70] [47]
        - Ice Jam Flood: A fluvial flood and cryospheric hazard resulting from the overflowing of a water channel whose flow capacity is restricted by amassed ice. [71] [82]
    - Coastal Flood: A flood adjacent to a large stationary body of water (e.g. a lake, reservoir, sea, or ocean) resulting from the overflowing of shoreline boundary [37] [74] [70]
        - Storm Surge: A coastal flood and convective hazard resulting from the storm-driven rise of the coastal water level through the action of low air pressure and high winds on the water's surface. [1]
        - Dam Break/Glacial Lake Outburst Flood: (elaborated under Flash/Dynamic/Torrential Flood)
    - Pluvial Flood: A flood resulting from precipitation and may occur independently of the overflowing of a water body. [18] [37] [74] [8] [70]
        - Rainfall Flood: A pluvial flood resulting from rainfall of long duration and/or high intensity occurring on saturated or impermeable and causing water accumulation in poorly draining areas. [79] [82] [54]
        - Snowmelt Flood: A pluvial flood, and cryospheric hazard resulting from the precipitation of snow and its subsequent thawing driven by temperature as well as the precipitation of rain. [82] [26]
    - Groundwater Flood: A flood resulting from the precipitation-driven rise of the level of groundwater to at or above the level of the surface. [37] [74] [70]
- Saltwater Intrusion: A hydrospheric hazard resulting from the displacement of fresh groundwater by saltwater in a coastal aquifer by way of reduced groundwater recharge and/or sea level rise. [34] [47]
- Mud Flow: (elaborated under Flowing Mass Movement)
- Debris Flow: (elaborated under Flowing Mass Movement)
- Erosion (elaborated under Lithospheric Hazard)
- Convective Hazard (elaborated under Atmospheric Hazard)
- Extreme Precipitation Hazard (elaborated under Atmospheric Hazard)
- Drought (elaborated under Atmospheric Hazard)

Atmospheric Hazard:

A CCDNH posing a risk to housing and/or critical infrastructure resulting from the interaction of forces and elements in the atmosphere (wind, temperature, mixed-phase atmospheric water). [78]

- Convective Hazard: An atmospheric hazard resulting from convection and producing high winds and intense precipitation. [80] [1] [47]
    - Cyclone: A convective and hydrospheric hazard resulting from a cyclonic convective storm with extreme winds and precipitation, located either inside or outside of the tropics. [43] [1] [67] [47]
        - Tropical Cyclone: A cyclone between the latitudes of 30° N and 30° S (Hurricane, Typhoon, etc…). [43] [1] [67] [47]
        - Extratropical Cyclone: A cyclone outside of the latitudes of 30° N and 30° S (Nor'Easter, Wind Storm, etc…). [47]
    - Severe Thunderstorm: A convective hazard resulting from a severe, non-cyclonic, convective storm producing lightning and high winds and capable of producing a single or multiple types of precipitation. [1] [5]
        - Hail Storm: A severe thunderstorm and cryospheric hazard producing hailstones. [1] [26]
        - Tornado: A severe thunderstorm producing a violently rotating pendant column of air with extremely high winds. [1]
    - Storm Surge: (elaborated under Coastal Flood)
- Drought: An atmospheric and hydrospheric hazard resulting from an extended hydrological imbalance driven by combinations of abnormally low precipitation and abnormally high evapotranspiration. [80] [1] [85] [47]
    - Runoff Drought: A drought resulting primarily from abnormally low streamflow. [1]
    - Aquifer Drought: A drought resulting from abnormally low groundwater and the potential subsidence of the ground surface. [1] [3]
- Extreme Precipitation Hazard: An atmospheric and hydrospheric hazard resulting from precipitation with high enough magnitude to fall above a set high percentile of the distribution of available historical data for a certain area and duration of time. The precipitation may take various forms including rain, snow, and hail. [47] [41]
- Extreme Heat: An atmospheric hazard resulting from an air temperature maximum, minimum, or average which exceeds a set high percentile of the distribution of available historical data for a certain area and duration of time. [80] [62] [40]
- Wildfire: An atmospheric hazard resulting from the ignition of fire in a landscape with the correct climatic factors, fuel availability, and topography to allow for spreading and spotting. [84] [19] [70]
- Erosion: (elaborated under Lithospheric Hazard)

Lithospheric Hazard:
A CCDNH posing a risk to housing and/or critical infrastructure resulting from motion of solid, non-water components of the earth's surface. [78]

- Mass Movement: A lithospheric hazard resulting from the movement of substantial masses of various solid components of the earth's surface downwards. A mass movement is driven by the action of gravity and can be characterized by a single dominant mode of movement. [4] [3]
    - Flowing Mass Movement: A mass movement resulting from the variable-rate flow-like movement of material at a set or variable level of water saturation. The flow-like movement of the material is characterized by an evenly distributed velocity profile resembling that of a viscous fluid. [45] [21] [86]
        - Mud Flow: A flowing mass movement and hydrospheric hazard resulting from the rapid or extremely rapid movement of silt, and clay with high water saturation. [45] [44] [3]
        - Debris Flow: A flowing mass movement and hydrospheric hazard resulting

        - from the rapid or extremely rapid movement of debris with high water saturation. [45] [44] [48] [3]
        - Earth Flow: A flowing mass movement resulting from the rapid, slow, or intermittent movement of plastic soil with a variety of possible levels of water saturation. [44]
        - Flash/Dynamic/Torrential Flood: (elaborated under Fluvial Flood).
    - Falling Mass Movement: A mass movement resulting from the shear displacement-free detachment, falling, rolling, and bouncing of rocks, boulders, debris, or silt. [21] [44] [3]
        - Rock Fall: A falling mass movement resulting from the falling rock fragments. [44]
    - Subsiding Mass Movement: A mass movement resulting from the downward movement of surface material through settling, compaction, or collapse. [62] [3]
        - Sinkhole: A subsiding mass movement resulting from the abrupt formation of a depression or hole in the ground's surface driven by the collapse of a limestone karst cavern. [3]
        - Permafrost Degradation (elaborated under Cryospheric Hazard)
    - Sliding Mass Movement: A mass movement resulting from the sliding of rocks, clay, silt, gravel, sand, or debris on a rotational or planar rupture surface or a narrow zone of intense shear strain. [21] [86]
- Erosion: A lithospheric, hydrospheric, and atmospheric hazard resulting from the gradual detachment, entrainment and transportation of small masses of rock or sediment driven by combinations of gravity, precipitation, wind, and flowing water. [3] [47]
    - Coastal Erosion: Erosion resulting from retreat of a shoreline driven by the loss of coastal sediment or bedrock. [3] [47]

Cryospheric Hazard:
A CCDNH posing a risk to housing and/or critical infrastructure resulting from the phase change, presence, or absence of solid water. [26]

- Snow Avalanche: A cryospheric hazard resulting from the rapid descent of snow down a slope while entraining more snow and other material. [27] [76] [47]
- Permafrost Degradation: A cryospheric hazard and subsiding mass movement resulting from the thawing and subsequent shrinkage and subsidence of permafrost and thermokarst. [26] [3] [47] [58]
- Ice Jam Flood (elaborated under Fluvial Flood)
- Dam Break/Glacial Lake Outburst Flood (elaborated under Flash/Dynamic/Torrential Flood)
- Snowmelt Flood (elaborated under Pluvial Flood)
- Hail Storm (elaborated under Severe Thunderstorm)

Organizational Design:

Table 3 organizes hazard classes beneath the root class "CCDNH Posing a Risk to Housing and/or Critical Infrastructure". This class establishes the focus of the taxonomy by defining this survey's hazards and assets of interest in addition to outlining the characteristics required of the taxonomies eligible classes. The definition of the root class relies heavily on the definition put forth in the introduction for CCDNH as well as the definitions of related terms such as *natural hazard* (Argyroudis et al. 2019, 4)(Alexander 1993, 4) and *extreme climate event* (IPCC AR6 2022, "Climate extreme (extreme weather or climate event)")(National Academies of Science, Engineering, and Medicine 2014)(Alexander 1993, 5). While all inform the creation of this root class, its precise definition is specific to this survey.

This survey refers to the first division below the root class using hazard spheres (Alexander 1993, 5): hydrospheric, cryospheric, lithospheric, and atmospheric. This approach is primarily inspired by the taxonomy of natural disasters put forth by Skidmore (2022) and the definition of the terms *hazard* provided by Argyroudis et al. (2019). Skidmore (2022) selects five primary categories into which to sort natural disasters: biological, geophysical/extraterrestrial, hydrological, meteorological, and climatological (Skidmore 2022, 14). Argyroudis et al. (2019) select only three categories: geological, meteorological, and hydrological (Argyroudis et al. 2019, 4). Table 3 adapts these sets of categories to the context of CCDNHs by first excluding biological and extraterrestrial, neither of which describes hazards considered to be predominantly climate change driven. The categories of meteorological, and climatological are then merged to create an atmospheric category due to their strong similarities and difficult delineation. Geophysical and hydrological are rephrased as lithospheric and hydrospheric in order to standardize the language used across the classes (Alexander 1993, 5). Finally, a cryospheric category is added in order to more clearly categorize hazard classes involving solid water (Ding et al. 2021, 2). The resulting hazard spheres sort hazard classes based on a mixture of the general forces driving their occurrence, the elements and states involved, and the dominant location in which they occur.

<u>Hydrospheric Hazard</u>:

Each hazard sphere is subclassed to create a set of hazard classes fitting its characteristics. The first, "Hydrospheric Hazard", is divided into eight subclasses on the basis of the mechanism(s) giving rise to the risk: "Flood", "Saltwater Intrusion", "Erosion", "Mud Flow", "Debris Flow", "Convective Hazard", "Extreme Precipitation Hazard", and "Drought". The diversity of these subclasses is made possible by the broad definition of "Hydrospheric Hazard" which only requires that a hazard be dependent on the presence or absence of liquid water in order to be considered to be hydrospheric. Within the reviewed literature a similar diversity of classes is included under adjacent or combined terms as seen in Table 4.

<u>Table 4</u>: Hydrospheric Hazard Summary

Category in the Literature Sources *	Flood	Convective Hazard	Drought	Mass Movement †	Snow Avalanche †
Atmospheric and Hydrological Hazards (Alexander 1993, Chapter 3)					
Hydrological Natural Disasters (Skidmore 2022, 14)					
Hydrological Extremes					

(Brutti et al. 2024, 14)					
Hydrological Extremes (Trenberth 2014, 123)					

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.

† Class is not a subclass of "Hydrospheric Hazard" in Table 12 but is placed in an equivalent or adjacent category in the literature.

The lists in Table 4 (and tables 5 through 11) only contain those hazards meeting the eligibility criteria of Table 3. From the lists of hazards in Table 4, two hazards are excluded and several others are added to create the "Hydrospheric Hazard" subclasses in Table 3. Snow avalanches are fully excluded from being considered as hydrospheric because they are primarily driven by the presence or absence of solid not liquid water. Mass movements are not included as a subclass of "Hydrospheric Hazard" because most mass movements do not require the presence of liquid water to occur to occur (Cruden and Varnes 1996, 38)(Hungr, Leroueil, and Picarelli 2014)(Varnes 1978, 24). Those mass movements that do require liquid water are represented by the classes "Mud Flow" and "Fluvial/Dynamic/Torrential Flood". "Saltwater Intrusion" (IPCC AR6 2022, "Salt-water intrusion/encroachment"), "Mud Flow" (Hungr et al. 2014, 185), "Debris Flow" (Jacobs et al. 2018, 489), "Erosion" (Alexander 1993, 218), "Extreme Precipitation Hazard" (IPCC AR6 2022, "Extreme/heavy precipitation event"), and "Wildfire" (Public Safety Canada 2024, 74) are all added despite their absence from the lists provided in Table 4 because each depends substantially on the presence or absence of liquid water . The division of the direct subclasses of "Hydrospheric Hazard" is justified by their widely varying mechanisms.

Among the immediate subclasses of "Hydrospheric Hazard", only "Flood" is subclassed further here ("Convective Hazard" and "Drought" are subclassed further under other hazard spheres). Similarly to the hydrospheric hazards, the literature splits floods into specific flood hazards in a variety ways. These are shown in Table 5.

<u>Table 5a</u>: Flood Summary

Sources *	Fluvial Flood			
		Flash/Dynamic/ Torrential Flood		Ice Jam Flood
			Dam Break/Glacial Lake Outburst Flood	
(Alexander 1993, 120)				
(Armal, Porter et al. 2020, 3)				
(Bates et al. 2021, 2)				
(Cea and Costabile 2022, 1)				
(Dawson et al. 2018, 10)				
(FEMA 2024c, 5-3)				
(Friedland 2009, 13)				
(Galasso, Pregnolato, and Parisi 2021, 8)				
(Gourevitch et al. 2023, 252)				
(Koks et al. 2019, 5)				
(Merz et al. 2010, 1702)				
(Public Safety Canada 2023, 95)				
(Quesada-Ganuza, Garmendia, and Gandini 2023, 28)				
(Sayers et al. 2015, 21)				
(Skidmore 2022, 14)				
(Stephenson 2008, 14)				

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.

Table 5b: Flood Summary (cont'd)

Sources *	Coastal Flood		Pluvial Flood			Groundwater Flood
		Storm Surge		Rainfall Flood	Snowmelt Flood	
(Alexander 1993, 120)						
(Armal, Porter et al. 2020, 3)						
(Bates et al. 2021, 2)						
(Cea and Costabile 2022, 1)						
(Dawson et al. 2018, 10)						
(FEMA 2024c, 5-3)						
(Friedland 2009, 13)						
(Galasso, Pregnolato, and Parisi 2021, 8)						
(Gourevitch et al. 2023, 252)						
(Koks et al. 2019, 5)						
(Merz et al. 2010, 1702)						
(Public Safety Canada 2023, 95)						
(Quesada-Ganuza, Garmendia, and Gandini 2023, 28)						
(Sayers et al. 2015, 21)						
(Skidmore 2022, 14)						
(Stephenson 2008, 14)						

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.

The number and identity of the flood hazards included by each source is largely dependent on the scope and subject of each and few sources organize these hazards beyond hierarchy-free lists. In order to incorporate these flood hazards into Table 3, “Flood” is first assigned the subclasses “Fluvial Flood”, “Coastal Flood”, “Pluvial Flood”, and “Groundwater Flood”, a grouping that is supported by the literature (Public Safety Canada 2024, 95)(Dawson et al. 2018, 10)(Sayers et al. 2015, 21). These subclasses are used to separate the remaining flood classes based on the primary source of water driving inundation: a water channel in the case of “Fluvial Flood”, a stationary body of water in the case of “Coastal Flood”, precipitation in the case of “Pluvial Flood”, and an aquifer in the case of “Groundwater Flood”. The first three of these subclasses are subclassed further.

The class “Fluvial Flood” is subclassed into “Flash/Dynamic/Torrential Flood” and “Ice Jam Flood”. These classes are separated on the basis of mechanism: a flash, dynamic, or torrential flood is driven by a sudden and significant increase in the flow rate while an ice jam flood is driven by the constriction of the channel’s flow capacity. This splitting of fluvial floods partially aligns with a few sources (Tarasova et al. 2019, 14)(Public Safety Canada 2024, 151)(Stein, Pianosi, and Woods 2020, 1518-1519) that include both flash floods and ice jam floods but also include rainfall floods, snowmelt floods, groundwater floods, and storm surges, as shown in Table 6. Table 3 does not include these four as subclasses of “Fluvial Flood” because none of them exclusively occur in or around rivers and streams. In order to comply with the requirements of subClassOf relationships and be a subclass of “Fluvial Flood”, every rainfall flood, snowmelt flood, groundwater flood, or storm surge would need to be describable as a fluvial flood. “Storm Surge” is instead made a subclass of “Coastal Flood” while the classes “Rainfall Flood” and “Snowmelt Flood” are made subclasses of “Pluvial Flood” and “Groundwater Flood” is split off into its own flood subclass.

Table 6: Fluvial Flood Summary

Sources *	Flash/ Dynamic/ Torrential Flood		Ice Jam Flood	Rainfall Flood †	Snowmelt Flood †	Groundwater Flood †	Storm Surge †
		Dam Break/ Glacial Lake Outburst Flood					
(Public Safety Canada 2024, 151)							
(Stein, Pianosi, and Woods 2020, 1518-1519)							
(Tarasova et al. 2019, 14)							

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.
† Class is not a subclass of “Fluvial Flood” in Table 12 but is placed in an equivalent or adjacent category in the literature.

“Dam Break/Glacial Lake Outburst Flood” is included as a subclass of “Flash/Dynamic/Torrential Flood” without explicit support from the reviewed literature. The literature classifies dam break and glacial lake outburst floods as fluvial floods (Public Safety Canada 2024, 151)(Tarasova et al. 2019, 14)(Ding et al. 2021, 10) but never describes them directly as flash, dynamic, or torrential floods. The placement of “Dam Break/Glacial Lake Outburst Flood” as a subclass of “Flash/Dynamic/Torrential Flood” is instead based on their shared characteristics such as the rapid increase of flow rate, presence of entrained material, and location in steep narrow catchments (Public Safety Canada 2024, 95)(Papathoma-Köhle, Schlögl, and Fuchs 2019, 1)(Fuchs et al. 2019, 1)(Luo et al. 2023, 2)(Alexander 1993, 200-201)(Ding et al. 2021, 7)(Hungr, Leroueil, and Picarelli 2014, 186). It is reasoned that all dam break and glacial lake outburst floods are also flash, dynamic, or torrential floods because a sudden large discharge of water from a dammed reservoir or glacial lake rapidly increases the flow rate in the downstream catchment (Alexander 1993, 201).

“Coastal Flood”, the next subclass of “Flood”, is subclassed into “Storm Surge” and “Dam Break/Glacial Lake Outburst Flood”. While storm surges are repeatedly referred to as coastal floods by the reviewed literature (Alexander 1993, 120)(Friedland 2009, 20)(Public Safety Canada 2024, 97)(Skidmore 2022, 14)(Fleming et al. 2018, 329), dam break and glacial lake outburst floods are never described as coastal floods in the literature. “Dam Break/Glacial Lake Outburst Flood” is made a subclass of “Coastal Flood” because the definition of “Coastal Flood” used in Table 3 aptly describes the floods that occur when dams and glacial moraines fail: the rapid discharge of water from a reservoir or glacial lake represents an overflowing of the water body’s usual shoreline boundary (Ding et al. 2021, 7)(IPCC AR6 2022, “Glacial lake outburst flood (GLOF)/Glacier lake outburst”)(Hungr, Leroueil, and Picarelli 2014, 186). As such, it is reasoned that all dam break and glacial lake outburst floods are also coastal floods and that a subClassOf/superClassOf relationship can exist between “Dam Break/Glacial Lake Outburst Flood” and “Coastal Flood”.

Finally, “Pluvial Flood” is subclassed into “Rainfall Flood” and “Snowmelt Flood”. This split is made on the basis of the primary mechanism involved in the classes: direct rainfall accumulation and snowmelt water accumulation respectively. The literature provides a basis for the inclusion of “Rainfall Flood” and “Snowmelt Flood” as subclasses of “Pluvial Flood” while also including flash floods (Table 7). Flash floods are excluded from Table 3 because not all flash floods are caused by precipitation, as demonstrated by dam break and glacial lake outburst floods.

Table 7: Pluvial Flood Summary

Sources *	Rainfall Flood	Snowmelt Flood	Flash/Dynamic/Torrential Flood †
(Galasso, Pregnolato, and Parisi 2021, 8)			
(Public Safety Canada 2024, 95)			

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.
† Class is not a subclass of “Pluvial Flood” in Table 12 but is placed in an equivalent or adjacent category in the literature.

Atmospheric Hazard:

Similarly to “Hydrospheric Hazard”, “Atmospheric Hazard” is first divided into subclasses based on mechanism driving the risk to housing and/or critical infrastructure: “Extreme Heat”, “Convective Hazard”, “Extreme Precipitation Hazard”, “Drought”, “Wildfire”, and “Erosion”. This choice of subclasses is largely inspired by the categorizations shown in Table 8. None of these categorizations refers explicitly or exclusively to atmospheric hazards, instead using similar or combined terms.

In selecting subclasses for “Atmospheric Hazard”, snow avalanches and floods are both excluded on the basis that their primary mechanisms do not rely heavily on the interaction of atmospheric forces and elements. Meanwhile, two classes, “Extreme Precipitation Hazard” and “Erosion”, are added without being present in Table 8. “Extreme Precipitation Hazard” is included due to the key role played by atmospheric water in its mechanism. The inclusion of “Erosion” as a subclass is justified by its reliance on both wind and atmospheric water.

Table 8: Atmospheric Hazard Summary

Category in the Literature Sources *	Convective Hazard	Drought	Extreme Heat	Wildfire	Flood †	Snow Avalanche †
Atmospheric and Hydrological Extremes (Alexander 1993, 120)						
Meteorological and Climatological (Skidmore 2022, 14)						
Extreme Weather/ Climate Events (Stephenson 2008, 14-15)						

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.
† Class is not a subclass of “Atmospheric Hazard” in Table 12 but is placed in an equivalent or adjacent category in the literature.

Of the subclasses of “Atmospheric Hazard”, only “Convective Hazard” and “Drought” have eligible subclasses that can be found in the literature. For “Convective Hazard”, the immediate subclasses selected are “Cyclone”, “Severe Thunderstorm”, and “Storm Surge”, each of which possesses a unique mechanism. The class “Convective Hazard” is adapted from a taxonomy proposed by Stephensen (2008) which includes to “convective phenomena” and clarifies that they refer to three eligible hazards: tornadoes, severe thunderstorms, and hail storms (waterspouts are not considered by this survey to pose a significant risk to housing or critical infrastructure to be eligible) (Stephensen 2008, 14). As part of the adaption, Table 3 includes cyclones as convective hazards on the basis that cyclones, tropical and extratropical, are necessarily convective weather systems (Alexander 1993, 157). This contrasts the Stephensen (2008) taxonomy which includes both tropical and extratropical cyclones as classes separate from convective phenomena (14). As for the subclass “Severe Thunderstorm”, it is added in accordance with Stephensen’s definition of convective phenomena and used as a superclass for “Tornado” and “Hail Storm”, both of which are hazards dependent on severe thunderstorms (Allen 2018, 1)(Stephensen 2008, 14)(Alexander 1993, 170). Finally, “Storm Surge” is added as a subclass of “Convective Hazard” because its mechanism is dependent on the low pressure, wind, and precipitation associated with convective hazards (Alexander 1993, 137).

“Drought” is split into the subclasses “Runoff Drought” and “Aquifer Drought”, each of which occurs in a distinct part of the water cycle (Alexander 1993, 144). Despite being included as a major category of droughts by Alexander (1993), precipitation droughts are truncated from Table 3 on the basis that they could not be directly linked to impacts on housing or critical infrastructure, therefore failing to meet the traceability criteria.

Lithospheric Hazard:

The first level of subclasses beneath “Lithospheric Hazard” contains “Mass Movement” and “Erosion”. These two classes are distinguished by their dominant driving force: “Mass Movement” is primarily driven by gravity acting on material and moving it downwards (Alexander 1993, 243)(Ali et al. 2023, 1) while “Erosion” is primarily driven by the flow or movement of a material’s medium (i.e. water, wind) causing the detachment and entrainment of material (IPCC AR6 2022, “Soil erosion”)(Alexander 1993, 218). The list of “Geophysical/Extraterrestrial” natural disasters from Skidmore (2022) provides the only concise reference against which to compare the subclasses of “Lithospheric Hazard” (Skidmore 2022, 14). With the exception of “Mass Movement (Dry)”(Skidmore 2022, 14), all of the natural disasters listed by Skidmore are not considered to be CCDNHs. As seen in Table 9, the literature contains one other classification of hazards under the lithospheric-adjacent term “Disasters and the Land Surface” courtesy of Alexander (1993). This term is sourced from the title of a chapter and the list of hazards in Table 9 comes from the different sections of the chapter. This list contains erosion in addition to mass movements, justifying its inclusion in Table 3. Alexander (1993) also includes a section on wildfires. Table 3 does not include “Wildfire” as a subclass of “Lithospheric Hazard” because the motion of surface solids is not significant enough to wildfires to warrant “Lithospheric Hazard” membership. The other hazards included in the chapter such as earthquakes and desertification are not used in Table 3 because the former is not a CCDNH and the latter is not directly connected to impacts on assets of interest by the literature.

Table 9: Lithospheric Hazard Summary

Category in the Literature Sources *	Mass Movement	Erosion	Wildfire †
Disasters and the Land Surface (Alexander 1993, Chapter 4)			
Geophysical/Extraterrestrial Natural Disasters (Skidmore 2022, 14)			

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.
† Class is not a subclass of “Lithospheric Hazard” in Table 12 but is placed in an equivalent or adjacent category in the literature.

“Mass Movement” is itself divided into four subclasses based on mode of movement: “Flowing Mass Movement”, “Falling Mass Movement”, “Subsiding Mass Movement”, and “Sliding Mass Movement”. Table 10 demonstrates the sources of these classes in the literature. Importantly, the lists in

Table 10 do not make mention of truncated mass movement modes such as creeping mass movements (Martinsen 1994, 128), slumping mass movements (Alexander 1993, 252)(Martinsen 1994, 128), spreading mass movements (Alexander 1993, 252)(Varnes, 1978, 11)(Hungr, Leroueil, and Picarelli 2014, 190)(Cruden and Varnes 1996, 38), toppling mass movements (Alexander 1993, 252)(Varnes, 1978, 11)(Hungr, Leroueil, and Picarelli 2014, 190)(Cruden and Varnes 1996, 38), slope deformations (Hungr, Leroueil, and Picarelli 2014, 190), or complex mass movements (Alexander 1993, 252)(Varnes, 1978, 11). As with the potential subclasses of "Drought", none of these modes of mass movement can be connected with impacts on assets of interest.

Table 10: Mass Movement Summary

Sources *	Flowing Mass Movement	Falling Mass Movement	Subsiding Mass Movement	Sliding Mass Movement
(Alexander 1993, 252)				
(Cruden and Varnes 1996, 38)				
(Dawson et al. 2018, 12-13)				
(Hungr, Leroueil, and Picarelli 2014, 190)				
(Martinsen 1994, 128)				
(Skidmore 2022, 14)				
(Varnes, 1978, 11)				

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.

"Flowing Mass Movement" and "Falling Mass Movement" are both subclassed further based on the dominant material involved in the movement. Under "Flowing Mass Movement", this results in the classes "Mud Flow", "Debris Flow", "Earth Flow", and "Flash/Dynamic/Torrential Flood" whose dominant solid components are water saturated soil (Hungr et al. 2014, 185), debris (Alexander 1993, 254), plastic soil (Hungr et al. 2014, 187), and water-suspended sediment (Papathoma-Köhle, Schlögl, and Fuchs 2019, 1) respectively. The flowing mass movement classifications in Table 11 support the inclusion of all of these classes with the exception of "Flash/Dynamic/Torrential Flood". "Flash/Dynamic/Torrential Flood" is added on account of its high sediment concentration (Papathoma-Köhle, Schlögl, and Fuchs 2019, 1)(Luo et al. 2023, 2) which fulfills the requirement involving the flow-like movement of solid material. The four subclasses of "Flowing Mass Movement" represent a small subset of the total number of flowing mass movements suggested by the literature, the rest of which are truncated on the basis that they lack traceability to impacts on assets of interest (Hungr 2005, 14-15)(Varnes 1978, 11)(Cruden and Varnes 1996, 38)(Hungr, Leroueil, and Picarelli 2014, 190)(Alexander 1993, 252-255)(Luo et al. 2023, 2).

Table 11: Flowing Mass Movement Summary

Sources *	Mud Flow	Debris Flow	Earth Flow

(Alexander 1993, 252-255)			
(Cruden and Varnes 1996, 38)			
(Hungr 2005, 14-15)			
(Hungr, Leroueil, and Picarelli 2014, 190)			
(Varnes 1978, 11)			

* Only includes classes which meet the first inclusion criteria of Table 3, eligibility.

When applied to “Falling Mass Movement”, the materials based classification results in a single subclass: “Rock Fall”. The inclusion of rock falls as falling mass movements is supported by a few classification systems from the literature (Varnes 1978, 11)(Cruden and Varnes 1996, 38)(Hungr, Leroueil, and Picarelli 2014, 190). These same sources all also include falls of a variety of other materials. Those other potential falling mass movements are once again omitted due to an inability to connect them with impacts on assets of interest.

The final subclass of “Mass Movement” which is itself subclassed is “Subsiding Mass Movement”. This class possesses the subclasses “Sinkhole” and “Permafrost Degradation”. Similarly to the subclasses of “Flowing Mass Movement” and “Falling Mass Movement”, these subclasses each is delineated by their material: karst in the case of sinkholes and thermokarst in the case of permafrost degradation (Alexander 1993, 283-284). While subsidence is connected elsewhere to permafrost degradation (Markon et al. 2018, 1197)(Ding et al. 2021, 4), Alexander provides the only example which classifies both sinkholes and permafrost degradation as forms of subsidence (Alexander 1993, 283-284).

“Sliding Mass Movement” is a class with many potential subclasses (Varnes 1978, 11)(Hungr, Leroueil, and Picarelli 2014, 190)(Cruden and Varnes 1996, 38)(Alexander 1993, 252-255). However, all of these potential classes fail to meet the traceability and/or differentiability criteria and are therefore truncated. The only sliding mass movements which could potentially avoid truncation are landslides. Landslides are widely referenced but poorly defined in the literature. Thus, instead of allocating landslides a class of their own, they are treated as a synonym of “Sliding Mass Movement” and not a specific subclass of it.

It is important to note that the reviewed literature classifies mass movements using a variety of metrics other than movement mode and material type. These include water content (Hungr 2005, 13)(Cruden and Varnes 1996, 38) and velocity (Hungr 2005, 13)(Hungr, Leroueil, and Picarelli 2014, 169)(Cruden and Varnes 1996, 38)(Alexander 1993, 251) among others. These are not used to categorize the mass movement classes of Table 3 because these characteristics tend to be variable or unclarified for the individual subclasses of “Mass Movement”.

The second subclass of “Lithospheric Hazard”, “Erosion”, is assigned only “Coastal Erosion” as a subclass. The decision to include “Coastal Erosion” is supported by the overlapping characteristics between coastal and general erosion as well as by the literature (Alexander 1993, 287)(Markon et al. 2018, 1198). Both of these sources also highlight other forms of erosion such as fluvial erosion (Alexander 1993, 218)(Markon et al. 2018, 1198), alluvial erosion (Alexander 1993, 222-223), and rainsplash erosion (Alexander 1993, 221). All of these must however be truncated from Table 3 because none meet the traceability criteria.

Cryospheric Hazard:

Table 3's final hazard sphere, "Cryospheric Hazard", is divided into six mechanism-delineated subclasses: "Snow Avalanche", "Permafrost Degradation", "Ice Jam Flood", "Dam Break/Glacial Lake Outburst Flood", "Snowmelt Flood", and "Hail Storm". Beyond their common reliance on solid water (its phase change, presence, or absence), the mechanisms of these classes differ significantly from one another as demonstrated by their respective definitions in Table 3. Cryospheric hazards are only tabulated by one source in the literature (Ding et al. 2021). Of the "Cryospheric Hazard" subclasses in Table 3, Ding et al. (2021) include all but ice jam floods as cryospheric hazards. "Ice Jam Flood" is included as a subclass of "Cryospheric Hazard" because it requires the presence of solid water and possesses a mechanism which is independent, and therefore differentiable, from its closest analogue in Table 3, "Snowmelt Flood" (Tarasova et al. 2019, 11).

In addition to the six "Cryospheric Hazard" subclasses included in Table 3, the literature contains others which must be excluded on the basis of ineligibility (they are not CCDNHs). The most notable of these are blizzards and heavy snowfalls which, despite posing significant risks to transportation infrastructure and being entirely dependent on the presence of solid water (Alexander 1993, 2001)(Andrey et al. 2003, 323), are not expected to increase in frequency or magnitude with climate change (Ding et al. 2021, 4).

None of the subclasses of "Cryospheric Hazard" are themselves assigned subclasses. The lack of subclasses does not result from the absence of potential subclasses in the reviewed literature. "Snow Avalanche", in particular, possesses a variety of potentially eligible subclasses such as loose-snow avalanches (Eckert et al. 2024, 372)(Schweizer, Jamieson, and Schneebeli 2003, 1)(Alexander 1993, 187), slab avalanches (Eckert et al. 2024, 372)(Schweizer, Jamieson, and Schneebeli 2003, 1)(Alexander 1993, 187), dry slab avalanches (Eckert et al. 2024, 372)(Alexander 1993, 187), wet slab avalanches (Eckert et al. 2024, 371)(Alexander 1993, 187)(Schweizer, Jamieson, and Schneebeli 2003, 8), and glide avalanches (Eckert et al. 2024, 371). All of these potential "Snow Avalanche" subclasses are truncated because their mechanisms are not sufficiently differentiable and their impact on housing or critical infrastructure is not traceable.

Taxonomic Structure:

A specialized and in-depth discussion of precisely how the definitions and structures of Table 3 abide by the rules and guidelines set out in the methods section can be found in Appendix B.

Taxonomy of Impacts

Table 12 contains a taxonomy of the impacts of CCDNHs on housing and critical infrastructure. The taxonomy is constructed using only one criterion to dictate the inclusion and exclusion of potential impact classes:

1. Eligibility: Is eligible to be included in Table 12. Impact classes eligible for inclusion represent direct negative effects on infrastructure or housing, significantly impeding the full functionality of the asset. The impact class is attributable to at least one CCDNH.

This criterion is broad and, when applied to the impact classes encountered in the reviewed literature, very few fail to meet it. The result is that the classes in Table 12 closely reflect the diversity of specific CCDNH impacts on assets of interest present in reviewed literature. Notably, the taxonomy of impacts' lack of non-eligibility criteria means that little to no truncation is used in its creation.

Table 12: Taxonomy of CCDNH Impacts on Housing and Critical Infrastructure

ROOT CLASS
Impact of CCDNH:
A direct negative effect of a CCDNH on a physical asset of interest. The effect significantly impedes the ability of the asset to maintain its full intended functionality.

Physical Impact:
An impact of a CCDNH impeding the ability of a physical asset to fulfill its intended function while changing the state or structure of the asset.

- Physical Impact on Housing: A physical impact impeding the function of building that provides housing.
  - Physical Impact on Non-Structural Housing Element: A physical impact on housing impeding the function of an element of a building that is not critical to its structural integrity.
    - Loss of Roof Component: A physical impact on a non-structural housing element resulting from the removal or dislodgement of the roof flashing, sheathing, or guttering of a building. Has "Tropical Cyclone" [38] [68] [35] [1] [32] as a potential driver.
    - Water Damage to Interior: A physical impact on a non-structural housing element and a physical impact on an emergency facility resulting from the entrance of water or humidity into normally dry areas of a building, causing damage. Has "Fluvial Flood" [71] [75] [30], "Pluvial Flood" [71], "Flash/Dynamic/Torrential Flood" [71] [30], "Snowmelt Flood" [71], "Dam Break/Glacial Lake Outburst Flood" [71], "Flowing Mass Movement" [56], "Ice Jam Flood" [71], and "Tropical Cyclone" [38] [68] [35] [1] [32] as potential drivers.
    - Failure of Fenestration: A physical impact on a non-structural housing element and a physical impact on an emergency facility resulting from the removal or collapse of the window or door of a building. Has "Fluvial Flood" [75] [30], "Tropical Cyclone" [38] [68] [35] [1] [32], "Tornado" [1], "Flash/Dynamic/Torrential Flood" [30], and "Flowing Mass Movement" [56] as potential drivers.
    - Damage to Wall Cladding: A physical impact on a non-structural housing element resulting from the deterioration or removal of the cladding on the exterior or interior wall of a building. Has "Storm Surge" [35], "Tropical Cyclone" [38] [68] [35] [32], "Mass Movement" [56], and "Wildfire" [64] as potential drivers.
    - Melting of Frame/Shutter: A physical impact on a non-structural housing

element resulting from the melting of the aluminium window frame or shutter of a building. Has "Wildfire" [64] as a potential driver.

    - Removal of Appurtenant Structure: A physical impact on a non-structural housing element and a physical impact on an emergency facility resulting from the destruction or displacement of the structure (porch, garage, gazebo, shed, awning, AC unit, etc…) which is attached or adjacent to a building. Has "Storm Surge" [35] and "Tropical Cyclone" [38] [35] as potential drivers.
    - Inundation of Basement: A physical impact on a non-structural housing element resulting from the accumulation of water in the basement of a building. Has "Flood" [9] [71] [70], “Fluvial Flood” [71], “Pluvial Flood” [71], “Flash/Dynamic/Torrential Flood” [71], “Snowmelt Flood” [71], “Dam Break/Glacial Lake Outburst Flood” [71], “Ice Jam Flood” [71], and “Flowing Mass Movement” [56] as potential drivers.
    - Mold Growth: A physical impact on a non-structural housing element resulting from the introduction and spread of harmful mold on interior surfaces. Has “Flood” [10] [7] as a potential driver.
  - Physical Impact on Structural Housing Element: A physical impact on housing impeding the function of an element that is critical to the structural integrity of a building.
    - Damage to Structural Housing Element: A physical impact on a structural housing element resulting from the deterioration of the structural element of a building, falling short of the destruction of the element.
      - Cracking of Supporting Element: Damage to a structural housing element resulting from the cracking of the wall, column, or foundation of a building. Has "Tropical Cyclone" [35] [32], “Drought” [2] [3], “Mass Movement” [66] [56], “Flowing Mass Movement” [56], “Aquifer Drought” [3], and "Fluvial Flood" [75] as potential drivers.
      - Racking of Elevated Structure: Damage to a structural housing element resulting from the lateral movement or deformation of the pile or pillar supporting a building. Has "Tropical Cyclone" [35] [32] and “Storm Surge” [35] as potential drivers.
      - Scour/Destabilization of Foundation: Damage to a structural housing element, a physical impact on a natural gas transportation and distribution network, a physical impact on a pier or abutment, and a physical impact on an embankment, cutting, or culvert resulting from the removal or lateral destabilization of the material around or under the foundation. Has "Storm Surge" [35], “Coastal Erosion” [3], “Flowing Mass Movement” [56], and “Permafrost Degradation” [58] as potential drivers.
    - Destruction of Supporting Housing Element: A physical impact on a structural housing element resulting from the collapse, removal, or displacement of the supporting element of a building.
      - Failure of Roof Structure: Destruction of a structural housing element resulting from the removal or collapse of part or all of the roof structure of a building. Has "Tropical Cyclone" [38] [68] [35] [1] [32], “Mass Movement” [56], and “Tornado” [1] as potential drivers.
      - Failure of Wall: Destruction of a structural housing element resulting from the collapse or removal of the wall of a building. Has "Tropical Cyclone" [38] [35] [32], “Tornado” [1] [32], “Fluvial Flood” [75], and "Flowing Mass Movement" [56] as potential drivers.

        - Failure of Column: Destruction of a structural housing element resulting from the plastic hinge failure of the column of a building. Has "Flowing Mass Movement" [56] as a potential driver
        - Failure of Foundation: Destruction of a structural housing element resulting from the scouring or sliding collapse of the foundation of a building. Has “Tropical Cyclone” [32], "Storm Surge" [35], “Fluvial Flood” [75], and "Flowing Mass Movement" [56] as potential drivers.
  - Physical Impact on Housing Structure: A physical impact on housing impeding the function of a section or the entirety of a building’s structure.
    - Removal/Slippage from Foundation: A physical impact on the housing structure resulting from the shifting of a building on or entirely off of its foundation. Has “Flood” [35] [31], "Storm Surge" [35], "Tropical Cyclone" [35] [32], and “Mass Movement” [56] as potential drivers.
    - Partial/Complete Collapse of Building: A physical impact on the housing structure resulting from the total failure or destruction of a section or the entirety of a building. Has “Mass Movement” [66] [71] [56] [30] [3], “Snow Avalanche” [27] [1], "Tropical Cyclone" [35] [1] [32], “Tornado” [1], "Fluvial Flood" [71] [75] [30], “Flash/Dynamic/Torrential Flood” [71] [30], “Pluvial Flood” [71], “Snowmelt Flood” [71], “Dam Break/Glacial Lake Outburst Flood” [71], “Ice Jam Flood” [71], “Sinkhole” [3], “Earth Flow” [56], "Wildfire" [64], and "Flowing Mass Movement" [56] [30] as potential drivers.
- Physical Impact on Critical Infrastructure Network: A physical impact impeding the function of an infrastructure network which provides or supports the goods and services necessary to maintain the full functionality of housing.
  - Physical Impact on Electrical Network: A physical impact on a critical infrastructure network impeding the function of the network generating, transmitting, and distributing electricity to housing.
    - Physical Impact on Electrical Station: A physical impact on an electrical network impeding the function of a plot of land containing components necessary to the functionality of the energy network.
      - Inundation: A physical impact on an electrical station, water supply or wastewater treatment site, road, tunnel, or railway and a physical impact on a solid waste network resulting from the accumulation of water in a normally dry area in, on, or around an asset. Has "Flood" [18] [71] [23] [89] [60] [90] [49], “Flash/Dynamic/Torrential Flood” [90], “Fluvial Flood” [18] [23], “Coastal Flood” [18] [23] [89] [90], “Storm Surge” [90], “Pluvial Flood” [18] [23] [89], “Groundwater Flood” [23], and “Snowmelt Flood” [49] as potential drivers.
      - Disruption of Hydropower Plant Generating Capacity: A physical impact on an electrical station resulting from the inhibiting of a hydropower plant’s ability to reach its full or normal electricity generation capacity. Has “Flood” [90], "Runoff Drought" [60] [90], and “Extreme Precipitation Hazard” [89] as potential drivers.
      - Disruption of Power Plant Cooling: A physical impact on an electrical station resulting from a shortage of cool water needed to cool power plant components. Has "Extreme Heat" [60] [90] as a potential driver.
    - Physical Impact on Electrical Line: A physical impact on an electrical network impeding the function of the grid necessary to the transmission and distribution of electricity.
      - Damage to Line: A physical impact on an electrical or ICT line

resulting from the degradation or severing of the line. Has "Extreme Heat" [23] [89] [8] [40] [90], “Severe Thunderstorm” [23], “Extreme Precipitation Hazard” [1], “Wildfire” [90], and "Tropical Cyclone" [89] [62] as potential drivers.

      - Toppling of Pylon: A physical impact on an electrical line resulting from the collapse, overturning, or displacement of a pylon supporting lines. Has "Snow Avalanche" [27], "Flood" [23], “Flash/Dynamic/Torrential Flood” [90], and “Severe Thunderstorm” [23] as potential drivers.
    - Brownout/Blackout of Grid: A physical impact on an electrical network resulting from the disruption in the ability to adequately meet electricity demand. Has "Extreme Heat" [89] [60] [90], “Extreme Precipitation Hazard” [62] [90], “Severe Thunderstorm” [90], and “Tropical Cyclone” [89] [90] as potential drivers.
  - Physical Impact on Natural Gas Transportation and Distribution Network: A physical impact on a critical infrastructure network impeding the function of a network transporting and distributing natural gas to homes.
    - Damage to Pumping Station: A physical impact on a natural gas transportation and distribution network resulting from the degradation and loss of functionality of a pumping station used to move natural gas along a pipeline. Has “Flood” [90] as a potential driver.
    - Scour/Destabilization of Foundation: (elaborated under Damage to Structural Housing Element). Has “Flash/Dynamic/Torrential Flood” [90] and “Permafrost Degradation” [58] as potential drivers.
  - Physical Impact on Water Supply/Wastewater Network: A physical impact on a critical infrastructure network impeding the function of the network supplying clean water to housing or removing and treating wastewater from housing.
    - Physical Impact on Water Supply/Wastewater Treatment Site: A physical impact on a water supply or wastewater network impeding the function of a plot of land containing components necessary for the treatment of water to be supplied or wastewater.
      - Obstruction of Treatment Site Chemical Supply: A physical impact on a water supply or wastewater site resulting from the disruption of the regular supply of the chemicals necessary for the treatment of wastewater. Has "Mass Movement" [23] as a potential driver.
      - Disruption of Water Supply Quality: A physical impact on a water supply or wastewater site resulting from the decline of the quality of the water supplied to housing. Has "Flood" [89] [7], “Wildfire” [70], “Rainfall Flood” [7], "Drought" [89], and "Saltwater Intrusion" [58] as potential drivers.
      - Inundation: (elaborated under Physical Impact on Electrical Station). Has "Flood" [23] [49], “Storm Surge” [58], “Fluvial Flood” [23], “Coastal Flood” [23], “Pluvial Flood” [23], and “Groundwater Flood” [23] as potential drivers.
    - Sewer Overflow: A physical impact on a wastewater network resulting from the overflowing of a sewer as a result of a blockage or an unusually elevated volumetric flow rate. Has “Coastal Flood” [48] and "Extreme Precipitation Hazard" [23] [48] [60] [7] as potential drivers.
    - Overtopping/Failure of Dam: A physical impact on a water supply or wastewater network resulting from either the unplanned passage of water

overtop of or the partial/complete collapse of a natural or artificial dam. Has "Snow Avalanche" [26], "Severe Thunderstorm" [62], "Extreme Precipitation Hazard" [62] [60] [26], and "Mass Movement" [26] [2] as potential drivers.

- Physical Impact on Solid Waste Network: A physical impact on a critical infrastructure network impeding the function of the network collecting, transporting, disposing, and storing solid waste for housing.
  - Inundation: (elaborated under Physical Impact on Electrical Station). Has "Flood" [23] [74] as a potential driver.
- Physical Impact on Information and Communication Technology (ICT) Network: A physical impact on a critical infrastructure network impeding the function of the network providing internet, phone, and radio services to housing.
  - Damage to Mobile Phone/Cellular Tower: A physical impact on an ICT network resulting from the degradation and loss of functionality of the components necessary for the provision of ICT services. Has "Severe Thunderstorm" [23] and "Tropical Cyclone" [89] [1] as potential drivers.
  - Damage to Line: (elaborated under Physical Impact on Electrical Line). Has "Extreme Precipitation Hazard" [1], "Snow Avalanche" [1], "Groundwater Flood" [89], and "Tropical Cyclone" [89] as potential drivers.
- Physical Impact on Emergency Services Network: A physical impact on a critical infrastructure network impeding the function of the network providing emergency healthcare and firefighting services to housing.
  - Physical Impact on Emergency Facility: A physical impact on an emergency services network impeding the function of a facility providing emergency services (i.e. hospital, fire station, etc…).
    - Water Damage to Interior: (elaborated under Physical Impact on Non-Structural Housing Element). Has "Tropical Cyclone" [32], "Fluvial Flood" [74], and "Coastal Flood" [74] as potential drivers.
    - Removal of Appurtenant Structure: (elaborated under Physical Impact on Non-Structural Housing Element). Has "Tropical Cyclone" [32] as a potential driver.
    - Failure of Fenestration: (elaborated under Physical Impact on Non-Structural Housing Element). Has "Tropical Cyclone" [32] as a potential driver.
  - Obstruction/Burying: (elaborated under Physical Impact on Road). Has "Mass Movement" [66] as a potential driver.
- Physical Impact on Transportation Network: A physical impact on a critical infrastructure network impeding the function of the network transporting goods and people to and from housing.
  - Physical Impact on Road: A physical impact on a transportation network impeding the function of a road.
    - Obstruction/Burying: A physical impact on a road or railway and a physical impact on an emergency services network resulting from the blockage of a road or railway by solid material. Has "Snow Avalanche" [8] [1], "Sliding Mass Movement" [8], "Debris Flow" [8], "Mud Flow" [8], and "Tropical Cyclone" [62] [48] as potential drivers.
    - Washout: A physical impact on a road, embankment, cutting, or culvert resulting from the rapid erosion, removal and entrainment of a section of the surface or base of the asset. Has "Flood" [8] [62] [70], "Pluvial Flood" [8], "Flash/Dynamic/Torrential Flood" [8], "Sliding Mass Movement" [62], and "Extreme Precipitation Hazard" [48] as

    potential drivers.
    - Damage to Surface: A physical impact on a road resulting from the deterioration of the road surface. Has "Pluvial Flood" [8], "Permafrost Degradation" [58], “Earth Flow” [62], "Extreme Heat" [89] [8] [62] [48], “Drought” [48], "Extratropical Cyclone" [48], and "Wildfire" [8] as potential drivers.
    - Destabilization of Base: A physical impact on a road resulting from the loss of structural integrity of the materials making up the base of the road. Has "Permafrost Degradation" [62] [58], “Groundwater Flood” [48], “Erosion” [48], “Coastal Erosion” [3], and "Sinkhole" [23] as potential drivers.
    - Inundation: (elaborated under Physical Impact on Electrical Station). Has “Flood” [88] [23] [8] [62] [90] [50], “Fluvial Flood” [23], “Coastal Flood” [23] [62] [90], “Storm Surge” [62], “Pluvial Flood” [88] [23] [8] [62] [90], “Debris Flow” [48], and “Groundwater Flood” [23] as potential drivers.
- Physical Impact on Railway: A physical impact on a transportation network impeding the function of a railway.
    - Buckling of Rail: A physical impact on a railway resulting from the deformation and misalignment of rails in the railway. Has "Extreme Heat" [88] [23] [89] [62] [48] as a potential driver.
    - Obstruction/Burying: (elaborated under Physical Impact on Road). Has "Snow Avalanche" [1], “Severe Thunderstorm” [88], and “Mass Movement” [8] [62] as potential drivers.
    - Failure of Slope: (elaborated under Physical Impact on Embankment/Cutting/Culvert). Has "Mass Movement" [23] and “Coastal Erosion” [3] as potential drivers.
    - Inundation: (elaborated under Physical Impact on Electrical Station). Has "Flood" [71] [88] [23] [62] [48] [90], “Fluvial Flood” [71] [23], “Pluvial Flood” [71] [23], “Groundwater Flood” [23], “Coastal Flood” [88] [23] [62] [90], “Flash/Dynamic/Torrential Flood” [71], “Snowmelt Flood” [71], “Dam Break/Glacial Lake Outburst Flood” [71], and “Ice Jam Flood” [71] as potential drivers.
- Physical Impact on Bridge: A physical impact on a transportation network impeding the function of a bridge.
    - Physical Impact on Bridge Deck/Superstructure: A physical impact on a bridge impeding the function of the deck or superstructure of the bridge.
        - Overtopping: A physical impact on a bridge deck or superstructure resulting from the passage of water and debris overtop of the deck or superstructure. Has “Flood” [8] [31] [62], "Fluvial Flood" [8], and “Storm Surge” [62] as potential drivers.
        - Expansion/Contraction: A physical impact on a bridge deck or superstructure resulting from the temperature driven change in size of components of the deck or superstructure. Has "Extreme Heat" [8] [62] as potential driver.
        - Removal/Collapse: A physical impact on a bridge deck or superstructure resulting from the displacement or failure of the deck or superstructure. Has “Flood” [48] [31] [50],

        "Wildfire"[8], "Tropical Cyclone" [62], and "Storm Surge" [48] as potential drivers.

    - Physical Impact on Pier/Abutment: A physical impact on a bridge impeding the function of a pier or abutment of the bridge.
        - Build-up of Debris: A physical impact on a pier or abutment resulting from the accumulation of debris disrupting water flow around the pier or abutment. Has "Flood" [8] [31] and "Fluvial Flood" [8] as potential drivers.
        - Settlement of Foundation: A physical impact on a pier or abutment and a physical impact on an embankment, cutting, or culvert resulting from the subsidence of the materials into which the foundation is anchored. Has "Permafrost Degradation" [62] as a potential driver.
        - Failure of Bank/Riprap Protection: A physical impact on a pier or abutment resulting from the severe erosion or collapse of the bank or riprap protection of the bridge. Has "Fluvial Flood" [8] and "Coastal Erosion" [3] as potential drivers.
        - Scour/Destabilization of Foundation: (elaborated under Damage to Structural Housing Element). Has "Flood" [8] [20] [62] [31], "Fluvial Flood" [8] [20], "Storm Surge" [62], and "Extreme Precipitation Hazard" [62] [48] as potential drivers.

- Physical Impact on Tunnel: A physical impact on a transportation network impeding the function of a tunnel.
    - Blockage of Portal: A physical impact on a tunnel resulting from the obstruction of an entrance to the tunnel. Has "Rock Fall" [8] and "Earth Flow" [62] as potential drivers.
    - Inundation: (elaborated under Physical Impact on Electrical Station). Has "Flood" [62] [48], "Storm Surge" [62], "Pluvial Flood" [62], "Groundwater Flood" [48], "Extreme Precipitation Hazard" [62], and "Convective Hazard" [48] as potential drivers.
    - Degradation of Support Structure: A physical impact on a tunnel resulting from the deformation, melting, corrosion, or erosion of walls, reinforcing bars, and lining of the tunnel. Has "Mass Movement" [8], "Extreme Precipitation Hazard" [62], "Wildfire" [8], "Rainfall Flood" [62], "Coastal Flood" [62], and "Saltwater Intrusion" [62] as potential drivers.
- Physical Impact on Embankment/Cutting/Culvert: A physical impact on a transportation network impeding the function of an embankment, cutting, or culvert.
    - Failure of Slope: A physical impact on an embankment, cutting, culvert, or railway resulting from the erosion, instability, and eventually failure and collapse of the material making up the slope of the embankment or cutting. Has "Pluvial Flood" [8], "Sliding Mass Movement" [8], "Debris Flow" [8], "Mud Flow" [8], "Drought" [8], "Extreme Precipitation Hazard" [23] [62], "Extreme Heat" [8], and "Permafrost Degradation" [62] as potential drivers.
    - Scour/Destabilization of Foundation: (elaborated under Damage to Structural Housing Element). Has "Fluvial Flood" [8] as a potential driver.
    - Foundation Settlement: (elaborated under Physical Impact to

Pier/Abutment). Has “Permafrost Degradation” [62] and “Pluvial Flood” [8] as potential drivers.

- Washout: (elaborated under Physical Impact on Road). Has “Extreme Precipitation Hazard” [62], “Flood” [8] [62], and "Fluvial Flood" [8] as potential drivers.

Non-Physical Impact:
An impact of a CCDNH impeding the ability of a physical asset to fulfill its intended function without changing the structure or state of the asset.

- Non-Physical Impact on Housing: A non-physical impact impeding the function of a building providing housing.
    - Depression of Property Value: A non-physical impact on housing resulting from the decrease of the value of the building, unit, or land parcel. Has "Flood" [9] [39] [34] [70], “Fluvial Flood” [9], “Pluvial Flood” [9], “Coastal Flood” [9] [34], “Storm Surge” [9], “Mass Movement” [66], and "Tropical Cyclone" [34] as potential drivers.
    - Inflation of Insurance Premium: A non-physical impact on housing resulting from the increase of the cost of insuring the building, unit, or land parcel. Has "Flood" [70] and "Extreme Heat" [91] as potential drivers.
    - Rise in Utilities Bill: A non-physical impact on housing resulting from the increase of the sum regularly owed to pay for the utilities, like electricity and water, used by the building. Has "Extreme Heat" [60] [90] and "Drought" [60] as potential drivers.
- Non-Physical Impact on Critical Infrastructure Network: A non-physical impact impeding the function of an infrastructure network providing or supporting the goods and services necessary to maintain the full functionality of housing.
    - Non-Physical Impact on Critical Infrastructure Operation: A non-physical impact on a critical infrastructure network impeding the smooth operation of the network.
        - Non-Physical Impact on Transportation Network Operation: A non-physical impact on the operation of a critical infrastructure network impeding the transportation of goods and people to and from housing.
            - Reduction in Visibility: A non-physical impact on the operation of a transportation network resulting from the decrease in the possible visible distance on the network. Has "Wildfire" [8] [62], “Drought” [88], and “Extreme Precipitation Hazard” [1] [6] as potential drivers.
            - Rise in Vehicle Hours of Delay: A non-physical impact on the operation of a transportation network resulting from the increase of the aggregate delay time of all the vehicles simultaneously on the network. Has “Extreme Precipitation Hazard” [88] [62] [48] [7], "Tropical Cyclone" [62], “Extreme Heat” [62] [48], “Coastal Flood” [62] [48], and "Flood" [88] [48] as potential drivers.
            - Rise in Vehicle Accident Rate: A non-physical impact on the operation of a transportation network resulting from the increase of the rate of accidents involving the vehicles on the network. Has "Extreme Precipitation Hazard" [88] [62] [48] [1] [26] [6] [7], "Flood" [62], “Severe Thunderstorm” [88] [6], “Hail Storm” [6], and "Convective Hazard" [62] as potential drivers.
        - Non-Physical Impact on an Emergency Services Network Operation: A non-physical impact on the operation of a critical infrastructure network impeding the provision of emergency services to housing.
            - Cessation of Service: A non-physical impact on the operation of an

emergency services network resulting from the complete loss of function of an emergency facility providing emergency services. Has “Tropical Cyclone” [32] and “Extreme Precipitation Hazard” [1] as potential drivers.

    - Overload of Service: A non-physical impact on the operation of an emergency services network resulting from the increase in demand on the network beyond its maximum operating capacity. Has "Extreme Heat" [89] and “Tropical Cyclone” [1] as potential drivers.
- Non-Physical Impact on Critical Infrastructure Maintenance: A non-physical impact on a critical infrastructure network impeding the ability of the network to be maintained according to its operating specifications.
    - Reduction in Workable Maintenance Hours: A non-physical impact on the maintenance of a critical infrastructure network resulting from the decrease in the number of hours in which maintenance work to the network and its components may be safely conducted. Has "Extreme Precipitation Hazard" [62] [1] and "Extreme Heat" [62] [48] as potential drivers.
    - Rise in Maintenance Costs: A non-physical impact on the maintenance of a critical infrastructure network resulting from the increase of the per unit or per hour cost of conducting maintenance work on the network and its components. Has "Tropical Cyclone" [48], “Severe Thunderstorm” [62], “Extreme Heat” [62] [48], “Drought” [48], “Extreme Precipitation Hazard” [62], “Erosion” [23], “Permafrost Degradation” [62] [48], “Coastal Flood” [62], “Fluvial Flood” [8] and "Flood" [8] [62] [48] as potential drivers.

Class Design:

In a notable departure from Table 3, Table 12 assigns every leaf class a driving hazard. These are appended to their definitions and may include one or more driving hazards. These are a selection of CCDNHs which are cited in the reviewed literature as being able to give rise to the impact to which they are appended. Each of the potential driving hazards references a corresponding class in Table 3’s taxonomy of hazards and is used to inform the traceability criterion of Table 3.

Another difference between the taxonomies is that Table 12 only provides citations for leaf classes as opposed to Table 3’s approach of providing citations for all classes aside from the root class. This is because the non-leaf classes of Table 12 and their definitions are included purely as organizational tools used to understand the relationships between the formally established leaf impact classes. While some classes take inspiration from organizational decisions in the literature, none appear in the taxonomy exactly as they are represented in the literature.

Organizational Design:

The root class of Table 12, “Impact of CCDNH”, plays a similar role to the root class of Table 3: it defines the central topic of the taxonomy as well as the characteristics shared across all of its classes (the eligibility criterion). Unlike in Table 3 however, this root class is not reliant on a set of specific definitions from the literature. The evaluation of the impacts of hazards on assets of interest is widespread in the reviewed literature. Sources performing these evaluations typically define their own sets of hazards and assets of interest, as is done in this survey.

Below the root class, the taxonomy of impacts is first divided based on whether the mechanism of the impact results in a change of the state or structure of the asset. This binary split results in the classes “Physical Impact” and “Non-Physical Impact”. Distinguishing between physical and non-physical impacts is important because the response and adaptation to each type of impact has the potential to differ significantly. Responding and adapting to physical impacts generally involves making changes to the physical structure of the asset or to the maintenance of its physical structure (Argyroudis et al. 2019, 2)(National Academies of Sciences, Engineering, and Medicine 2014, 10)(Papathoma-Köhle 2019, 7). Meanwhile, the response and adaptation to non-physical impacts is primarily approached by changing the policies governing the operation and maintenance of the impacted asset (Gourevitch et al. 2023, 256)(National Academies of Sciences, Engineering, and Medicine 2014, 8).

<u>Physical Impact</u>:

“Physical Impact” possesses two subclasses: “Physical Impact on Housing” and “Physical Impact on Critical Infrastructure Network”. These subclasses are differentiated by the asset class they impact, a subclassing justification which is used repeatedly throughout this taxonomy. Housing and critical infrastructure networks represent vastly different assets in terms of the impact-vulnerable components they contain. Relative to critical infrastructure networks, housing is less structurally complex since housing is regarded by this survey to include just buildings providing housing. Even as these buildings vary in shape, size, and design, they can be reasonably generalized to possess a relatively concise set of characteristics (walls, roof, fenestration, etc…)(Dabbeek et al. 2020, 786)(FEMA 2024a, 4-8-4-15). Critical infrastructure networks, however, vary significantly based on the type of service they provide (Joint Research Centre 2013, 16, 36)(FEMA 2024a, 7-1-10-19).

<u>Physical Impact on Housing</u>:

The physical impacts of CCDNHs on housing included in the taxonomy of impacts are pulled from a mix of descriptions of damage states and other less organized references to specific impacts in the reviewed literature. Tables 13a and 13b provide a tabulation of some of the impacts on housing alongside how their presence is distributed across the reviewed sources. The sources included in Table 13 are limited to those which discuss two or more of the physical impacts on housing in Table 12. A result of this source selection is that the impact class “Mold Growth” is not associated with any of the sources included in Table 13 despite being discussed in by two reviewed sources (Angel et al. 2018, 21)(Merz et al. 2010, 1708).

In the taxonomy of impacts, these classes are first grouped based on the type of housing component being impacted. The taxonomy differentiates between non-structural building elements, structural building elements, and entire building structures (Ginger et al. 2007, 215)(Brzev 2013, 2)(Luo et al. 2023, 7)(Friedland 2009, 25)(Schwarz and Maiwald 2003, 4)(Papathoma-Köhle 2022, 7). These different types of components act as a proxy for the severity of the impact on housing: impact severity increases from non-structural elements to structural elements and from structural elements to the entire building structure.

Table 13 demonstrates that the subclasses assigned to “Physical Impact on Non-Structural Housing Element” are an amalgamation of different sources with no one source spanning all of them. These subclasses are split based on the specific non-structural housing element being impacted (roof component, wall cladding, appurtenant structure, etc…). This form of subclassing is regularly applied to housing elements in the literature (Friedland 2009, 56)(FEMA 2024b, 5-176-5-179).

The class representing the second of the three housing element types, “Physical Impact on Structural Housing Element”, is split into two subclasses on the basis of the level of impact: damage and destruction (Ettinger et al. 2016, 564)(Friedland 2009, 46). Similarly to the different structural elements, these levels represent different intensities of impact. Each side of this split is assigned its own subclasses which are once again amalgamated from the sources included in Table 13. Two sources, Luo et al. (2023) and Friedland (2009), include nearly all of the leaf impact classes on structural elements, each missing only one. The subclasses of “Damage to Structural Housing Element” are divided based on the mode of impact while the subclasses of “Destruction of Structural Housing Element” are divided based on the element impacted. This difference in division approach is a result of the perceived greater modal breadth of *damage* relative to *destruction*.

“Physical Impact on Housing Structure”, the third type category of housing elements, is only divided into two subclasses: “Removal/Slippage from Foundation” and “Partial/Complete Building Collapse”. These classes are made distinct by their mechanism of impact (FEMA 2024b, 5-179)(Friedland 2009, 56)(Luo et al. 2023, 6-7). Notably, the removal or slippage of a building’s superstructure over its foundation can occur independently of the partial or complete collapse of that superstructure (FEMA 2024b, 5-179).

Table 13a: Physical Impact on Housing Summary

Source *	Physical Impact on Non-Structural Housing Element							
	Loss of Roof Component	Water Damage to Interior	Failure of Fenestration	Damage to Wall Cladding	Melting of Aluminium Frame/ Shutter	Removal of Appurtenant Structure	Inundation of Basement	Mold Growth
(Alexander 1993, 169-170, 176-180)								
(Ettinger et al. 2016, 572)								
(FEMA 2024b, 5-97-5-99, 5-176-5-179)								
(Friedland 2009, 25, 56)								
(Ginger et al. 2007, 217, 220)								
(Luo et al. 2023, 4, 6-7)								
(Papathoma-Köhle et al. 2007,)								
(Papathoma-Köhle et al. 2022, 7)								
(Pita et al. 2012, 81-82)								
(Quesada-Ganuza, Garmendia, and Gandini 2023, 28)								
(Schwarz 2009, 3)								

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

Table 13b: Physical Impact on Housing Summary (cont'd)

Source *	Physical Impact on Structural Housing Element							Physical Impact on Housing Structure	
	Damage to Structural Housing Element			Destruction of Structural Housing Element					
	Cracking of Supporting Elements	Racking of Elevated Structure	Scour/Destabilization of Foundation	Failure of Roof Structure	Failure of Wall	Failure of Column	Failure of Foundation	Removal/ Slippage from Foundation	Partial/ Complete Building Collapse
(Alexander 1993, 169-170, 176-180)									
(Ettinger et al. 2016, 572)									
(FEMA 2024b, 5-97-5-9, 5-176-5-179)									
(Friedland 2009, 25, 56)									
(Ginger et al. 2007, 217)									
(Luo et al. 2023, 4, 6-7)									
(Papathoma-Köhle et al. 2007,)									
(Papathoma-Köhle et al. 2022, 7)									
(Pita et al. 2012, 81-82)									
(Quesada-Ganuza, Garmendia, and Gandini 2023, 28)									
(Schwarz 2009, 3)									

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

Physical Impact on Critical Infrastructure:

Given the much wider variety of functions and components contained under the umbrella of critical infrastructure, the class “Physical Impact on Critical Infrastructure Network” is subdivided based on the service provided by the network before considering individual impacts. This results in the classes “Physical Impact on Electrical Network”, “Physical Impact on Natural Gas Transportation and Distribution Network”, “Physical Impact on Water Supply/Wastewater Network”, “Physical Impact on Solid Waste Network”, “Physical Impact on Information and Communication Technology (ICT) Network”, “Physical Impact on Emergency Services Network”, and “Physical Impact on Transportation Network”. Each is concerned with a specific infrastructure network which provides services to housing which are critical to its full functionality. The specific services selected to count as critical infrastructure are inspired by classifications from a variety of sources in the literature (Dawson et al. 2018, 11)(Pitlakis et al. 2014, 9-10)(Joint Research Centre 2013, 1). Notably, the second two of these sources are concerned with SYNER-G, an integrated methodology for evaluating the vulnerability of buildings, infrastructure, and critical facilities to seismic events. Pitlakis et al. (2014) and the Joint Research Centre (2013) present taxonomies of all of the assets included in SYNER-G as well as the important components of these assets. While seismic events are not considered to be CCDNHs, SYNER-G’s asset taxonomies help shape the assets and components considered critical enough for inclusion into Table 12.

The first infrastructure network specific subclass of Table 12 is “Physical Impact on Electrical Network”. Table 14 contains all of the leaf impact classes on electrical networks present in the literature. The table also shows the distribution of the impacts across the sources which discuss two or more of those impacts. Of the four sources included in Table 14, one source, the USGCRP chapter on *Energy Supply, Delivery, and Demand*, (Zamuda et al. 2018), includes all the impacts in the table. However, no source in the table groups the impacts beyond clarifying that they are impacts on energy infrastructure (Wilbanks and Fernandez 2014, 42)(Zamuda et al. 2018, 177). Table 12 nevertheless introduces three subclasses to “Physical Impact on Electrical Network”, dividing it based on the class of electrical network component being impacted: “Physical Impact on Electrical Station”, “Physical Impact on Electrical Line”, and “Brownout/Blackout of Grid”. These groupings of electrical network components are borrowed from the SYNER-G Taxonomy for Electrical Power Network (Joint Research Centre 2013, 36), representing the classes *Line*, *Station*, and *Network* respectively. The physical impacts on stations and lines are further subclassed with impacts on stations being split by impact mechanism (Zamuda et al. 2018, 177) and impacts on lines by impacted component (Dawson et al. 2018, 6)(Zamuda et al. 2018, 177).

Table 14: Physical Impact on Electrical Network Summary

Source *	Physical Impact on Electrical Station			Physical Impact on Electrical Line		Brownout/ Blackout of Grid
	Inundation	Disruption of Hydropower Plant Generating Capacity	Disruption of Power Plant Cooling	Damage to Overhead Line	Toppling of Pylon	
(Dawson et al. 2018, 6)						
(Maxwell et al. 2018, 445, 447, 451)						
(Wilbanks and						

Fernandez 2014, 42-43)						
(Zamuda et al. 2018, 177, 181)						

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

Table 12's second infrastructure network specific subclass is "Physical Impact on Natural Gas Transportation and Distribution Network". This class limits its focus to the transportation and distribution of natural gas. The network components involved in the collection and refining of natural gas are not considered to be critical to housing in the immediate term aftermath of a CCDNH. The literature only includes two specific impacts on the natural gas network components responsible for transportation and distribution: "Scour/Destabilization of Foundation" (Markon et al. 2018, 1197)(Zamuda et al. 2018, 179, 180) and "Damage to Pumping Station" (Zamuda et al. 2018, 180). These classes are made distinct by the specific natural gas network components they impact (Joint Research Centre 2013, 40-41)(Pitilakis 2014, 8) and both are included as direct subclasses of "Physical Impact on Natural Gas Transportation and Distribution Network".

The third subclass of impacted critical infrastructure networks, "Physical Impact on Water Supply/Wastewater Network", is summarized in Table 15. Of the four sources included in Table 15 none propose specific classifications for the impacts they discuss. In contrast, Table 12 proposes three direct subclasses of "Physical Impact on Water Supply/Wastewater Network" which are distinguished from one another by the water network component being impacted. These components are treatment sites, sewers, and reservoirs respectively which roughly aligns with the treatment plant, tunnel, and open cut reservoir asset classes from SYNER-G (Joint Research Centre 2013, 51-53)(Pitilakis 2014, 8). "Physical Impact on Water Supply/Wastewater Treatment Site" is subclassed further to account for three specific impacts on treatment sites, each of which is unique in its mechanism of impact (Dawson et al. 2018, 6, 11)(Markon et al. 2018, 1202): "Obstruction of Treatment Site Chemical Supply", "Disruption of Water Supply Quality", and "Inundation".

Table 15: Physical Impact on Water Supply/Wastewater Network Summary

Sources *	Physical Impact on Water Supply/Wastewater Treatment Site			Sewer Overflow	Overtopping/ Failure of Dam
	Obstruction of Treatment Site Chemical Supply	Disruption of Water Supply Quality	Inundation		
(Angel et al. 2018, 900)					
(Dawson et al. 2018, 6, 9, 11)					
(Markon et al. 2018, 1202)					
(Maxwell et al. 2018, 444, 451)					

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

“Physical Impact on Solid Waste Network”, the fourth subclass of “Physical Impact on Critical Infrastructure Network”, possesses only one specific physical impact in the reviewed literature: “Inundation” (Dawson et al. 2018, 11)(Sayers et al. 2015, 25) and “Obstruction . This class represents both the potential inundation of landfills (Sayers et al. 2015, 25) and the potential inundation of infrastructure necessary to the transportation of solid waste (Dawson et al. 2018, 11).

The next type of critical infrastructure networks considered in Table 12 is information and communication technology (ICT) networks. Only two specific CCDNH impacts on such networks are identified in the literature: “Damage to Base Station/Cellular Tower” (Alexander 1993, 169)(Dawson et al. 2018, 10-11)(Wilbanks and Fernandez 2014, 53) and “Damage to Line” (Alexander 1993, 186, 202-203)(Wilbanks and Fernandez 2014, 53). These classes are separated from one another by the ICT network component being affected. The sources discussing these impacts provide no formal classification of these impacts and SYNER-G does not propose any classification of ICT networks. Thus, the division of these leaf impact classes relies on the fact that only three network components are ever discussed in the reviewed literature: stations (Alexander 1993, 202)(Dawson et al. 2018, 11)(Wilbanks and Fernandez 2014, 53), towers (Alexander 1993, 169)(Wilbanks and Fernandez 2014, 53), and lines (Alexander 1993, 186, 203)(Wilbanks and Fernandez 2014, 53). In the leaf impact class “Damage to Base Station/Cellular Tower”, stations and towers are combined (Kuai, Zhao, and Guo 2024, 8) under assumption that they often occupy the same site.

“Physical Impact on Emergency Services Network” is the second to last subclass of “Physical Impact on Critical Infrastructure Network”. This class is assigned two component-defined subclasses which concern physical impacts on the emergency facilities and emergency services transportation infrastructure respectively. The introduction of the subclass “Obstruction/Burying” as a subclass accounts for the description that Papathoma-Köhle et al. (2007) provide of the impact that the blockage or roads has on emergency services networks (775-776). Outside of this source, emergency service networks tend to be defined using only the specific emergency facilities they contain, ignoring transportation infrastructure (Joint Research Centre 2013, 68-71)(Pitilakis et al. 2014, 9)(Sayers et al. 2015, 24-25, 114)(FEMA 2024a, 7-5). “Physical Impact on Emergency Facility” is split into three subclasses on the basis of the specific components of these emergency facilities (FEMA 2024b, 5-254)(Sayers et al. 2015, 24). All three are subclasses shared with “Physical Impact on Non-Structural Housing Element”.

<u>Physical Impact on Transportation Network</u>:

The final and broadest subclass of “Physical Impact on Critical Infrastructure Network” is “Physical Impact on Transportation Network”. The class is divided into subclasses representing major components of transportation networks: “Physical Impact on Road”, “Physical Impact on Bridge”, “Physical Impact on Tunnel”, “Physical Impact on Embankment/Cutting/Culvert”, and “Physical Impact on Railway”. This selection of components is inspired by the a series of transportation asset classifications in the literature (Argyroudis et al. 2019, 6)(FEMA 2024a, 9-1-9-17)(Joint Research Centre 2013, 55-61)(Pitilakis et al. 2014, 9). Notably, Table 12 excludes harbors (FEMA 2024a, 9-17-9-18)(Joint Research Centre 2013, 61-64)(Pitilakis et al. 2014, 9), airports (FEMA 2024a, 9-19-9-20), and public transportation (FEMA 2024a, 10-6-9-19). Each of these assets can compellingly be argued to be critical to housing: harbours and airports may be the only lifelines for isolated communities and public transportation is often essential to mobility in urban areas. However, the literature does not provide substantial enough discussion of CCDNH impacts on these assets to warrant their inclusion.

Roads, the first set of impacted transportation network components, are identified as being susceptible to five major CCDNH impacts from the literature: “Obstruction/Burying”, “Washout”, “Damage to Surface”, “Destabilization of Base”, and “Inundation”. Each class is made unique by the specific mechanism of its impact on roads. These subclasses are represented in Table 16 alongside their distribution across some sources in the literature. The table demonstrates that three sources, Jacobs et al. (2018), the National Academies of Sciences, Engineering, and Medicine (NASEM) (2014), and Argyroudis et al. 2019, discuss all or most of the impacts on roads. NASEM (2014) and Argyroudis et al. (2019) present particularly helpful classifications of mechanism-delineated impacts, going as far as to organize them by specific CCDNH (National Academies of Sciences, Engineering, and Medicine 2014, 6-7)(Argyroudis et al. 2019, 3).

Table 16: Physical Impact on Road Summary

Sources *	Obstruction/ Burying	Washout	Damage to Surface	Destabilization of Base	Inundation
(Argyroudis et al. 2019, 3)					
(Dawson et al. 2018, 11-12)					
(Jacobs et al. 2018, 485, 487, 489)					
(Markon et al. 2018, 1197)					
(National Academies of Sciences, Engineering, and Medicine 2014, 6-7)					

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

The second subclass of “Physical Impact on Transportation Network” is “Physical Impact on Railway”. As shown in Table 17, this impact class is itself split into four subclasses on the basis of the unique mechanical characteristics of each. None of the sources in Table 17 contain all four of the impacts but three contain all but one (Dawson et al. 2018)(National Academies of Sciences, Engineering, and Medicine 2014)(Wang et al. 2020). Of these, Dawson et al. (2018) provide the clearest classification of the impacts on railways by organizing mechanically-distinct impacts on transportation infrastructure relative to the level of global temperature change (11). A CCDNH-divided impact classification is provided by Wang et al. (2020) though mechanism-based separation between individual impacts is less clear (7).

Table 17: Physical Impact on Railway Summary

Sources *	Buckling of Rail	Obstruction/Burying	Failure of Slope	Inundation

(Dawson et al. 2018, 11)				
(Jacobs et al. 2018, 481)				
(National Academies of Sciences, Engineering, and Medicine 2014, 37)				
(Wang et al. 2020, 7)				

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

The next impact subclass of “Physical Impact on Transportation Network” involves physical CCDNH impacts on bridges. As summarized in Table 18, “Physical Impact on Bridge” is first divided based on the bridge component subject to impact into “Physical Impact on Bridge Deck/Superstructure” and “Physical Impact on Pier/Abutment”. The classification of bridge components is shown by the literature to vary significantly by application (Argyroudis et al. 2019, 6)(FEMA 2024a, 9-6)(Joint Research Centre 2013, 19). Piers, abutments, decks, and superstructures are all included in the literature, but their specific groupings in Table 18 are meant to allow for the distinction between impacts to components interfacing with the ground and those interfacing solely with other bridge components.

Physical Impact on Bridge Deck/Superstructure” is assigned three subclasses of its own, each representing a unique mechanism of impact on decks and superstructures. Though not organized as in Table 12, all three of these impact mechanisms are found in NASEM (2014). “Physical Impact on Pier/Abutment” includes its own set of four subclasses. Similarly to the impacts on decks and superstructures, the impacts on piers and abutments are delineated by their mechanisms of impact. No one source discusses all four of the impact classes. Argyroudis et al. (2019) provides the most complete tabulation, including the classes “Build-up of Debris”, “Failure of Bank/Riprap Protection”, and “Scour/Destabilization of Foundation” (2-3).

<u>Table 18</u>: Physical Impact on Bridge Summary

Sources *	Physical Impact on Bridge Deck/Superstructure			Physical Impact on Pier/Abutment			
	Overtopping	Expansion/ Contraction	Removal/Collapse	Build-up of Debris	Settlement of Foundation	Failure of Bank/Riprap Protection	Scour/Destabilization of Foundation
(Argyroudis et al. 2019, 2-3)							
(FEMA 2024c, 9-2-9-3)							
(Jacobs et al. 2018, 485-486)							
(National Academies of Sciences, Engineering, and Medicine 2014, 6-7, 127)							

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

The class “Physical Impact on Tunnel” is summarized in Table 19. It is assigned three mechanically-distinct subclasses: “Blockage of Portal”, “Inundation”, and “Degradation of Support Structure”. Only two sources in the reviewed literature, Argyroudis et al. (2019) and NASEM (2014), discuss two or more of the impacts, and only NASEM include all three. Both sources distinguish impacts mechanically and Argyroudis et al. (2019) clearly tabulate tunnel-specific impacts (3).

Table 19: Physical Impact on Tunnel Summary

Sources *	Blockage of Portal	Inundation	Degradation of Support Structure
(Argyroudis et al. 2019, 3)			
(National Academies of Sciences, Engineering, and Medicine 2014, 6-7)			

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

“Physical Impact on Embankment/Cutting/Culvert”, the final subclass of “Physical Impact on Transportation Network”, amalgamates three similar transportation network components: embankments, cuttings, and culverts. This amalgamation is inspired by the SYNER-G transportation asset taxonomies which refer to “embankments, trenches, and slopes” (Joint Research Centre 2013, 55)(Pitilakis 2014, 9) and the classifications of Argyroudis et al. (2019) which use the asset category “cuttings/slopes/embankments”(3). Embankments, cuttings, and culverts are all forms of sloped earthwork which share susceptibility to similar CCDNH impacts. All are also critical to the structural integrity and durability of other transportation network components like roads and railways (Joint Research Centre 2013, 56, 58)(Pitilakis 2014, 9). The four impacts on embankments, cuttings, and culverts are separated by impact mechanism and summarized in Table 20. Similarly to the physical impacts on tunnels in Table 19, only Argyroudis et al. (2019) and NASEM (2014) discuss two or more of the impacts. Argyroudis et al. (2019) include all four of the impacts and once again organizes them into a clear, mechanism-separated tabulation (3).

Table 20: Physical Impact on Embankment/Cutting/Culvert Summary

Sources *	Failure of Slope	Scour/Destabilization of Foundation	Foundation Settlement	Washout
(Argyroudis et al. 2019, 3)				
(National Academies of Sciences, Engineering, and Medicine 2014, 6-7, 90)				

* The inclusion of sources is limited to those discussing two or more of the impacts in the table.

Non-Physical Impact:

“Non-Physical Impact” represents the second major branch of CCDNH impact classes. Reflecting the subclassing of “Physical Impact”, “Non-Physical Impact” is first split into “Non-Physical Impact on

Housing” and “Non-Physical Impact on Critical Infrastructure Network”. This is once again a division made based on the asset being impacted. The justification for this subdivision is the same as the one used to subdivide “Physical Impact”(Argyroudis et al. 2019, 2)(Gourevitch et al. 2023, 256)(National Academies of Sciences, Engineering, and Medicine 2014, 8, 10)(Papathoma-Köhle 2019, 7).

The first branch, “Non-Physical Impacts on Housing”, is much more sparsely populated than its physical counterpart, only possessing three subclasses. This reflects the scarcity of specific non-physical CCDNH impacts on housing in the reviewed literature, which is largely focussed on the immediate-term physical effects of CCDNHs on the built environment. The three subclasses, “Depression of Property Value” (Armal et al. 2020, 12)(Fleming et al. 2018, 329-330)(Gourevitch 2023, 250)(Papathoma-Köhle et al. 2007, 777)(Public Safety Canada 2024, 98), “Inflation of Insurance Premium” (Public Safety Canada 2024, 98)(Zhang et al. 2008, 270), and “Rise in Utilities Bill” (Maxwell et al. 2018, 441, 447)(Zamuda et al. 2018, 176), are made distinct by the specific non-physical properties of housing which each impacts. While no source in the literature discusses all three of these impacts, Public Safety Canada (2024) does approach formally classifying two of them, labelling the devaluation of properties and increasing insurance premiums as “possible losses”(98) in the face of flooding.

“Non-Physical Impact”’s second branch concerns non-physical impacts on critical infrastructure networks and is summarized in Table 21. The first split of this branch produces the subclasses “Non-Physical Impact on Critical Infrastructure Network Operation” and “Non-Physical Impact on Critical Infrastructure Network Maintenance”. The operation and maintenance of critical infrastructure networks are separated on the basis that each is a unique component process of network function and each is susceptible to a distinct set of non-physical impacts (Eidsvig, Kristensen, and Vangelsten 2017, 485)(National Academies of Sciences, Engineering, and Medicine 2014, 42, 44-47).

“Non-Physical Impact on Critical Infrastructure Network Operation” is itself assigned two subclasses representing impacts on the operations of infrastructure networks providing two different services: transportation and emergency services. This division is justified in the same way as the service-based division of physical impacts on critical infrastructure networks (Dawson et al. 2018, 11)(Pitlakis et al. 2014, 9-10)(Joint Research Centre 2013, 1). The class “Non-Physical Impact on Transportation Network Operation” is assigned three mode-distinct subclasses: “Reduction in Visibility”, “Rise in Vehicle Hours of Delay”, and “Rise in Vehicle Accident Rate”. These three categories are most directly borrowed from the tabulations of climate change impacts on transportation infrastructure presented by NASEM (2014) and Wang et al. (2020). As seen in Table 21, both of these sources include all three of the classes (National Academies of Sciences, Engineering, and Medicine 2014, 6)(Wang et al. 2020, 7). The class of non-physical impacts concerned with the operation of emergency services networks is divided into two subclasses based on impact mode. Only one source from the literature, Alexander (1993), discusses both of these impacts. Other sources not included in Table 21 do discuss one class or the other but none of those classes are included in Table 21 (these can be found in Table 12). Alexander (1993) discusses these impacts separately (169, 205), providing little precedent for the mode separation of these classes in Table 12.

The second subdivision of non-physical impacts on critical infrastructure networks, “Non-Physical Impact on Critical Infrastructure Network Maintenance”, possesses two subclasses representing impacts on the number of workable maintenance hours and the cost of maintenance respectively. Jacobs et al. (2018) provides discussions of the two subclasses but stops short of categorizing them (489). Meanwhile, NASEM (2014) includes both in a formal mode-separated tabulation (6), justifying the separation by mode of these classes in Table 12.

Table 21: Non-Physical Impact on Critical Infrastructure Network Summary

Sources *	Non-Physical Impact on Critical Infrastructure Network Operation					Non-Physical Impact on Critical Infrastructure Network Maintenance	
	Non-Physical Impact on Transportation Network Operation			Non-Physical Impact on Emergency Services Network Operation		Reduction in Workable Maintenance Hours	Rise in Maintenance Costs
	Reduction in Visibility	Rise in Vehicle Hours of Delay	Rise in Vehicle Accident Rate	Cessation of Service	Overload of Service		
(Alexander 1993, 169, 201, 203-205)							
(Andrey et al. 2003, 320)							
(Angel et al. 2018, 900-901)							
(Argyroudis et al. 2019, 2-3)							
(Jacobs et al. 2018, 487, 489)							
(National Academies of Sciences, Engineering, and Medicine 2014, 6-8)							
(Wang et al. 2020, 7)							

Taxonomies of Risk Factors

The third and final taxonomy presented by this survey is the taxonomy of risk factors presented in Table 22. Similarly to the taxonomy of impacts, Table 22 relies on a single, 'eligibility' criterion to dictate the inclusion and exclusion of potential impact classes. Here however, this criterion is subdivided to fit each of the three the major sections of the taxonomy:

1. Eligibility: Is eligible to be included in Table 22. Factor classes eligible for inclusion represent direct influences on the probability and consequence of a CCDNH. This criterion is interpreted separately for each the classes contained within each of the three major sections of the taxonomy

(factors impacting CCDNH frequency and/or magnitude, factors impacting asset vulnerability, and factors impacting asset exposure):

   a. Eligible factors affecting frequency and/or magnitude are characteristics or forces in the environment that exert direct influence on the mechanism of a CCDNH.
   b. Eligible factors affecting asset vulnerability are characteristics of assets of interest which directly influence the susceptibility of those assets to a given CCDNH.
   c. Eligible factors affecting asset exposure are characteristics of assets of interest which directly influence measures of the presence and/or value of those assets in a given area.

The factor classes excluded by this eligibility criterion largely fall short of the criterion's requirement of directness. Factors which act upon the probability or consequence of a CCDNH through an already included intermediary factor are considered indirect. Without non-eligibility criteria, the taxonomy of impacts is not subject to the truncation of classes.

Table 22: Taxonomy of Risk Factors Influencing the Probability and Consequences of CCDNHs

ROOT CLASS **CCDNH Risk Factor:** An element influencing the probability and consequence of a CCDNH. The probability and consequence of a CCDNH may be represented by the frequency and/or magnitude of the CCDNH, the vulnerability of assets of interest to the CCDNH, or the exposure of assets of interest to the CCDNH.
Factor Impacting CCDNH Frequency and/or Magnitude: A CCDNH risk factor capable of influencing the frequency and/or magnitude of a CCDNH in a geographical area of interest.
● Factor Impacting Flood Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either flood rate of occurrence or flood size and severity. ○ Transitory Factor Impacting Flood Frequency and/or Magnitude: A factor impacting flood frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales. ■ Precipitation: (elaborated under Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude) [11] [18] [73] [71] [79] [82] [88] [63] [87] [21] [23] [74] [89] [30] [8] [62] [48] [60] [34] [35] [1] [85] [26] [54] [70] [2] [90] [7] [41] ■ Sea Level/Tide Range: A transitory factor impacting flood, and erosion, saltwater intrusion, and permafrost degradation frequency and/or magnitude resulting from the average elevation of the sea surface and the range of tidal values experienced. [9] [11] [18] [73] [71] [52] [23] [74] [89] [8] [62] [48] [34] [35] [1] [26] [29] [70] [90] [58] [41] ■ Snowmelt/Icemelt: A transitory factor impacting flood, mass movement, drought, erosion, and snow avalanche frequency and/or magnitude resulting from the melting of accumulated snow or ice, the timing of the melting, and the volume of water produced. [79] [82] [87] [21] [62] [48] [1] [26] [70] [41] ■ Seasonality: A transitory factor impacting flood, convective hazard, snow avalanche, extreme precipitation hazard, and extreme heat frequency and/or magnitude resulting from the time of year and associated meteorological factors. [18] [79] [82] [63] [87] [74] [62] [34] [1] [70] [3] [58]

        - Soil Moisture: A transitory factor impacting flood, mass movement, and erosion frequency and/or magnitude resulting from the amount of water accumulated in the soils making up the ground. [18] [79] [82] [74] [1] [2]
        - Evapotranspiration: (elaborated under Transitory Factor Impacting Drought Frequency and/or Magnitude) [79] [74] [1]
        - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [18] [63] [30] [1] [85] [70] [7]
    - Terrain Factor Impacting Flood Frequency and/or Magnitude: A factor impacting flood frequency and/or magnitude resulting from a characteristic of the relief, composition, or location.
        - Slope: A terrain factor impacting flood, mass movement, erosion, and snow avalanche frequency and/or magnitude, a spatial factor impacting housing flood, mass movement, and wildfire vulnerability, and a spatial factor impacting critical infrastructure mass movement and extreme precipitation hazard vulnerability resulting from the angle of the land surface. [11] [73] [63] [28] [1]
        - Aspect: A terrain factor impacting flood, mass movement, erosion, and snow avalanche frequency and/or magnitude resulting from the cardinal direction faced by a slope. [4] [63] [27] [1]
        - Curvature: A terrain factor impacting flood, mass movement, and snow avalanche frequency and/or magnitude resulting from the shape of the land surface (i.e. concave, convex, or flat). [63]
        - Elevation: A terrain factor impacting flood and mass movement frequency and/or magnitude, a spatial factor impacting critical infrastructure flood and saltwater intrusion vulnerability, and a spatial factor impacting housing convective hazard and wildfire vulnerability resulting from the altitude above sea level. [9] [73] [79] [82] [52] [63] [87] [48] [35] [26] [54] [3]
        - Permeability: A terrain factor impacting flood frequency and/or magnitude, a soil characteristic impacting erosion frequency and/or magnitude, and a spatial characteristic impacting critical infrastructure extreme precipitation hazard vulnerability resulting from the degree to which the material making up the land surface permits water to pass through. [18] [71] [63] [74] [30] [1] [85] [70] [7] [9] [73] [79] [82] [52] [87] [54] [3]
        - Storage Capacity/Porosity: A terrain factor impacting flood frequency and/or magnitude and a soil characteristic impacting erosion frequency and/or magnitude resulting from the volume of water able to be absorbed by the ground through percolation or infiltration, a function of whether the ground contains spaces able to be filled by fluids. [18] [79] [82] [63] [1]
        - River Density: A terrain factor impacting flood frequency and/or magnitude resulting from the length of water channels (i.e. rivers, streams, torrents) in a particular area. [63] [1]
        - Basin/Catchment Characteristic: A terrain factor impacting flood frequency and/or magnitude resulting from the specific shape, size, or location of a drainage basin or catchment. [11] [79] [82] [87] [36] [1] [29] [2]
        - Channel Characteristic: A terrain factor impacting flood frequency and/or magnitude resulting from the cross-sectional area, roughness, and flow capacity of a water channel. [11] [18] [30] [62] [1] [2] [3] [7]
        - Land Use: A terrain factor impacting flood, mass movement, convective hazard, wildfire, drought, erosion, and extreme heat frequency and/or magnitude resulting from the type human activity occurring (i.e. urban

development, crop cultivation, logging, pastoral farming, etc…). [71] [63] [48] [1] [29] [70] [2] [41]
    - Lithology: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [63] [74] [1]
  - Flood Characteristic Impacting Flood Magnitude: A factor impacting flood magnitude resulting from a specific characteristic of a flood event.
    - Flood Extent: A flood characteristic impacting flood magnitude resulting from the area of land surface inundated by the flood. [9] [11] [18] [39] [10] [79] [82] [52] [74] [30] [34] [35] [1] [29] [41] [50]
    - Inundation Depth: A flood characteristic impacting flood magnitude resulting from the depth of accumulated water in an inundated area by the flood. [9] [11] [18] [39] [10] [73] [75] [52] [37] [74] [30] [36] [8] [48] [34] [35] [1] [54] [41] [31] [50]
    - Flow Velocity: A flood characteristic impacting flood magnitude, a flow characteristic impacting erosion frequency and/or magnitude, and a snow avalanche characteristic impacting snow avalanche magnitude resulting from the rate of flow or movement of water. [11] [18] [10] [65] [75] [52] [63] [30] [36] [8] [35] [1]
    - Discharge: A flood characteristic impacting flood magnitude and a flow characteristic impacting erosion frequency and/or magnitude resulting from the volume of water passing through a point per unit time. [11] [10] [79] [82] [87] [30] [8] [34] [1] [26] [2]
    - Rate of Rise: A flood characteristic impacting flood magnitude resulting from the increase in height of the water level of the flood per unit time. [18] [10] [82] [35] [1]
    - Duration: (elaborated under Wildfire Characteristic Impacting Wildfire Magnitude) [18] [10] [75] [80] [82] [37] [87] [74] [36] [48] [35] [1] [50]
    - Debris: (elaborated under Convective Hazard Characteristic Impacting Convective Hazard Magnitude) [31]
- Factor Impacting Mass Movement Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either mass movement rate of occurrence or mass movement size and severity.
  - Transitory Factor Impacting Mass Movement Frequency and/or Magnitude: A factor impacting mass movement frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
    - Freeze/Thaw Weathering: (elaborated under Transitory Factor Impacting Erosion Frequency and/or Magnitude) [21] [44] [26] [3]
    - Desiccation: A transitory factor impacting mass movement frequency and/or magnitude resulting from the extreme drying of the ground's surface and the reduction of the shear strength of its material. [3]
    - Breakdown of Soil Structure: A transitory factor impacting mass movement frequency and/or magnitude resulting from the weathering of soils and the change of their composition, reducing soil cohesion. [21] [3]
    - Vegetation: A transitory factor impacting mass movement, flood, convective hazard, erosion, snow avalanche, permafrost degradation, and extreme heat frequency and/or magnitude, a spatial factor impacting housing flood, mass movement, wildfire, and erosion vulnerability, and a spatial factor impacting critical infrastructure mass movement, wildfire, drought, and extreme heat vulnerability resulting from the presence, type, and proximity of vegetation. [4] [21] [86]

        - Soil Moisture: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [4] [53] [3]
        - Precipitation: (elaborated under Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude) [4] [56] [21] [44] [53] [57] [3]
        - Snowmelt/Icemelt: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [21]
    - Terrain Factor Impacting Mass Movement Frequency and/or Magnitude: A factor impacting mass movement frequency and/or magnitude resulting from the relief, composition, or location.
        - Proximity to Water Body: A terrain factor impacting mass movement frequency and/or magnitude, a spatial factor impacting critical infrastructure flood, erosion, saltwater intrusion, and extreme precipitation hazard vulnerability, and a spatial factor impacting housing flood, convective hazard, and erosion vulnerability resulting from the distance from a body of water. [4] [56] [57]
        - Proximity to Road: A terrain factor impacting mass movement frequency and/or magnitude resulting from the distance from a road. [4] [57]
        - Lithology: A terrain factor impacting mass movement, flood, and snow avalanche frequency and/or magnitude resulting from the characteristics of the bedrock present. [4] [56] [63] [53] [57] [3]
        - Presence of Lateral/Underlying Support: A terrain factor impacting mass movement frequency and/or magnitude resulting from presence or absence of a slope's lateral or underlying support. [3]
        - Slope Load: A terrain factor impacting mass movement and flood frequency and/or magnitude resulting from the mass of material present applying stress to a slope. [21] [44] [3]
        - Slope: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [4] [56] [53] [57] [3]
        - Aspect: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [4] [56] [1] [57]
        - Curvature: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [57]
        - Elevation: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [4] [56] [53] [57]
        - Land Use: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [4] [21]
    - Mass Movement Characteristic Impacting Mass Movement Magnitude: A factor impacting mass movement magnitude resulting from a specific characteristic of a mass movement event.
        - Vertical/Horizontal Distance: A mass movement characteristic impacting mass movement magnitude and a snow avalanche characteristic impacting snow avalanche magnitude resulting from the vertical or horizontal distance travelled by material over the course of the event. [3]
        - Depleted Mass/Volume: A mass movement characteristic impacting mass movement magnitude, an erosion characteristic impacting erosion magnitude, and a snow avalanche characteristic impacting snow avalanche magnitude resulting from the mass or volume of material displaced in the event. [21] [3]
        - Velocity of Movement: A mass movement characteristic impacting mass movement magnitude resulting from the velocity at which material involved in

the mass movement is displaced. [56] [21] [44] [3] [86]
        - <u>Cohesion of Mass</u>: A mass movement characteristic impacting mass movement magnitude resulting from the degree to which the material involved in the mass movement remains intact. [3]
        - <u>Mechanism of Movement</u>: A mass movement characteristic impacting mass movement magnitude resulting from the mode of movement involved in the mass movement (i.e. fall, topple, slide, spread, flow, etc…). [21] [44] [3] [86]
- <u>Factor Impacting Wildfire Frequency and/or Magnitude</u>: A factor impacting CCDNH frequency and/or magnitude capable of influencing either wildfire rate of occurrence or wildfire size and severity.
    - <u>Transitory Factor Impacting Wildfire Frequency and/or Magnitude</u>: A factor impacting wildfire frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
        - <u>Fuel Characteristic Impacting Wildfire Frequency and/or Magnitude </u>: A transitory factor impacting wildfire frequency and/or magnitude resulting from a characteristic of the potential wildfire fuel available.
            - <u>Fuel Load</u>: A fuel characteristic impacting wildfire frequency and/or magnitude resulting from the amount of available fuel. [24] [64] [81] [84] [62] [3]
            - <u>Fuel Continuity</u>: A fuel characteristic impacting wildfire frequency and/or magnitude resulting from the interconnectedness of available fuel. [81] [84]
            - <u>Fuel Moisture</u>: A fuel characteristic impacting wildfire frequency and/or magnitude resulting from the water content of available fuel. [24] [81] [84]
            - <u>Fuel Type</u>: A fuel characteristic impacting wildfire frequency and/or magnitude resulting from the kinds of available fuel. [24] [81] [84] [3]
        - <u>Wind Characteristic Impacting Wildfire Frequency and/or Magnitude</u>: A transitory factor impacting wildfire frequency and/or magnitude resulting from a characteristic of ambient wind conditions.
            - <u>Wind Direction</u>: A wind characteristic impacting wildfire frequency and/or magnitude, a convective hazard characteristic impacting convective hazard magnitude, and a transitory factor impacting snow avalanche frequency and/or magnitude resulting from the direction of local winds. [81] [84] [3]
            - <u>Wind Variability</u>: A wind characteristic impacting wildfire frequency and/or magnitude resulting from the rate, magnitude, and frequency of changes to local wind direction and speed. [84] [3]
            - <u>Wind Speed</u>: (elaborated under Transitory Hazard Impacting Convective Hazard Frequency and/or Magnitude) [64] [81] [84] [3]
        - <u>Air Temperature</u>: (elaborated under Extreme Heat Characteristic Impacting Extreme Heat Magnitude) [64] [84] [70]
        - <u>Solar Radiation</u>: A transitory factor impacting wildfire, snow avalanche, and extreme heat frequency and/or magnitude resulting from the amount of solar energy reaching the earth's surface. [84]
        - <u>Precipitation</u>: (elaborated under Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude) [84] [3]
        - <u>Humidity</u>: (elaborated under Transitory Factor Impacting Convective Hazard Frequency and/or Magnitude) [84] [3]
        - <u>Atmospheric Instability</u>: (elaborated under Transitory Factor Impacting

Convective Hazard Frequency and/or Magnitude) [84]

- Terrain Factor Impacting Wildfire Frequency and/or Magnitude: A factor impacting wildfire frequency and/or magnitude resulting from a characteristic of the relief, composition, or location.
    - Topography: A terrain factor impacting wildfire frequency and/or magnitude, a spatial factor impacting housing convective hazard and snow avalanche vulnerability, and a spatial factor impacting critical infrastructure snow avalanche vulnerability resulting from the forms and features of the ground surface. [81] [84] [19] [70] [3]
    - Land Use: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [25] [64] [81] [84] [70]
- Wildfire Characteristic Impacting Wildfire Magnitude: A factor impacting wildfire magnitude resulting from a specific characteristic of a wildfire event.
    - Duration: A wildfire characteristic impacting wildfire magnitude, a flood characteristic impacting flood magnitude, a drought characteristic impacting drought magnitude, an extreme precipitation hazard characteristic impacting extreme precipitation hazard magnitude, and an extreme heat characteristic impacting extreme heat magnitude resulting from the length of time between the start of the event and the end of the event. [84] [70] [3]
    - Fireline Intensity: A wildfire characteristic impacting wildfire magnitude resulting from the released heat energy per unit length of a fireline of the wildfire. [24] [84] [19] [70] [3]
    - Rate of Spread: A wildfire characteristic impacting wildfire magnitude resulting from the distance per unit time consumed by the wildfire. [24] [84] [70] [3]
    - Spotting Activity/Distance: A wildfire characteristic impacting wildfire magnitude resulting from the ignition of new fires by burning material transported downwind from the original wildfire. [84] [3]
    - Predictability of Fire Behavior: A wildfire characteristic impacting wildfire magnitude resulting from the degree to which the intensity, direction of spread, and spotting of the wildfire can be predicted. [24] [81] [84] [19] [70]
    - Pyrocumulonimbus Formation: A wildfire characteristic impacting wildfire magnitude resulting from the formation of a convective fire thunderstorm driving erratic fire spread. [84]
    - Burnt Area: A wildfire characteristic impacting wildfire magnitude resulting from the area of land consumed by the wildfire. [24] [64] [84] [19]
    - Vegetative Damage: A wildfire characteristic impacting wildfire magnitude and a convective hazard characteristic impacting convective hazard magnitude resulting from the types of vegetation damaged and level of damage incurred. [24] [64] [81] [19] [70] [3]

- Factor Impacting Convective Hazard Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either convective hazard rate of occurrence or convective hazard size and severity.
    - Transitory Factor Impacting Convective Hazard Frequency and/or Magnitude: A factor impacting convective hazard frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
        - Large-Scale Flow Patterns: A transitory factor impacting convective hazard and drought frequency and/or magnitude resulting from presence and change of large-scale atmospheric circulation. [62] [46] [85] [41]
        - Atmospheric Instability: A transitory factor impacting convective hazard

frequency and/or magnitude and a climatic factor impacting wildfire frequency and/or magnitude resulting from the rising and convection or layers of air with different temperatures and densities. [80] [1] [26] [5]

- Humidity: A transitory factor impacting convective hazard, extreme precipitation hazard, and extreme heat frequency and/or magnitude and a climatic factor impacting wildfire frequency and/or magnitude resulting from the water content of ambient air. [1] [85] [5]
- Mean Sea Surface Temperature: A transitory factor impacting convective hazard frequency and/or magnitude resulting from the temperature of water at the sea or ocean surface. [14] [62] [46] [1] [85] [5]
- Air Temperature: (elaborated under Extreme Heat Characteristic Impacting Extreme Heat Magnitude) [1] [5]
- Seasonality: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [87] [14] [46] [85] [5] [41]
- Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [32]

- Terrain Factor Impacting Convective Hazard Frequency and/or Magnitude: A factor impacting convective hazard frequency and/or magnitude resulting from a characteristic of the relief, composition, or location.
  - Surface Roughness: A terrain factor impacting convective hazard frequency and/or magnitude resulting from the local land cover. [32]
  - Wave Exposure: A terrain factor convective hazard frequency and/or magnitude resulting from the unobstructed overwater distance on which winds can act and develop and grow waves. [32]
  - Historical Tracks: A terrain factor convective hazard frequency and/or magnitude resulting from the location of past convective hazard tracks. [14] [43] [46] [35] [1] [54] [41] [32]
  - Land Use: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [42] [32]
- Convective Hazard Characteristic Impacting Convective Hazard Magnitude: A factor impacting convective hazard magnitude resulting from a specific characteristic of a convective hazard event.
  - Central Pressure: A convective hazard characteristic impacting convective hazard magnitude resulting from the minimum and average atmospheric pressure at the center of the system. [14] [62] [38] [68] [35] [27] [1] [67] [32]
  - Pressure Drop: A convective hazard characteristic impacting convective hazard magnitude resulting from the difference between the central pressure of a system and the environmental pressure around it. [14] [68] [32]
  - Debris: A convective hazard characteristic impacting convective hazard magnitude, a flood characteristic impacting flood magnitude, and a snow avalanche characteristic impacting snow avalanche magnitude resulting from the presence and quantity of debris entrained by the event. [23] [38] [68] [35] [1] [32]
  - Storm Surge Height: A convective hazard characteristic impacting convective hazard magnitude resulting from the maximum height of water rise above typical sea-level driven by the system making landfall. [43] [62] [35] [1] [32]
  - Wind Speed: A convective hazard characteristic impacting convective hazard magnitude, a wind characteristic impacting wildfire frequency and/or magnitude, and a transitory factor impacting drought, erosion, snow avalanche, and extreme heat frequency and/or magnitude resulting from the maximum and

    average wind speeds present. [42] [14] [43] [62] [38] [68] [46] [35] [1] [26] [67] [32] [85]
        - Radius of Maximum Winds: A convective hazard characteristic impacting convective hazard magnitude resulting from the distance between the centre of the system and the radius at which maximum wind speeds occur or to the edge of the funnel. [14] [68] [35] [1] [67] [32]
        - Radius of Maximum Extent/Funnel Radius: A convective hazard characteristic impacting convective hazard magnitude resulting from the distance between the center of the system and the edge of the precipitation area. [68] [85]
        - Vorticity/Rotational Velocity: A convective hazard characteristic impacting convective hazard magnitude resulting from the spin of the system and the velocity at which it does so. [46] [1] [5]
        - Translational Velocity: A convective hazard characteristic impacting convective hazard magnitude resulting from the lateral velocity of the system. [68] [35] [1] [32]
        - Genesis Location: A convective hazard characteristic impacting convective hazard magnitude resulting from the location of system formation. [14]
        - Precipitation: (elaborated under Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude) [43] [62] [35] [1] [26] [5] [32] [85]
        - Vegetative Damage: (elaborated under Wildfire Characteristic Impacting Wildfire Magnitude) [35]
        - Wind Direction: (elaborated under Wind Characteristic Impacting Wildfire Frequency and/or Magnitude) [32]
- Factor Impacting Drought Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either drought rate of occurrence or drought severity.
    - Transitory Factor Impacting Drought Frequency and/or Magnitude: A factor impacting drought frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
        - Evapotranspiration/Water Demand: A transitory factor impacting drought and extreme precipitation hazard frequency and/or magnitude resulting from the amount of water necessary to offset the water lost to evaporation from the ground, transpiration from plants, and human activities (i.e. agriculture, housing, power generation, etc…). [71] [89] [90] [80] [1] [85] [7] [41]
        - Water Supply: A transitory factor impacting drought frequency and/or magnitude resulting from the fluctuation of the supply of water available through runoff or groundwater. [71] [1] [85]
        - Precipitation: (elaborated under Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude) [80] [91] [62] [1] [85] [5] [90] [41]
        - Air Temperature: (elaborated under Extreme Heat Characteristic Impacting Extreme Heat Magnitude) [71] [80] [91] [1] [85] [70] [7] [41]
        - Wind Speed: (elaborated under Convective Hazard Characteristic Impacting Convective Hazard Magnitude) [1]
        - Large-Scale Flow Patterns: (elaborated under Transitory Factor Impacting Convective Hazard Frequency and/or Magnitude) [85]
        - Snowmelt/Icemelt: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [85] [90]
    - Terrain Factor Impacting Drought Frequency and/or Magnitude: A factor impacting

    wildfire frequency and/or magnitude resulting from a characteristic of the relief, composition, or location.
        - Albedo: A terrain factor impacting drought frequency and/or magnitude resulting from the ratio of solar radiation absorbed by the ground to that reflected by the ground. [1]
        - Land Use: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [71] [1]
    - Drought Characteristic Impacting Drought Magnitude: A factor impacting drought magnitude resulting from a specific characteristic of a drought event.
        - Moisture Balance: A drought characteristic impacting drought magnitude resulting from the difference between the water entering an environment (i.e. precipitation, increasing surface or subsurface storage, etc…) and the water leaving that environment (i.e. evapotranspiration, runoff, decreasing surface or subsurface storage, etc…). [1] [85] [41]
        - Duration: (elaborated under Wildfire Characteristic Impacting Wildfire Magnitude) [80] [1] [85] [90] [41]
- Factor Impacting Erosion Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either erosion rate of occurrence or erosion severity.
    - Transitory Factor Impacting Erosion Frequency and/or Magnitude: A factor impacting erosion frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
        - Flow Characteristic Impacting Erosion Frequency and/or Magnitude: A transitory factor impacting erosion frequency and/or magnitude resulting from a characteristic of flowing water driving erosion.
            - Flow Turbulence: A flow characteristic impacting erosion frequency and/or magnitude resulting from the chaotic changing of water flow direction and velocity. [30]
            - Discharge: (elaborated under Flood Characteristic Impacting Flood Magnitude). [23] [26]
            - Flow Velocity: (elaborated under Flood Characteristic Impacting Flood Magnitude) [10]
        - Freeze/Thaw Weathering: A transitory factor impacting erosion and mass movement frequency and/or magnitude resulting from the repeated freezing and/or thawing of water on or in the ground’s surface. [8] [62] [26] [3] [58]
        - Coastal Sea Ice: A transitory factor impacting erosion frequency and/or magnitude resulting from the presence or absence of sea ice near or adjoining a coast. [62] [26] [58]
        - Sea Level/Tide Range: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [91] [23] [74] [62] [26] [70] [58] [41]
        - Desiccation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [8]
        - Precipitation: (elaborated under Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude) [8] [62] [48] [1] [70] [3] [7] [23]
        - Snowmelt/Icemelt: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [70] [58]
        - Wind Speed: (elaborated under Convective Hazard Characteristic Impacting Convective Hazard Magnitude) [3]
        - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [62] [70] [3]

            - <u>Soil Moisture</u>: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [8] [3]
    - <u>Terrain Factor Impacting Erosion Frequency and/or Magnitude</u>: A factor impacting erosion frequency and/or magnitude resulting from a characteristic of the ground's relief, composition, or location.
        - <u>Soil Characteristic Impacting Erosion Frequency and/or Magnitude</u>: A terrain factor impacting erosion frequency and/or magnitude resulting from a characteristic of the soils making up the ground.
            - <u>Stratification</u>: A soil characteristic impacting erosion frequency and/or magnitude and a snowpack characteristic impacting snow avalanche frequency and/or magnitude resulting from the stacking of layers with different properties. [3]
            - <u>Soil Composition</u>: A soil characteristic impacting erosion frequency and/or magnitude and a spatial characteristic impacting housing convective hazard vulnerability resulting from the grain size, shape, and relative density of materials make up soil. [3]
            - <u>Storage Capacity/Porosity</u>: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude [63] [3]
            - <u>Permeability</u>: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude). [70] [3]
        - <u>Aspect</u>: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [3]
        - <u>Slope</u>: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [3]
        - <u>Land Use</u>: (elaborated under Terrain Factor Impact Flood Frequency and/or Magnitude) [2] [3]
    - <u>Erosion Characteristic Impacting Erosion Magnitude</u>: A factor impacting erosion frequency and/or magnitude resulting from a specific characteristic of an erosion event.
        - <u>Distance Eroded</u>: An erosion characteristic impacting erosion magnitude and a permafrost degradation characteristic impacting permafrost degradation magnitude resulting from the distance receded by a coast- or riverline. [26] [58]
        - <u>Depleted Mass/Volume</u>: (elaborated under Mass Movement Characteristic Impacting Mass Movement Magnitude) [23] [62] [26] [2] [3] [58] [91]
- <u>Factor Impacting Snow Avalanche Frequency and/or Magnitude</u>: A factor impacting CCDNH frequency and/or magnitude capable of influencing either avalanche rate of occurrence or avalanche severity.
    - <u>Transitory Factor Impacting Snow Avalanche Frequency and/or Magnitude</u>: A factor impacting snow avalanche frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
        - <u>Snowpack Characteristic Impacting Snow Avalanche Frequency and/or Magnitude</u>: A transitory factor impacting snow avalanche frequency and/or magnitude resulting from a characteristic of snow accumulated on the ground.
            - <u>Snow Density</u>: A snowpack characteristic impacting snow avalanche frequency and/or magnitude resulting from the mass per unit volume of the snow. [76] [1]
            - <u>Age of Snow</u>: A snowpack characteristic impacting snow avalanche frequency and/or magnitude resulting from the length of time since the snow was deposited by precipitation. [27] [76] [1]
            - <u>Snow Wetness</u>: A snowpack characteristic impacting snow avalanche

                        frequency and/or magnitude resulting from the moisture level of the snow. [27] [76] [1] [26]
            - Snow Temperature: A snowpack characteristic impacting snow avalanche frequency and/or magnitude resulting from the temperature of the snow. [27] [76] [1]
            - Stratification: (elaborated under Soil Characteristic Impacting Erosion Frequency and/or Magnitude) [27] [76] [1] [26]
        - Air Temperature: (elaborated under Extreme Heat Characteristic Impacting Extreme Heat Magnitude) [27] [76] [1] [26]
        - Wind Speed: (elaborated under Convective Hazard Characteristic Impacting Convective Hazard Magnitude) [27] [76] [1]
        - Wind Direction: (elaborated under Wind Characteristic Impacting Wildfire Frequency and/or Magnitude) [76] [1]
        - Precipitation: (elaborated under Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude) [27] [76] [1] [26]
        - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [27] [76] [1] [26]
        - Seasonality: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [27] [76] [1] [26]
        - Snowmelt/Icemelt: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [27] [1]
        - Solar Radiation: (elaborated under Transitory Factor Impacting Wildfire Frequency and/or Magnitude) [76] [1]
    - Terrain Factor Impacting Snow Avalanche Frequency and/or Magnitude: A factor impacting snow avalanche frequency and/or magnitude resulting from a characteristic of the ground's relief, composition, or location.
        - Slope: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [27] [76] [1]
        - Aspect: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [27] [76] [1]
        - Curvature: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [27] [76]
        - Lithology: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [1]
    - Snow Avalanche Characteristic Impacting Snow Avalanche Magnitude: A factor impacting snow avalanche frequency and/or magnitude resulting from a specific characteristic of an avalanche event.
        - Flow/Slab Depth: A snow avalanche characteristic impacting snow avalanche magnitude resulting from the thickness of the flowing snow or of the released snow slab. [27] [76] [1]
        - Depleted Mass/Volume: (elaborated under Mass Movement Characteristic Impacting Mass Movement Magnitude) [27] [1]
        - Flow Velocity: (elaborated under Flood Characteristic Impacting Flood Magnitude) [27] [1]
        - Debris: (elaborated under Convective Hazard Characteristic Impacting Convective Hazard Magnitude) [27] [76] [1]
        - Vertical/Horizontal Distance: (elaborated under Mass Movement Characteristic Impacting Mass Movement Magnitude) [27] [1]
- Factor Impact Saltwater Intrusion Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either saltwater intrusion rate of occurrence

or saltwater intrusion severity.

- Transitory Factor Impacting Saltwater Intrusion Frequency and/or Magnitude: A factor impacting saltwater intrusion frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
  - Sea Level/Tidal Range: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [91] [62] [34] [47]
  - Water Demand: (elaborated under Transitory Factor Impacting Drought Frequency and/or Magnitude) [47]

- Factor Impacting Permafrost Degradation Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either permafrost degradation rate of occurrence or permafrost degradation severity.
  - Transitory Factor Impacting Permafrost Degradation Frequency and/or Magnitude: A factor impacting permafrost degradation frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
    - Ground Temperature: A transitory factor impacting permafrost degradation frequency and/or magnitude resulting from the near-surface temperature of the ground. [26] [58]
    - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [3] [58]
    - Air Temperature: (elaborated under Extreme Heat Characteristic Impacting Extreme Heat Magnitude) [62] [34] [26] [3] [58] [41]
    - Sea Level/Tidal Range: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [26]
  - Permafrost Degradation Characteristic Impacting Permafrost Degradation Magnitude: A factor impacting permafrost degradation frequency and/or magnitude resulting from a specific characteristic of a permafrost degradation event.
    - Rate of Thaw: A permafrost degradation characteristic impacting permafrost degradation frequency and/or magnitude resulting from the area of permafrost thawed per unit time. [58] [41]
    - Distance Eroded: (elaborated under Erosion Characteristic Impacting Erosion Magnitude) [62] [26]
- Factor Impacting Extreme Precipitation Hazard Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either extreme precipitation hazard rate of occurrence or extreme precipitation hazard severity.
  - Transitory Factor Impacting Extreme Precipitation Hazard Frequency and/or Magnitude: A factor impacting extreme precipitation hazard frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
    - Air Temperature: (elaborated under Extreme Heat Characteristic Impacting Extreme Heat Magnitude) [91] [27] [85] [41]
    - Humidity: (elaborated under Transitory Factor Impacting Convective Hazard Frequency and/or Magnitude) [85] 94]
    - Evapotranspiration: (elaborated under Transitory Factor Impacting Drought Frequency and/or Magnitude) [85] [41]
    - Seasonality: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [79] [87] [53] [85] [41]
  - Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude: A factor impacting extreme precipitation hazard frequency and/or magnitude resulting from a specific characteristic of an extreme precipitation hazard event.

        - Precipitation: An extreme precipitation hazard characteristic impacting extreme precipitation hazard magnitude, a transitory factor impacting flood, mass movement, drought, erosion, and snow avalanche frequency and/or magnitude, a climatic factor impacting wildfire frequency and/or magnitude, and a convective hazard characteristic impacting convective hazard magnitude resulting from the occurrence of precipitation as well as its form and intensity (i.e. L/m^2 of rainwater accumulation per unit time, snow depth accumulation per unit time, average hailstone diameter, etc…). [87] [27] [85] [47] [41]
        - Duration: (elaborated under Wildfire Characteristic Impacting Wildfire Magnitude) [87] [62] [85] [47]

- Factor Impacting Extreme Heat Frequency and/or Magnitude: A factor impacting CCDNH frequency and/or magnitude capable of influencing either extreme heat rate of occurrence or extreme heat severity.
    - Transitory Factor Impacting Extreme Heat Frequency and/or Magnitude: A factor impacting extreme heat frequency and/or magnitude resulting from a non-permanent effect which can be expected to vary across relatively short timescales.
        - Seasonality: (elaborated under Transitory Factor Impacting Flood Frequency and/or Magnitude) [40] [7] [90]
        - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [12] [71] [89] [40] [7]
        - Humidity: (elaborated under Transitory Factor Impacting Convective Hazard Frequency and/or Magnitude) [71] [40]
        - Solar Radiation: (elaborated under Transitory Factor Impacting Wildfire Frequency and/or Magnitude) [71] [40]
        - Wind Speed: (elaborated under Transitory Hazard Impacting Convective Hazard Frequency and/or Magnitude) [71]
    - Terrain Factor Impacting Extreme Heat Frequency and/or Magnitude: A factor impacting extreme heat frequency and/or magnitude resulting from a characteristic of the ground's relief, composition, or location.
        - Land Use: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [71] [89] [48] [40] [7]
    - Extreme Heat Characteristic Impacting Extreme Heat Magnitude: A factor impacting extreme heat frequency and/or magnitude resulting from a specific characteristic of an extreme heat event.
        - Apparent Temperature/Thermal Comfort: An extreme heat characteristic impacting extreme heat magnitude resulting from the human-perceived temperature, a function of air temperature, humidity, solar radiation, and wind. [71] [40]
        - Air Temperature: An extreme heat characteristic impacting extreme heat magnitude and a transitory factor impacting wildfire, convective hazard, drought, snow avalanche, permafrost degradation, and extreme precipitation hazard frequency and/or magnitude resulting from the temperature of ambient air. [71] [80] [23] [62] [40] [90] [7]
        - Duration: (elaborated under Wildfire Characteristic Impacting Wildfire Magnitude) [71] [80] [62] [48] [40] [90]

Factor Impacting Asset Vulnerability:
A CCDNH risk factor capable of influencing the susceptibility of an asset of interest to negative impacts from a CCDNH.

- Factor Impacting Asset Flood Vulnerability: A factor impacting asset vulnerability to a flood event.
    - Factor Impacting Housing Flood Vulnerability: A factor impacting asset flood vulnerability of a building that provides housing.
        - Structural Factor Impacting Housing Flood Vulnerability: A factor impacting housing flood vulnerability resulting from a characteristic of the built structure of the building.
            - Wall/Frame Characteristic Impacting Housing Flood Vulnerability: A structural factor impacting housing flood vulnerability resulting from a characteristic of the walls and/or frame making up or surrounding the building.
                - Surrounding Wall: A wall/frame characteristic impacting housing flood and mass movement vulnerability resulting from the height and material of an appurtenant wall surrounding the building. [65]
                - Load Bearing Wall: A wall/frame characteristic impacting housing flood vulnerability resulting from the presence of load bearing walls in the building (instead of a load bearing frame). [37]
                - Wall/Frame Material: A wall/frame characteristic impacting housing flood, mass movement, convective hazard, wildfire, and snow avalanche vulnerability resulting from the material making up the building's walls or frame. [37] [30] [36] [35] [22] [33] [50]
                - Wall Thickness: A wall/frame characteristic impacting housing flood and mass movement vulnerability resulting from the thickness of the building's walls. [65]
            - Foundation Type/Material: A structural factor impacting housing flood, mass movement, convective hazard, and permafrost degradation vulnerability and a structural factor impacting critical infrastructure flood, mass movement, and permafrost degradation vulnerability resulting from the design, construction, and material of the foundation. [9] [75] [37] [35]
            - Year of Construction/Renovation/Refit: A structural factor impacting housing flood, mass movement, and convective hazard vulnerability and a structural factor impacting critical infrastructure extreme precipitation hazard and extreme heat vulnerability resulting from the amount of time elapsed since the construction, renovation, or refit of the building. [37] [35] [22]
            - Building Height/Number of Stories: A structural factor impacting housing flood, mass movement, convective hazard, wildfire, and drought vulnerability resulting from the height of the building and its number of stories. [9] [65] [75] [37] [30] [36] [35] [22] [33] [31] [50]
            - Floor Height: A structural factor impacting housing flood, mass movement, and convective hazard vulnerability resulting from the vertical distance between the level of the ground and the level of the building's floor. [9] [39] [65] [75] [35] [22]
            - Floor Material: A structural factor impacting housing flood vulnerability resulting from the primary material used in the construction of the building's floors. [37]

        - Position of Openings: A structural factor impacting housing flood, mass movement, and convective hazard vulnerability resulting from the height and location of the building’s fenestration and other openings. [65] [75] [36] [22]
        - Prefabricated/Mobile: A structural factor impacting housing flood, convective hazard, and wildfire vulnerability resulting from the status of the building as a prefabricated or mobile home. [75] [37] [33] [31]
        - Basement: A structural factor impacting housing flood, mass movement, and convective hazard vulnerability resulting from the presence of a basement. [9] [65] [37] [36] [35] [22] [31] [50]
        - Maintenance: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [65]
    - Spatial Factor Impacting Housing Flood Vulnerability: A factor impacting housing flood vulnerability resulting from a characteristic of the location or surrounding terrain of the building.
        - Multi-Building Alignment/Block Shape: A spatial factor impacting housing flood, convective hazard, mass movement, wildfire, and snow avalanche vulnerability resulting from the arrangement of a collection of nearby buildings. [65] [30] [36]
        - Building Orientation: A spatial factor impacting housing flood, convective hazard, mass movement, wildfire, and snow avalanche vulnerability resulting from the orientation of the building relative to forces being applied on it. [65] [37]
        - Building Density/Inter-Building Distance: A spatial factor impacting housing flood, mass movement, wildfire, and snow avalanche vulnerability and a multi-building arrangement characteristic impacting housing exposure resulting from the number of buildings, parcels, or properties per given area or the distance between them. [65] [30]
        - Proximity to Water Body: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [30] [35]
        - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [65]
        - Slope: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [65] [30]
- Factor Impacting Critical Infrastructure Flood Vulnerability: A factor impacting asset flood vulnerability of critical infrastructure necessary for the full functionality of housing.
    - Structural Factor Impacting Critical Infrastructure Flood Vulnerability: A factor impacting critical infrastructure flood vulnerability resulting from a characteristic of the built structure of the infrastructure.
        - Drainage: A structural factor impacting critical infrastructure flood, convective hazard, and extreme precipitation hazard vulnerability resulting from the capacity of the infrastructure to effectively shed water. [8] [62] [54]
        - Maintenance: A structural factor impacting critical infrastructure flood, mass movement, snow avalanche, permafrost degradation, and extreme precipitation hazard vulnerability and a structural factor impacting housing flood, mass movement, and convective hazard vulnerability resulting from the frequency with which maintenance is

performed and the level to which the structure is maintained. [28] [8] [62]

- Protective Barrier: A structural factor impacting critical infrastructure flood, mass movement, wildfire, snow avalanche, and extreme precipitation hazard vulnerability and a structural factor impacting housing erosion and snow avalanche vulnerability resulting from the presence and type of structures designed to protect the infrastructure from impacts (i.e. dike, retaining wall, fire break, etc…). [28] [8] [54] [70] [90]
- Foundation Type/Material: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [8]
- Height: (elaborated under Structural Factor Impacting Critical Infrastructure Convective Hazard Vulnerability) [31]

■ Spatial Factor Impacting Critical Infrastructure Flood Vulnerability: A factor impacting critical infrastructure flood vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.

- Elevation: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [89] [62] [48] [90]
- Proximity to Water Body: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [89] [70] [90]

- Factor Impacting Asset Mass Movement Hazard Vulnerability: A factor impacting asset vulnerability to a mass movement event.
  - Factor Impacting Housing Mass Movement Vulnerability: A factor impacting asset mass movement vulnerability of a building that provides housing.
    - Structural Factor Impacting Housing Mass Movement Vulnerability: A factor impacting housing mass movement vulnerability resulting from a characteristic of the built structure of the building.
      - Wall/Frame Characteristic Impacting Housing Mass Movement Vulnerability: A structural factor impacting housing mass movement vulnerability resulting from a characteristic of the walls and/or frame making up or surrounding the building.
        - Surrounding Wall: (elaborated under Wall/Frame Characteristic Impacting Housing Flood Vulnerability) [65] [66]
        - Wall/Frame Material: (elaborated under Wall/Frame Characteristic Impacting Housing Flood Vulnerability) [66] [56] [36] [22]
        - Wall Thickness: (elaborated under Wall/Frame Characteristic Impacting Housing Flood Vulnerability) [65]
      - Building Height/Number of Stories: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [65] [66] [56] [36] [22]
      - Basement: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [65] [56] [36]
      - Position of Openings: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [65] [66] [36] [22]
      - Foundation Type/Material: (elaborated under structural Factor Impacting Housing Flood Vulnerability) [66] [56] [22]
      - Maintenance: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [65] [56]
      - Floor Height: (elaborated under Structural Factor Impacting Housing

        - Flood Vulnerability) [65]
        - Year of Construction/Renovation/Refit: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [66] [22]
      - Spatial Factor Impacting Housing Mass Movement Vulnerability: A factor impacting housing mass movement vulnerability resulting from a characteristic of the location or surrounding terrain of the building.
        - Multi-Building Alignment/Block Shape: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [65] [56] [36]
        - Building Orientation: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [65] [56] [22]
        - Building Density/Inter-Building Distance: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [65]
        - Slope: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [65]
        - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [65]
    - Factor Impacting Critical Infrastructure Mass Movement Vulnerability: A factor impacting asset mass movement vulnerability of critical infrastructure necessary for the full functionality of housing.
      - Structural Factor Impacting Critical Infrastructure Mass Movement Vulnerability: A factor impacting critical infrastructure mass movement vulnerability resulting from a characteristic of the built structure of the infrastructure.
        - Maintenance: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [28] [53]
        - Protective Barrier: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [28] [8] [53]
        - Foundation Type/Material: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [62]
      - Spatial Factor Impacting Critical Infrastructure Mass Movement Vulnerability: A factor impacting critical infrastructure mass movement vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
        - Slope: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [8] [62] [53]
        - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [8]
- Factor Impacting Asset Convective Hazard Vulnerability: A factor impacting asset vulnerability to a convective hazard event.
    - Factor Impacting Housing Convective Hazard Vulnerability: A factor impacting asset convective hazard vulnerability of a building that provides housing.
      - Structural Factor Impacting Housing Convective Hazard Vulnerability: A factor impacting housing convective hazard vulnerability resulting from a characteristic of the built structure of the building.
        - Wall/Frame Characteristic Impacting Housing Convective Hazard Vulnerability: A structural factor impacting housing convective hazard vulnerability resulting from a characteristic of the walls and/or frame making up or surrounding the building.
          - Cladding Material/Anchoring: A wall/frame characteristic impacting housing convective hazard vulnerability resulting

from the material and anchoring style of the building's wall cladding. [38] [35] [2]
        - Frame Connections/Bracing: A wall/frame characteristic impacting housing convective hazard vulnerability resulting from the type of frame connections and bracing used in the building. [38] [32]
        - Wall/Frame Material: (elaborated under Wall/Frame Characteristic Impacting Housing Flood Vulnerability) [38] [35] [1] [22] [33] [32]
    - Roof Characteristic Impacting Housing Convective Hazard Vulnerability:
        - Roof Anchoring: A roof characteristic impacting housing convective hazard vulnerability resulting from the method by which the building's roof is anchored to the walls or frame. [38] [35] [1] [32]
        - Roof Pitch: A roof characteristic impacting housing convective hazard vulnerability resulting from the slope of the building's roof. [38] [68] [32]
        - Roof Type/Material: A roof characteristic impacting housing convective hazard vulnerability, a structural factor impacting housing wildfire vulnerability, and a structural factor impacting critical infrastructure convective hazard vulnerability resulting from the material and design of the building's roof. [38] [35] [1] [22] [32]
        - Roof Height: A roof characteristic impacting housing convective hazard vulnerability resulting from the vertical distance between the base and the peak of the roof. [38] [32]
    - Rain Admittance Factor: A structural factor impacting housing convective hazard vulnerability resulting from the percentage of rain impinging on the building. [68]
    - Floor Height: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [9] [35]
    - Year of Construction/Renovation/Refit: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [42] [38] [35] [22] [33]
    - Building Height/Number of Stories: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [9] [68] [35] [22] [33] [32]
    - Prefabricated/Mobile: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [35] [1] [33]
    - Foundation Type/Material: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [9] [38] [35] [22] [32]
    - Basement: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [9] [35]
    - Position of Openings: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [68] [22]
    - Maintenance: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [42] [68]
- Spatial Factor Impacting Housing Convective Hazard Vulnerability: A factor impacting housing convective hazard vulnerability resulting from a characteristic of the location or surrounding terrain of the building.

            - Topography: (elaborated under Terrain Factor Impacting Wildfire Frequency and/or Magnitude) [42] [38]
            - Elevation: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [35] [1]
            - Proximity to Water Body: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [35]
            - Multi-Building Alignment/Block Shape: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [32]
            - Building Orientation: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [32]
            - Soil Composition: (elaborated under Soil Characteristic Impacting Erosion Frequency and/or Magnitude) [32]
    - Factor Impacting Critical Infrastructure Convective Hazard Vulnerability: A factor impacting asset convective hazard vulnerability of critical infrastructure necessary for the full functionality of housing.
        - Structural Factor Impacting Critical Infrastructure Convective Hazard Vulnerability: A factor impacting critical infrastructure convective hazard vulnerability resulting from a characteristic of the built structure of the infrastructure.
            - Height: A structural factor impacting critical infrastructure convective hazard and flood vulnerability resulting from the vertical distance between the base and highest point of the structure or its components. [62]
            - Floor Area/Size of Building: (elaborated under Housing Characteristic Impacting Housing Exposure). [32]
            - Roof Type/Material: (elaborated under Roof Characteristic Impacting Housing Convective Hazard Vulnerability) [32]
            - Drainage: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [62] [54]
            - Maintenance: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [23] [62] [6]
            - Protective Barrier: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [23] [62] [54]
        - Spatial Factor Impacting Critical Infrastructure Convective Hazard Vulnerability: A factor impacting critical infrastructure convective hazard vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
            - Slope: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [6]
            - Proximity to Water Body: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [23] [89] [62] [54]
            - Elevation: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [62]
- Factor Impacting Asset Wildfire Vulnerability: A factor impacting asset vulnerability to a wildfire event.
    - Factor Impacting Housing Wildfire Vulnerability: A factor impacting asset wildfire vulnerability of a building that provides housing.
        - Structural Factor Impacting Housing Wildfire Vulnerability: A factor impacting housing wildfire vulnerability resulting from a characteristic of the built structure of the building.

            - Building Height/Number of Stories: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [64]
            - Roof Type/Material: (elaborated under Roof Characteristic Impacting Housing Convective Hazard Vulnerability) [64] [84]
            - Prefabricated/Mobile: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [64] [70]
            - Wall/Frame Material: (elaborated under Wall/Frame Characteristic Impacting Housing Flood Vulnerability) [64]
        - Spatial Factor Impacting Housing Wildfire Vulnerability: A factor impacting housing wildfire vulnerability resulting from a characteristic of the location or surrounding terrain of the building.
            - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [64] [81] [84] [70]
            - Slope: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [64] [81]
            - Elevation: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [81]
            - Building Density/Inter-Building Distance: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [64] [81] [70]
            - Multi-Building Alignment/Block Shape: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [81]
            - Building Orientation: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [81]
    - Factor Impacting Critical Infrastructure Wildfire Vulnerability: A factor impacting asset wildfire vulnerability of critical infrastructure necessary for the full functionality of housing.
        - Structural Factor Impacting Critical Infrastructure Wildfire Vulnerability: A factor impacting critical infrastructure wildfire vulnerability resulting from a characteristic of the built structure of the infrastructure.
            - Material Fire/Heat Resistance: A structural factor impacting critical infrastructure wildfire and extreme heat vulnerability resulting from the infrastructure's materials and their flammability and ability to withstand and adjust to heat. [8]
            - Protective Barrier: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [70]
        - Spatial Factor Impacting Critical Infrastructure Wildfire Vulnerability: A factor impacting critical infrastructure wildfire vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
            - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [62] [70]
- Factor Impacting Asset Drought Vulnerability: A factor impacting asset vulnerability to a drought event.
    - Factor Impacting Housing Drought Vulnerability: A factor impacting asset drought vulnerability of a building that provides housing.
        - Structural Factor Impacting Housing Drought Vulnerability: A factor impacting housing drought vulnerability resulting from a characteristic of the built structure of the building.
            - Building Height/Number of Stories: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [3]
    - Factor Impacting Critical Infrastructure Drought Vulnerability: A factor impacting

asset drought vulnerability of critical infrastructure necessary for the full functionality of housing.

        - <u>Structural Factor Impacting Critical Infrastructure Drought Vulnerability</u>: A factor impacting critical infrastructure drought vulnerability resulting from a characteristic of the built structure of the infrastructure.
            - <u>Material Desiccation Resistance</u>: A structural factor impacting critical infrastructure drought vulnerability resulting from the ability of the infrastructure's materials to withstand desiccation. [8]
        - <u>Spatial Factor Impacting Critical Infrastructure Drought Vulnerability</u>: A factor impacting critical infrastructure drought vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
            - <u>Vegetation</u>: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [8]
- <u>Factor Impacting Asset Erosion Vulnerability</u>: A factor impacting asset vulnerability to an erosion event.
    - <u>Factor Impacting Housing Erosion Vulnerability</u>: A factor impacting asset erosion vulnerability of a building that provides housing.
        - <u>Structural Factor Impacting Housing Erosion Vulnerability</u>: A factor impacting housing erosion vulnerability resulting from a characteristic of the built structure of the building.
            - <u>Protective Barrier</u>: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [3]
        - <u>Spatial Factor Impacting Housing Erosion Vulnerability</u>: A factor impacting housing erosion vulnerability resulting from a characteristic of the location or surrounding terrain of the building.
            - <u>Proximity to Water Body</u>: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [3]
            - <u>Vegetation</u>: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [3]
    - <u>Factor Impacting Critical Infrastructure Erosion Vulnerability</u>: A factor impacting asset erosion vulnerability of critical infrastructure necessary for the full functionality of housing.
        - <u>Spatial Factor Impacting Critical Infrastructure Erosion Vulnerability</u>: A factor impacting critical infrastructure erosion vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
            - <u>Proximity to Water Body</u>: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [23] [48]
- <u>Factor Impacting Asset Snow Avalanche Vulnerability</u>: A factor impacting asset vulnerability to a snow avalanche event.
    - <u>Factor Impacting Housing Snow Avalanche Vulnerability</u>: A factor impacting asset snow avalanche vulnerability of a building that provides housing.
        - <u>Structural Factor Impacting Housing Snow Avalanche Vulnerability</u>: A factor impacting housing snow avalanche vulnerability resulting from a characteristic of the built structure of the building.
            - <u>Protective Barrier</u>: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [1]
            - <u>Wall/Frame Material</u>: (elaborated under Wall/Frame Characteristic Impacting Housing Flood Vulnerability) [1]
        - <u>Spatial Factor Impacting Housing Snow Avalanche Vulnerability</u>: A factor impacting housing snow avalanche vulnerability resulting from a characteristic

of the location or surrounding terrain of the building.

            - <u>Building Density/Inter-Building Distance</u>: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [1]
            - <u>Multi-Building Alignment/Block Shape</u>: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [1]
            - <u>Building Orientation</u>: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [1]
            - <u>Topography</u>: (elaborated under Terrain Factor Impacting Wildfire Frequency and/or Magnitude) [27]
    - <u>Factor Impacting Critical Infrastructure Snow Avalanche Vulnerability</u>: A factor impacting asset snow avalanche vulnerability of critical infrastructure necessary for the full functionality of housing.
        - <u>Structural Factor Impacting Critical Infrastructure Snow Avalanche Vulnerability</u>: A factor impacting critical infrastructure snow avalanche vulnerability resulting from a characteristic of the built structure of the infrastructure.
            - <u>Protective Barrier</u>: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [28] [1]
            - <u>Maintenance</u>: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [28]
        - <u>Spatial Factor Impacting Critical Infrastructure Snow Avalanche Vulnerability</u>: A factor impacting critical infrastructure snow avalanche vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
            - <u>Topography</u>: (elaborated under Terrain Factor Impacting Wildfire Frequency and/or Magnitude) [27]
- <u>Factor Impacting Asset Saltwater Intrusion Vulnerability</u>: A factor impacting asset vulnerability to a saltwater intrusion event.
    - <u>Factor Impacting Critical Infrastructure Saltwater Intrusion Vulnerability</u>: A factor impacting asset saltwater intrusion vulnerability of critical infrastructure necessary for the full functionality of housing.
        - <u>Structural Factor Impacting Critical Infrastructure Saltwater Intrusion Vulnerability</u>: A factor impacting critical infrastructure saltwater intrusion vulnerability resulting from a characteristic of the built structure of the infrastructure.
            - <u>Material Saltwater Resistance</u>: A structural factor impacting critical infrastructure saltwater intrusion vulnerability resulting from the ability of the infrastructure's materials to avoid corrosion or degradation from contact with saltwater. [62]
        - <u>Spatial Factor Impacting Critical Infrastructure Saltwater Intrusion Vulnerability</u>: A factor impacting critical infrastructure saltwater intrusion vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
            - <u>Proximity to Water Body</u>: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [58]
            - <u>Elevation</u>: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [62]
- <u>Factor Impacting Asset Permafrost Degradation Vulnerability</u>: A factor impacting asset vulnerability to a permafrost degradation event.
    - <u>Factor Impacting Housing Permafrost Degradation Vulnerability</u>: A factor impacting

asset permafrost degradation vulnerability of a building that provides housing.

    - Structural Factor Impacting Housing Permafrost Degradation Vulnerability: A factor impacting housing permafrost degradation vulnerability resulting from a characteristic of the built structure of the building.
        - Foundation Type/Material: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [3]
- Factor Impacting Critical Infrastructure Permafrost Degradation Vulnerability: A factor impacting asset permafrost degradation vulnerability of critical infrastructure necessary for the full functionality of housing.
    - Structural Factor Impacting Critical Infrastructure Permafrost Degradation Vulnerability: A factor impacting critical infrastructure permafrost degradation vulnerability resulting from a characteristic of the built structure of the infrastructure.
        - Component Connection Flexibility: A structural factor impacting critical infrastructure permafrost degradation vulnerability resulting from the capacity of connections between the infrastructure's components to bend and adjust to changing orientations without failing. [58]
        - Foundation Type/Material: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [62]
        - Maintenance: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [62] [26]

- Factor Impacting Asset Extreme Precipitation Hazard Vulnerability: A factor impacting asset vulnerability to an extreme precipitation hazard event.
    - Factor Impacting Critical Infrastructure Extreme Precipitation Hazard Vulnerability: A factor impacting asset extreme precipitation hazard vulnerability of critical infrastructure necessary for the full functionality of housing.
        - Structural Factor Impacting Critical Infrastructure Extreme Precipitation Hazard Vulnerability: A factor impacting critical infrastructure extreme precipitation hazard vulnerability resulting from a characteristic of the built structure of the infrastructure.
            - Drainage: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [62]
            - Protective Barrier: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [62]
            - Year of Construction/Renovation/Refit: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [7]
            - Maintenance: (elaborated under Structural Factor Impacting Critical Infrastructure Flood Vulnerability) [6]
        - Spatial Factor Impacting Critical Infrastructure Extreme Precipitation Hazard Vulnerability: A factor impacting critical infrastructure extreme precipitation hazard vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
            - Permeability: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [7]
            - Slope: (elaborated under Terrain Factor Impacting Flood Frequency and/or Magnitude) [6]
            - Proximity to Water Body: (elaborated under Terrain Factor Impacting Mass Movement Frequency and/or Magnitude) [48]
- Factor Impacting Asset Extreme Heat Vulnerability: A factor impacting asset vulnerability to

an extreme heat event.

- Factor Impacting Critical Infrastructure Extreme Heat Vulnerability: A factor impacting asset extreme heat vulnerability of critical infrastructure necessary for the full functionality of housing.
    - Structural Factor Impacting Critical Infrastructure Extreme Heat Vulnerability: A factor impacting critical infrastructure extreme heat vulnerability resulting from a characteristic of the built structure of the infrastructure.
        - Material Fire/Heat Resistance: (elaborated under Structural Factor Impacting Critical Infrastructure Wildfire Vulnerability) [23] [89] [8] [62] [48]
        - Year of Construction/Renovation/Refit: (elaborated under Structural Factor Impacting Housing Flood Vulnerability) [8] [40]
    - Spatial Factor Impacting Critical Infrastructure Extreme Heat Vulnerability: A factor impacting critical infrastructure extreme heat vulnerability resulting from a characteristic of the location or surrounding terrain of the infrastructure.
        - Vegetation: (elaborated under Transitory Factor Impacting Mass Movement Frequency and/or Magnitude) [8]

Factor Impacting Asset Exposure:
A CCDNH risk factor aiding in quantifying the presence and/or value of assets in a given area which is susceptible to negative impacts from a CCDNH.

- Factor Impacting Housing Exposure: A factor impacting asset exposure of buildings that provide housing.
    - Building Characteristic Impacting Housing Exposure: A factor impacting housing exposure resulting from a characteristic of the building.
        - Building Value Measure Impacting Housing Exposure: A building characteristic impacting housing exposure resulting from a specific approach to quantifying the value of the building.
            - Replacement/Repair Cost: A building value measure impacting housing exposure and an infrastructure value measure impacting critical infrastructure exposure resulting from the cost of replacing an existing asset with a new asset of the same capacity or repairing it up to its prior capacity. [10] [52] [37] [36] [35] [22] [77] [33] [32] [31]
            - Maximum per Unit Area/Length Damage: A building value measure impacting housing exposure and an infrastructure value measure impacting critical infrastructure exposure resulting from the cost per unit area or length of damage incurred by an asset under conditions of maximum loss. [10] [52] [50]
            - Market/Depreciated Value: A building value measure impacting housing exposure resulting from the total value of the building structure and its contents prior to a CCDNH impact. [9] [39] [10] [35] [33] [50]
            - Insured Value: A building value measure impacting housing exposure resulting from the insured value of the building. [39] [10] [42] [36]
        - Floor Area/Size of Building: A building characteristic impacting housing exposure, an emergency facility capacity characteristic impacting emergency facility exposure, and a structural factor impacting critical infrastructure convective hazard vulnerability resulting from the total floor area contained in the building. [10] [36] [22] [33] [50] [77]

        - Number of Occupants/Dwellings per Building: A building characteristic impacting housing exposure resulting from the number of people occupying the building and the number of dwellings present. [9] [66] [22] [77] [33] [32]
    - Multi-Building Arrangement Characteristic Impacting Housing Exposure: A factor impacting housing exposure resulting from a characteristic of the spatial arrangement of multiple buildings.
        - Settlement Type: A multi-building arrangement characteristic impacting housing exposure resulting from the level of urbanization of a given area. [10] [52] [70] [22] [77] [50]
        - Building Density/Inter-Building Distance: (elaborated under Spatial Factor Impacting Housing Flood Vulnerability) [9] [39] [74] [42] [70] [22] [27] [77] [50]
- Factor Impacting Critical Infrastructure Exposure: A factor impacting asset exposure of critical infrastructure necessary for the full functionality of housing.
    - Infrastructure Characteristic Impacting Critical Infrastructure Exposure: A factor impacting critical infrastructure exposure resulting from a characteristic of a piece of infrastructure.
        - Infrastructure Value Measure Impacting Critical Infrastructure Exposure: An infrastructure characteristic impacting critical infrastructure exposure resulting from a specific approach to quantifying the value of the infrastructure.
            - Replacement/Repair Cost: (elaborated under Housing Value Measure Impacting Housing Exposure) [33] [31]
            - Maximum per Unit Area/Length Damage: (elaborated under Housing Value Measure Impacting Housing Exposure) [50]
        - Infrastructure Capacity Characteristic Impacting Critical Infrastructure Exposure: An infrastructure characteristic impacting critical infrastructure exposure resulting from a characteristic of the structure or capacity of a piece of infrastructure.
            - Emergency Facility Capacity Characteristic Impacting Critical Infrastructure Exposure: An infrastructure capacity characteristic impacting critical infrastructure exposure resulting from a characteristic of the structure or operating capacity of an emergency facility.
                - Population Served: An emergency facility capacity characteristic impacting critical infrastructure exposure resulting from the number of people within the service area of the facility. [33]
                - Floor Area/Size of Building: (elaborated under Housing Characteristic Impacting Housing Exposure) [33]
            - Utility Site Capacity Characteristic Impacting Critical Infrastructure Exposure: An infrastructure capacity characteristic impacting critical infrastructure exposure resulting from a characteristic of the structure or operating capacity of a site providing utilities.
                - Power Generating Capacity: A utility site capacity characteristic impacting critical infrastructure exposure resulting from the average power generation capacity of a power plant. [33]
                - Treatment/Pumping Capacity: A utility site capacity characteristic impacting critical infrastructure exposure resulting from the maximum volume of water treatable or

        pumpable daily by a water treatment plant or pumping station. [33]
      - Station Voltage: A utility site capacity site characteristic impacting critical infrastructure exposure resulting from the voltage used by an electrical substation. [33]
    - Transportation Infrastructure Capacity Characteristic Impacting Critical Infrastructure Exposure: An infrastructure capacity characteristic impacting critical infrastructure exposure resulting from a characteristic of the structure or operating capacity of a piece of transportation infrastructure.
      - Total Length: An infrastructure capacity characteristic impacting critical infrastructure exposure resulting from the total length linear infrastructure (road, railway, bridge, etc…) in a given area. [10] [66] [74] [54] [33] [50]
      - Number of Lanes/Tracks: An infrastructure capacity characteristic impacting critical infrastructure exposure resulting from the number of traffic lanes or tracks present in a road or railway. [33]
  - Number of Sites/Assets: An infrastructure characteristic impacting critical infrastructure exposure resulting from the number of nodal sites (emergency facility, train station, bus station, transmission/distribution station, pumping station, substation, power plant, etc…) and connecting assets (road, railway, transmission/power line, pipeline, etc…) in a given area. [74] [89] [29] [90]

Class Design:

Table 22 adopts a class design that hybridizes those used in tables 3 and 12. As in the taxonomy of hazards, the taxonomy of risk factors defines classes using just a subject and description. This approach omits the clarification of driving hazards which is used in the classes of the taxonomy of impacts. However, similarly to the taxonomy of impacts, Table 22 only provides citations for the leaf classes of the taxonomy. As with Table 12, this decision stems from the purely organizational character of the non-leaf classes, most of which possess little to no formal basis in the literature.

Organizational Design:

The root class of the taxonomy of risk factors fulfills the same function as that established for the root classes of tables 3 and 12. “CCDNH Risk Factor” establishes the central concept of the taxonomy, shaping its eligibility criterion, and thus determining the inclusion and exclusion of all other factor classes. Similarly to the root class of Table 3, “CCDNH Risk Factor” is tied to definitions in the literature, specifically, those of the term *risk*. The literature presents a wide variety of interpretations of *risk*. These include:

- *risk* as the possibility of negative impact (IPCC AR6 2022, “Risk”)(Quesada-Ganuza, Garmendia, and Gandini 2023, 20)(Reisinger et al. 2020, 4);
- *risk* as the probability of exceeding a certain degree of loss or level of severity (Eidsvig, Kristensen, and Vangelsten 2017, 482-483)(Heneka et al. 2006, 721);

- *risk* as the expected negative impact of a natural event (Cruden and Varnes 1996, 50)(National Academies of Sciences, Engineering, and Medicine 2014; 56)(Papathoma-Köhle et al. 2007, 766);
- and *risk* as the probability and consequence of the occurrence of a specific hazard (Public Safety Canada 2024, 153).

"CCDNH Risk Factor" most heavily relies on the definition put forth by Public Safety Canada (2024) which incorporates both the likelihood and degree of a hazard's impacts (153).

The definition of the root class elaborates three representations of risk, describing them as frequency and/or magnitude, vulnerability, and exposure. The first subclassing of "CCDHN Risk Factor" creates a division along the lines of these three representations of *risk*: "Factor Impacting CCDNH Frequency and/or Magnitude", "Factor Impacting Asset Vulnerability", "Factor Impacting Asset Exposure". Each of these three subclasses is populated. The split is inspired by the literature's frequent interpretation of *risk* as interactions of these and similar variables:

- *risk as* the dynamic interaction of *hazard* (frequency and/or magnitude), vulnerability, and exposure (Ettinger et al. 2015, 564)(IPCC AR6 2022, "Risk")(National Academies of Sciences, Engineering, and Medicine 2014, 56)(Reisinger et al. 2020, 6);
- *risk* as the interaction between *hazard* (frequency and/or magnitude) and exposure (Eidsvig, Kristensen, and Vangelsten 2017, 482-483)(Public Safety Canada 2024, 153);
- and *risk* as the interaction between *hazard* (frequency and/or magnitude) and vulnerability (Quesada-Ganuza, Garmendia, and Gandini 2023, 20).

The root class' definition as well as its subclasses adopt the first of these interpretations. Here, the term *hazard* is taken to signify frequency and/or magnitude. This approach is inspired by Reisinger et al. (2020) as well as the definition of *hazard* put forth by the IPCC (2022) (Reisinger et al. 2020, 7)(IPCC AR6 2022, "Hazard").

Notably, while the hazards for which risk factors are considered must be in some way worsened by climate change, the factors themselves do not need to be impacted by climate change in order to be included. For example, while the lithology of an area is unlikely to be significantly altered by climate change, it is important to consider in attempting to understand and predict the frequency and/or magnitude of mass movements.

<u>Summary Design</u>:

The three representations of risk elaborated above give rise to the hundreds of classes shown in Table 22. The following sections approach summarizing this large volume of information by discussing only a subset of the total number of classes in the taxonomy. All of the non-leaf classes in Table 22 are discussed, and the selection of classes for discussion is made from among only the leaf classes of the taxonomy. This selection targets the leaf classes which are most prevalent in the reviewed literature. The prevalence of a class is measured using the number of sources in which the class appears. In many cases, only the three most prevalent classes of each leaf class grouping (leaf classes that share a direct superclass) are discussed (i.e. Table 23). Throughout the summaries, situations arise in which multiple classes display the same prevalence in the literature. In such cases, the decision of which to discuss is made subjectively based on the perceived importance of the tied classes to the purpose of the taxonomy. These decisions are explained where they occur.

In addition to curtailing the number of classes summarized, some of the following sections also cut short the number of sources included in summary tables beyond the ‘discussing two or more of the impacts in the table’ criterion used in the summaries of the other taxonomies. This decision is similarly motivated by the unmanageably large number of different sources associated with some of the leaf class groupings in Table 22.

<u>Factor Impacting CCDNH Frequency and/or Magnitude</u>:

“Factor Impacting CCDNH Frequency and/or Magnitude” is assigned 11 subclasses, each concerning a separate CCDNH. These hazard classes correspond to the classes from Table 3 which exist exclusively as subclasses of the hazard spheres. Hazard sphere subclasses which possess other, non-hazard sphere superclasses (“Mud Flow”, “Debris Flow”, “Ice Jam Flood”, “Dam Break/Glacial Lake Outburst Flood”, “Snowmelt Flood”, and “Hail Flood”) are not given separate factor classes. This is because each already exists in the taxonomy of hazards as a subclass of one or more of the 11 hazards selected to receive factor classes.

The CCDNHs populating this level of Table 3 (direct subclasses of the hazard spheres) are selected because they represent the most general level of hazard classes which are still specific enough to be consistently associated with risk factors in the literature. Their superclasses in the taxonomy of hazards (“Hydrosheric Hazard”, “Atmospheric Hazard”, etc…) are far less frequently referenced in the literature. Moreover, the set of phenomena each describes is too diverse for many unambiguous factors impacting frequency and/or magnitude to be identified.

The first CCDNH for which factors impacting frequency and/or magnitude are considered is floods. “Factor Impacting Flood Frequency and/or Magnitude”, as summarized in Table 23, possesses three temporally-distinct subclasses: one concerning transitory factors (short-term); one concerning terrain factors (long-term); and one concerning characteristics of the CCDNH itself (immediate-term). The formation of separate subclasses for transitory and terrain factors is inspired most directly by Alexander (1993) who proposes a classification of the phenomena which influence the propensity of a river to flood (121-122). This classification divides the phenomena (factors) into “transient” and “permanent”. The category of transient phenomena gives rise to the class “Transitory Factor Impacting Flood Frequency and/or Magnitude” and many of the phenomena in that branch appear as subclasses in Table 23. Similarly, the category of permanent phenomena is very influential in the creation of the class “Terrain Factor Impacting Flood Frequency and/or Magnitude” and there is significant overlap between the concepts encompassed by each. The third subclass, “Flood Characteristic Impacting Flood Magnitude”, is introduced without being included in Alexander (1993)’s initial classification. It is notable because, unlike the transitory and terrain subclasses, the factors it describes only impact flood magnitude and not flood frequency. A discussion of the characteristics of a flood is immediate-term and takes as a given the occurrence of the flood. The inclusion of this subclass is most directly based on a separate classification from Alexander (1993) which describes “critical flood characteristics”(135) with additional support coming from the Saffir Simpson Scale descriptions (Friedland 2009, 33). Subsequent sections show that this approach to temporally dividing risk factors is extrapolated to nearly every other ‘factor impacting frequency and/or magnitude’ branch of the taxonomy.

Each of these three subclasses of factors impacting flooding frequency and/or magnitude are further subdivided into leaf factor classes. As clarified in the section on summary design, Table 23 only represents the three most prevalent such leaf factor classes for each of the three direct subclasses of "Factor Impacting Flood Frequency and/or Magnitude". Also following the previously set out summary design guidelines, only a limited selection of the total number of sources discussing leaf factor classes impacting flood frequency and/or magnitude are represented in Table 23. Due to the large volume of reviewed sources concerned with flooding, Table 23 is particularly stringent, only including sources which discuss six or more of the included classes. The direct subclasses of "Factor Impacting Flood Frequency and/or Magnitude" are each subdivided into leaf factor classes on the basis of 'measure quantifying a phenomenon' (physical, spatial, temporal). Across all three of these leaf factor class groupings, the best example of a similar categorization is provided by Alexander (1993) (122, 135).

Table 23: Factor Impacting Flood Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Flood Frequency and/or Magnitude †			Terrain Factor Impacting Flood Frequency and/or Magnitude †			Flood Characteristic Impacting Flood Magnitude †		
	Precipitation	Sea Level/ Tide Range	Seasonality ‡	Elevation	Permeability	Land Use	Flood Extent	Inundation Depth	Duration
(Alexander 1993, 120-122, 135, 137)									
(Cea and Costabile 2022, 1-2, 8, 17)									
(Friedland 2009, 13, 27, 33, 73, 160)									
(Jacobs et al. 2018, 486-487, 497)									
(Sayers et al. 2015, 21-22, 32, 39, 41, 45, 103)									
(Tarasova et al. 2019, 1, 4, 6, 9, 14)									

* The selected sources are those which discuss six or more of the nine leaf classes included in the table.
† The three subclasses of this class selected for display are the three which are most prevalent in the literature (total sources).
‡ "Land Use", "Channel Characteristic", and "Basin/Catchment Characteristic" are tied for number of sources.

The second subclass of "Factor Impacting CCDNH Frequency and/or Magnitude" is "Factor Impacting Mass Movement Frequency and/or Magnitude". As demonstrated by the summary in Table 24, this class is temporally subdivided in the same way as the previous class concerning floods. It possesses subclasses for transitory factors, terrain factors, and characteristics of the hazard itself, in this case, mass movements. Once again, the summary in Table 24 limits itself to showing only nine total leaf factor classes (the three most widely discussed from each grouping). The leaf factor classes included in each grouping are also made distinct in the same way as their corresponding groupings in Table 23: on the basis of ‘measure quantifying a phenomenon’ (physical, spatial, temporal). Clear classifications of transitory and terrain factors are provided by the literature (Alexander 1993, 244, 257)(Cruden and Varnes 1996, 70) as do description based classifications (Ali et al. 2023, 4, 6)(Luo et al. 2019, 4). Succinct descriptions of mass movement characteristics determining magnitude also exist in the literature (Alexander 1993, 258)(Cruden and Varnes 1996, 38, 40).

Table 24: Factor Impacting Mass Movement Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Mass Movement Frequency and/or Magnitude †			Terrain Factor Impacting Mass Movement Frequency and/or Magnitude †			Mass Movement Characteristic Impacting Mass Movement Magnitude †		
	Freeze/ Thaw Weathering	Soil Moisture	Precipitation	Lithology	Slope	Aspect	Depleted Mass/ Volume	Velocity of Movement	Mechanism of Movement
(Alexander 1993, 243-244, 257, 260, 273)									
(Ali et al. 2023, 4, 6)									
(Cruden and Varnes 1996, 41, 48-50, 70)									
(Hungr, Leroueil, and Picarelli 2014, 167, 169, 185, 191)									
(Klaver et al. 2024, 3, 5-6)									
(Luo et al. 2023, 9, 13)									
(Luo et al. 2019, 3)									
(Varnes 1978, 11, 21)									

* The selected sources are those which discuss two or more of the nine leaf classes included in the table.

† The three subclasses of this class selected for display are the three which are most prevalent in the literature (total sources).

The next CCDNH for which factors impacting frequency and/or magnitude are considered is wildfires. Table 25 provides a summary of the subclassing of “Factor Impacting Wildfire Frequency and/or Magnitude”, demonstrating the same approach used in Table 23 and Table 24 with an initial division into transitory factors, terrain factors, and hazard-specific characteristics. However, with the exception of the wildfire characteristics subclass, the approach to displaying the subdivision of the wildfire factors deviates from that of the previous two tables. Table 25’s specific summary approach is explained in the notes at the bottom of the table.

Similarly to the previous two tables, all three of the direct subclasses of “Factor Impacting Wildfire Frequency and/or Magnitude” delineate their own subclasses by the specific ‘measure quantifying a phenomenon’ (physical, spatial, temporal) that each represents. Starting with the transitory factors branch, the direct subclasses of “Transitory Factor Impacting Wildfire Frequency and/or Magnitude” most closely reflect the physical components factoring into the temporal phases of wildfires categorized by Tedim et al. (2018) (4, 13). The subclassing of “Transitory Factor Impacting Wildfire Frequency and/or Magnitude” also includes two non-leaf factor classes: “Fuel Characteristic Impacting Wildfire Frequency and/or Magnitude” and “Wind Characteristic Impacting Wildfire Frequency and/or Magnitude”. These two factor classes are introduced with organizational purposes in mind and to emphasize the significance of wind and fuel characteristics in determining the frequency and/or magnitude of wildfires (Alexander 1993, 302-303)(de Groot et al. 2013, 1)(Papathoma-Köhle et al. 2022, 3)(Syphard et al. 2012, 5-6)(Tedim et al. 2018, 8-9, 13). Both are subclassed further, distinguishing their subclasses by the measure and phenomenon that each represents. The subclasses included in each grouping reflect the descriptive classifications of both fuel and wind characteristics present in the literature (de Groot et al. 2013, 1-2)(Syphard et al. 2012, 5-6)(Tedim et al. 2018, 2, 6).

The next subclass of factors impacting wildfire frequency and/or magnitude, terrain factors, possesses only two subclasses of its own, both of which are shown in Table 25: “Topography” and “Land Use”. Both of these are well represented in the formal tabulations of wildfire factors in the literature (Public Safety Canada 2024, 70)(Syphard et al. 2012, 6-7)(Tedim et al. 2018, 17).

Finally, the subclassing of “Wildfire Characteristic Impacting Wildfire Magnitude” is summarized in Table 25 using only the three subclasses which are most prevalent in the literature. These subclasses closely reflect the classifications (formal and descriptive) of wildfire characteristics dictating magnitude which are found in the literature (de Groot et al. 2013, 1-2)(Public Safety Canada 2024, 70)(Tedim et al. 2018, 12).

Table 25: Factor Impacting Wildfire Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Wildfire Frequency and/or Magnitude ††			Terrain Factor Impacting Wildfire Frequency and/or Magnitude		Wildfire Characteristic Impacting Wildfire Magnitude †		
	Fuel Characteristic Impacting Wildfire Frequency and/or	Wind Characteristic Impacting Wildfire Frequency and/or	Air Temperature	Topography	Land Use	Fireline Intensity	Predictability of Fire Behavior	Vegetative Damage

	Magnitude †††	Magnitude †††						
	Fuel Load	Wind Speed						
(Alexander 1993, 298-300)								
(Collins et al. 2018, 374-376, 382)								
(de Groot et al. 2013, 1-2)								
(Papathoma-Köhle et al. 2022, 2-3, 5-6, 8)								
(Public Safety Canada 2024, 62, 64, 70)								
(Syphard et al. 2012, 2, 5-6, 9, 11)								
(Tedim et al. 2018, 2, 6, 16, 19)								

* The selected sources are those which discuss two or more of the eight leaf classes included in the table.
† The three subclasses of this class selected for display are the three which are most prevalent in the literature (total sources).
†† The two direct leaf subclasses of this class selected for display are the two which are most prevalent in the literature.
††† The subclass of this class selected for display is the most prevalent in the literature.

Convective hazards are the CCDNHs considered by the fourth subclass of factors impacting frequency and/or magnitude. This branch is summarized in Table 26 using a format identical to that used in Tables 23 and 24. “Factor Impacting Convective Hazard Frequency and/or Magnitude” possesses the same three temporally separated subclass types (transitory, terrain, and CCDNH characteristic), each of which is itself separated based on specific measures which each quantify a phenomenon. The literature contains descriptive classifications on which the subclassings of the transitory factors branch (Trenberth 2011, 124-125), terrain factors branch (FEMA 2024b, 4-38, 4-69-4-71), and convective hazard characteristics branch (Friedland 2009, 32-33)(NASEM 2014, 36) are primarily modelled. “Surface Roughness”, one of the subclasses within the terrain factors branch, is tied in prevalence with the class “Wave Exposure”. “Wave Exposure” is a risk factor connected to the frequency and/or magnitude of storm surges while “Surface Roughness” holds significance for convective hazard types beyond just cyclones during landfall (FEMA 2024b, 4-69-4-71, 4-160-4-161).

Table 26: Factor Impacting Convective Hazard Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Convective Hazard Frequency and/or Magnitude †	Terrain Factor Impacting Convective Hazard Frequency and/or Magnitude †	Convective Hazard Characteristic Impacting Convective Hazard Magnitude †

	Large-Scale Flow Patterns	Mean Sea Surface Temperature	Seasonality	Historical Tracks	Surface Roughness ‡	Land Use	Central Pressure	Wind Speed	Precipitation
(Alexander 1993, 137, 157, 164-165, 168)									
(Bloemendaal et al. 2020, 1, 3-4)									
(FEMA 2024b, 4-38, 4-41, 4-57, 4-69-4-70)									
(Friedland 2009, 13, 32-33)									
(Hunter et al. 2016, 244-245, 247-249, 252)									
(NASEM 2014, 36)									
(Trenberth 2011, 124, 129, 135)									

* The selected sources are those which discuss four or more of the nine leaf classes included in the table.

† The three subclasses of this class selected for display are the three which are most prevalent in the literature (total sources).

‡ “Surface Roughness” and “Wave Exposure" are tied for number of sources.

The fifth subclass of factors impacting CCDNH frequency and/or magnitude concerns droughts. Table 27 provides a summary which adopts the ‘three-most-prevalent’ leaf factor class selection approach for only transitory factors as the terrain and drought characteristic branches each contain only two leaf factor classes. “Factor Impacting Drought Frequency and/or Magnitude” is subclassed into the three typical classes of transitory factors, terrain factors, and hazard characteristics. Each of these is further subclassed with informal classifications in the literature supporting the subclasses assigned by the taxonomy to the transitory (Hayhoe et al. 2018, 91)(Stephenson 2008, 14-15)(Trenberth 2011, 124), terrain (Alexander 1993, 147-148), and drought characteristic (Alexander 1993, 144)(Trenberth 2011, 124) branches.

Table 27: Factor Impacting Drought Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Drought Frequency and/or Magnitude †	Terrain Factor Impacting Drought Frequency and/or Magnitude	Drought Characteristic Impacting Drought Magnitude

	Evapotranspiration/Water Demand	Precipitation	Air Temperature	Albedo	Land Use	Moisture Balance	Duration
(Alexander 1993, 144-145, 147-148)							
(Angel et al. 2018, 881)							
(Hayhoe et al. 2018, 91)							
(Quesada-Ganuza, Garmendia, and Gandini 2023, 29)							
(Stephenson 2008, 14-15)							
(Trenberth 2011, 124, 128, 133)							
(Zamuda et al. 2018, 176, 182)							
(Zhang et al. 2008, 270)							

* The selected sources are those which discuss two or more of the seven leaf classes included in the table.
† The three subclasses of this class selected for display are the three which are most prevalent in the literature (total sources).

Erosion is the next CCDNH considered. An abbreviated summary of the structure of the subclassing of “Factor Impacting Erosion Frequency and/or Magnitude” is contained in Table 28. Due to a more heavily subdivided structure, Table 28 varies significantly from the previous summary tables. Explanations of the specific choices made in the selection of classes for display are appended to the table.

The initial subclassing of “Factor Impacting Erosion Frequency and/or Magnitude” follows the transitory/terrain/CCDNH characteristic pattern. The first subclass, “Transitory Factor Impacting Erosion Frequency and/or Magnitude”, is once again itself divided on the basis of the specific measure and incorporates classifications from the literature (Dawson et al. 2018, 10)(NASEM 2014, 7). This class possesses one non-leaf subclass, “Transitory Factor Impacting Erosion Frequency and/or Magnitude”, which is introduced to emphasize the role of flowing water in the erosional process (Alexander 1993, 217). A tabulation of multiple flow characteristics in relation to erosion is not present in the reviewed literature. Instead, the flow characteristics included in the taxonomy are amalgamated from multiple sources (Dawson et al . 2018, 10)(Ding et al. 2021, 10)(Ettinger et al. 2016, 569)(Merz et al. 2010, 1707).

The second subclass, “Terrain Factor Impacting Erosion Frequency and/or Magnitude”, is also divided along ‘measure quantifying a phenomenon’ and the contents of its subdivision borrows heavily from a similar structure in the literature (Alexander 1993, 219). As with the transitory factor branch, one non-leaf class is included beneath the terrain factor class: “Soil Characteristic Impacting Erosion

Frequency and/or Magnitude”. The decision to emphasize soil characteristics as well as the decision of which soil characteristics to discuss are both primarily influenced by the classification put forth by Alexander (1993) (219).

“Erosion Characteristic Impacting Erosion Magnitude” is once again separated such that each subclass represents a distinct ‘measure quantifying a phenomenon’. As shown in Table 28, the literature discusses erosion magnitude in terms of either distance eroded (Markon et al. 2018, 1999) or amount of displaced material (Alexander 1993, 226). The distance eroded is used in circumstances where coast- or river-line erosion is concerned while the amount of displaced material more aptly describes inland erosion away from bodies of water.

Table 28: Factor Impacting Erosion Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Erosion Frequency and/or Magnitude †			Terrain Factor Impacting Erosion Frequency and/or Magnitude ††			Erosion Characteristic Impacting Erosion Magnitude	
	Flow Characteristic Impacting Erosion Frequency and/or Magnitude ††	Sea Level/ Tide Range	Precipitation	Soil Characteristic Impacting Erosion Frequency and/or Magnitude †		Land Use	Distance Eroded	Depleted Mass/ Volume
	Discharge			Storage Capacity/Porosity	Permeability			
(Alexander 1993, 219, 223-224, 345-346)								
(Dawson et al. 2018, 10)								
(Ding et al. 2021, 6, 10)								
(Markon et al. 2018, 1188, 1198-1199)								
(NASEM 2014, 7, 136)								
(Public Safety Canada 2024, 81, 102)								
(Zhang et al. 2008, 270)								

* The selected sources are those which discuss two or more of the nine leaf classes included in the table.
† The two leaf subclasses of this class selected for display are the two most prevalent in the literature (total sources).

†† The subclass of this class selected for display is the most prevalent in the literature.

The seventh subclass of “Factor Impacting CCDNH Frequency and/or Magnitude” is “Factor Impacting Snow Avalanche Frequency and/or Magnitude”. A non-exhaustive summary of the subclass structure below this class is provided by Table 29. Explanations of the table’s class and source selection process are appended to the table.

As before, a transitory/terrain/CCDNH characteristic split occupies the first level below “Factor Impacting Snow Avalanche Frequency and/or Magnitude” all three of these branches adhere to the ‘measure quantifying a phenomenon’ delineation is their own subdivision. The subclasses of the transitory factors class contain one non-leaf class, “Snowpack Characteristic Impacting Snow Avalanche Frequency and/or Magnitude”, alongside a collection of leaf factor classes inspired by similar classifications and descriptions in the literature (Alexander 1993, 197)(Eckert et al. 2024, 380)(Schweizer et al. 2003, 5-8). The leaf factor classes displayed in Table 29, “Air Temperature” and “Precipitation”, are tied in prevalence with the class “Vegetation”. Within the context of evaluating climate risk, “Air Temperature” and “Precipitation” are prioritized because both are deemed likely to be more immediately impacted by climate change than “Vegetation”. The subclass concerning snowpack characteristics is also divided on the base of measure, and the subclasses selected largely reflect the variables identified in the literature (Alexander 1993, 187, 197)(Schweizer et al. 2003, 7-9). Of these, Table 29 shows only “Snow Wetness” despite possessing the same prevalence in the literature as “Stratification”. This decision is once again justified by the context of climate risk in which wet snow avalanches are likely to become more common with climate change (Eckert et al. 2024, 379).

“Terrain Factor Impacting Snow Avalanche Frequency and/or Magnitude” is assigned subclasses in line with the literature’s terrain descriptions (Alexander 1993, 197)(Eckert et al. 2024, 372)(Schweizer et al. 2003, 3-4). The same holds true for “Snow Avalanche Characteristic Impacting Snow Avalanche Magnitude” and the literature’s avalanche descriptions (Alexander 1993, 188-189)(Eckert et al. 2024, 374, 379-380). Among the subclasses of this second branch which are shown in Table 29, “Flow Velocity” is included despite having the same prevalence as both “Depleted Mass/Volume” and “Vertical/Horizontal Distance”. All three are important avalanche metrics with “Depleted Mass/Volume” and “Vertical/Horizontal Distance” both being considered in avalanche categorization (Alexander 1993, 189)(Eckert et al. 2024, 372) and “Flow Velocity” being necessary in determining impact pressures (Alexander 1993, 188). Under such circumstances of similar importance, the decision to show only “Flow Velocity” is based on the fact that a climate change-driven increase in wet avalanche incidence is associated with a change in expected flow velocity (Eckert et al. 2024, 370).

<u>Table 29</u>: Factor Impacting Snow Avalanche Frequency and/or Magnitude Summary

<table>
<tr><td rowspan="3">Sources</td><td colspan="3">Transitory Factor Impacting Snow Avalanche Frequency and/or Magnitude ††</td><td colspan="3">Terrain Factor Impacting Snow Avalanche Frequency and/or Magnitude †</td><td colspan="3">Snow Avalanche Characteristic Impacting Snow Avalanche Magnitude †</td></tr>
<tr><td>Snowpack Characteristic Impacting Snow Avalanche Frequency and/or Magnitude †††</td><td rowspan="2">Air Temperature ‡</td><td rowspan="2">Precipitation ‡</td><td rowspan="2">Slope</td><td rowspan="2">Aspect</td><td rowspan="2">Curvature</td><td rowspan="2">Flow/Slab Depth</td><td rowspan="2">Flow Velocity ‡</td><td rowspan="2">Debris</td></tr>
<tr><td>Snow Wetness ‡</td></tr>
</table>

(Alexander 1993, 187-189, 191, 197)									
(Ding et al. 2021, 9)									
(Eckert et al. 2024, 372, 379-380)									
(Schweizer, Jamieson, and Schneebeli 2003, 1, 3-4, 8, 13)									

† The three leaf subclasses of this class selected for display are the three most prevalent in the literature (total sources) amongst this class' subclasses.
†† The two leaf subclasses of this class selected for display are the two most prevalent in the literature (total sources) amongst this class' subclasses.
††† The leaf subclass of this class is the most prevalent in the literature (total sources) amongst this class' subclasses.
‡ This leaf class is tied for number of sources with (an)other adjacent class(s) with which it shares a superclass.

The next CCDNH included under "Factor Impacting CCDNH Frequency and/or Magnitude" is Saltwater Intrusion. "Factor Impacting Saltwater Intrusion Frequency and/or Magnitude" has only three subclasses across two levels. This is deemed to be too few to warrant a full summary table. For organizational consistency with the other branches of factors impacting frequency and/or magnitude, the first subclassing level contains "Transitory Factor Impacting Saltwater Intrusion Frequency and/or Magnitude". Subclasses for terrain factors and saltwater intrusion characteristics are not introduced because examples of neither are found in the reviewed literature. The transitory factors class is assigned the classes "Sea Level/Tidal Range" and "Water Demand", each of which represents a distinct 'measure quantifying a phenomenon'. The subclasses are most directly sourced from the IPCC AR6 report's glossary definition for "Salt-water intrusion/encroachment".

Permafrost Degradation is the next CCDNH considered under "Factor Impacting CCDNH Frequency and/or Magnitude" and a partial summary of the class' subclassing is presented by Table 30. Similarly to the first subclass level under the previous saltwater intrusion class, "Factor Impacting Permafrost Degradation Frequency and/or Magnitude" only partially follows the transitory/terrain/CCDNH characteristic pattern, including only a class for transitory factors and another for permafrost degradation characteristics. Both of these branches are themselves subclassed on the basis of measure. The subclasses of "Transitory Factor Impacting Permafrost Degradation Frequency and/or Magnitude" follow descriptions and classifications from the literature (Alexander 1993, 284)(Markon et al. 2018, 1197). Meanwhile, the classes below "Permafrost Degradation Characteristic Impacting Permafrost Degradation Magnitude" are pieced together from multiple sources (Ding et al. 2021, 6)(Hayhoe et al. 2018, 92, 114).

Table 30: Factor Impacting Permafrost Degradation Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Permafrost Degradation Frequency	Permafrost Degradation Characteristic

	and/or Magnitude †			Impacting Permafrost Degradation Magnitude	
	Ground Temperature	Vegetation	Air Temperature	Rate of Thaw	Distance Eroded
(Alexander 1993, 284)					
(Ding et al. 2021, 1-2, 5-6, 10)					
(Hayhoe et al. 2018, 92, 114)					
(Markon et al. 2018, 1197, 1215)					
(NASEM 2014, 6)					

* The selected sources are those which discuss two or more of the five leaf classes included in the table.
† The three leaf subclasses of this class selected for display are the three most prevalent in the literature (total sources) amongst this class' subclasses.

Table 31 provides an abbreviated summary of "Factor Impacting Extreme Precipitation Hazard Frequency and/or Magnitude", the second to last set of factors impacting a specific CCDNH's frequency and/or magnitude. As with permafrost degradation, a lack of terrain factors in the literature leads to the first subdivision of this class containing subclasses for only transitory factors and extreme precipitation hazard characteristics. The subclasses of "Transitory Factor Impacting Extreme Precipitation Hazard Frequency and/or Magnitude" are drawn from descriptions of the mechanisms relating global warming to increasing incidence of extreme precipitation (Hayhoe et al. 2018, 88)(Trenberth 2016, 124-125). "Evapotranspiration" is among the classes shown in Table 31 despite being tied in prevalence with "Humidity" in the taxonomy. This decision is taken because, while "Humidity" is linked to "Evapotranspiration", "Evapotranspiration" is the phenomenon which stands to change more directly under warming conditions (Trenberth 2011, 131). The subclassing of "Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude" is similarly supported by the literature (Trenberth 2011, 131)(Vormoor et al. 2016, 34).

Table 31: Factor Impacting Extreme Precipitation Hazard Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Extreme Precipitation Hazard Frequency and/or Magnitude †			Extreme Precipitation Hazard Characteristic Impacting Extreme Precipitation Hazard Magnitude	
	Air Temperature	Evapotranspiration ‡	Seasonality	Precipitation	Duration
(Eckert et al. 2024, 380)					
(Hayhoe et al. 2018, 88, 95, 111)					
(IPCC AR6 2022, "Extreme/heavy precipitation event")					
(Trenberth 2011, 124-125, 130-131)					

(Vormoor et al. 2016, 34, 46)					

* The selected sources are those which discuss two or more of the five leaf classes included in the table.
† The three leaf subclasses of this class selected for display are the three most prevalent in the literature (total sources) amongst this class' subclasses.
‡ This leaf class is tied for number of sources with another adjacent class with which it shares a superclass.

The final subclass of "Factor Impacting CCDNH Frequency and/or Magnitude" is summarized in Table 32 and concerns extreme heat. The organization of subclasses beneath "Factor Impacting Extreme Heat Frequency and/or Magnitude" returns to the transitory/terrain/CCDNH characteristic pattern. "Transitory Factor Impacting Extreme Heat Frequency and/or Magnitude" is assigned measure-distinct subclasses in line with the literature's descriptions of the short-term inputs of extreme heat events (Habeeb, Vargo, and Stone 2015, 1652-1654)(Quesada-Ganuza, Garmendia, and Gandini 2023, 26-27). The terrain branch of factors impacting extreme heat frequency and/or magnitude possesses a single subclass: "Land Use". "Land Use" is used as a partial proxy for urban heat islands effects by evaluating a location on the degree to which it is urban or rural (Habeeb, Vargo, and Stone 2015, 1652)(Jacobs et al. 2018, 489)(Quesada-Ganuza, Garmendia, and Gandini 2023, 27). Finally, the class "Extreme Heat Characteristic Impacting Extreme Heat Magnitude" is divided along the lines of 'measure quantifying a phenomenon' into the three subclasses shown in Table 32. "Apparent Temperature/Thermal Comfort", "Air Temperature", and "Duration" are each used in the literature to quantify the magnitude of an extreme heat event (Habeeb, Vargo, and Stone 2015, 1652)(Quesada-Ganuza, Garmendia, and Gandini 2023, 26-28). "Apparent Temperature/Thermal Comfort" is included in addition to "Air Temperature" despite their clear similarities because the former better aids in capturing the user-centered risk posed by extreme heat to housing and critical infrastructure than the latter.

Table 32: Factor Impacting Extreme Heat Frequency and/or Magnitude Summary

Sources *	Transitory Factor Impacting Extreme Heat Frequency and/or Magnitude †			Terrain Factor Impacting Extreme Heat Frequency and/or Magnitude	Extreme Heat Characteristic Impacting Extreme Heat Magnitude		
	Seasonality	Vegetation	Solar Radiation	Land Use	Apparent Temperature/ Thermal Comfort	Air Temperature	Duration
(Angel et al. 2018, 882, 897, 902-903)							
(Habeeb, Vargo, and Stone 2015, 1652-1655)							
(Jacobs et al. 2018, 489)							
(NASEM 2014, 45)							
(Quesada-Ganuza,							

Garmendia, and Gandini 2023, 26-28)							
(Stephenson 2008, 12)							
(Wilbanks and Fernandez 2014, 44)							
(Zamuda et al. 2018, 181)							

* The selected sources are those which discuss two or more of the seven leaf classes included in the table.
† The three leaf subclasses of this class selected for display are the three most prevalent in the literature (total sources) amongst this class' subclasses.

.Factor Impacting Asset Vulnerability:

"Factor Impacting Asset Vulnerability" is introduced to Table 22 as a representation of the vulnerability component of the three part model of risk proposed in the literature (Ettinger et al. 2015, 564)(IPCC AR6 2022, "Risk")(National Academies of Sciences, Engineering, and Medicine 2014, 56)(Reisinger et al. 2020, 6). Like "Factor Impacting CCDNH Frequency and/or Magnitude", the first division of this class is between the 11 CCDNH's from Table 3 which exist exclusively as subclasses of the hazard sphere classes. Once again, this subclassing is organizational with no perfect analogues in the literature. The granularity of CCDNH selected targets the level at which the most vulnerability factors are discussed by the literature.

The first of these subclasses is summarized in Table 33 and exemplifies the subdivision approach taken for all of the subsequent subclasses. This approach hinges on two levels of subclassing: one based on the category of asset impacted and one on the relativity (intrinsic vs. relative) of the factor. Table 33 demonstrates this first split with the classes "Factor Impacting Housing Flood Vulnerability" and "Factor Impacting Critical Infrastructure Flood Vulnerability". The delineation of flood vulnerability factors between housing and infrastructure in the literature is generally restricted to large-scale government reports (Joint Research Centre 2017)(FEMA 2024c), with journal articles limiting their scope to one or the other. Both of these branches are then assigned subclasses which are made distinct by their character as either intrinsic or relative traits of the asset of interest. In the housing branch, the intrinsic traits of housing are represented by "Structural Factor Impacting Housing Flood Vulnerability" and include characteristics of building structures which factor into their vulnerability to negative impact from flooding. "Spatial Factor Impacting Housing Flood Vulnerability" encapsulates the relative traits of housing, namely the position of the building relative to terrain features and other buildings. The relativity-based split between structural and spatial factors impacting flood vulnerability is present in the literature but never clearly stated (Friedland 2009, 15-16)(Papathoma-Köhle, Schlögl, and Fuchs 2019, 5-6).

Within the level below the relativity split, Table 33 shows that "Structural Factor Impacting Housing Flood Vulnerability" possesses a collection of leaf factor subclasses as well as one non-leaf factor subclass: "Wall/Frame Characteristic Impacting Housing Flood Vulnerability". The collection of leaf factor classes is separated based on 'measure quantifying structural state', following a host of similar classifications from the literature (Dabbeek and Silva 2020, 786)(Galasso, Pregnolato, and Parisi 2021, 4, 8)(Papathoma-Köhle, Schlögl, and Fuchs 2019, 4). Meanwhile, the class concerning wall and frame characteristics serves to organize a set of factors, separated on the same ‘measure quantifying structural state’, which are critical to the structural integrity of housing and, thus, its vulnerability (Galassoto, and Parisi 2021, 7)(Papathoma-Köhle, Schlögl, and Fuchs 2019, 4). The other branch of the split, “Spatial Factor Impacting Housing Flood Vulnerability”, is subclassed into only leaf factor classes. This set of subclasses is delineated based on the ‘measure quantifying spatial state’ characterized by each of the subclasses. Formal tabulations of many of these factors are present in the literature (Ettinger et al. 2016, 567)(Papathoma-Köhle, Schlögl, and Fuchs 2019, 4).

The subdivision of the factors affecting the flood vulnerability of critical infrastructure mostly mirrors that of the housing branch. The first split is once again on the basis of relativity with one subclass dedicated to the structural factors of critical infrastructure and the other to its spatial factors. Both the structural and spatial factors possess exclusively leaf factor classes. The set of structural factor subclasses closely matches the classification of Argyroudis et al. (2019) (3) while the set of spatial factor subclasses is described but never tabulated (Zamuda et al. 2018, 176). Notably, in summarizing “Structural Factor Impacting Critical Infrastructure Flood Vulnerability”, Table 33 displays that the leaf class “Maintenance” is discussed by none of the sources included in the table. This is a result of the frequency analysis approach to source selection for the table as well as the minimal overlap between the sources discussing housing flood vulnerability and those discussing critical infrastructure flood vulnerability.

Table 33: Factor Impacting Asset Flood Vulnerability Summary

<table>
<tr><td rowspan="4">Sources *</td><td colspan="5">Factor Impacting Housing Flood Vulnerability</td><td colspan="4">Factor Impacting Critical Infrastructure Flood Vulnerability</td></tr>
<tr><td colspan="3">Structural Factor Impacting Housing Flood Vulnerability †</td><td colspan="2">Spatial Factor Impacting Housing Flood Vulnerability †</td><td colspan="2">Structural Factor Impacting Critical Infrastructure Flood Vulnerability †</td><td colspan="2">Spatial Factor Impacting Critical Infrastructure Flood Vulnerability</td></tr>
<tr><td>Wall/ Frame Characteristic Impacting Housing Flood Vulnerability ††</td><td rowspan="2">Building Height/ Number of Stories</td><td rowspan="2">Basement</td><td rowspan="2">Multi-Building Alignment / Block Shape</td><td rowspan="2">Building Orientation ‡</td><td rowspan="2">Maintenance</td><td rowspan="2">Protective Barrier</td><td rowspan="2">Elevation</td><td rowspan="2">Proximity to Water Body</td></tr>
<tr><td>Wall/ Frame Material</td></tr>
<tr><td>(Dabbeek and Silva 2020, 787-788)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>(Ettinger et al. 2016, 567, 578)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>(Friedland 2009, 16,</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

28)									
(Fuchs et al. 2019, 590-591, 593)									
(Galasso, Pregnolato, and Parisi 2021, 4, 7-8)									
(Joint Research Centre 2017, 45, 70)									
(Papathoma-Köhle, Schlögl, and Fuchs 2019, 4)									
(Zamuda et al. 2018, 176, 188)									

* The selected sources are those which discuss three or more of the nine leaf classes included in the table.
† The two leaf subclasses of this class selected for display are the two most prevalent in the literature (total sources) amongst this class' subclasses.
†† The leaf subclass of this class is the most prevalent in the literature (total sources) amongst this class' subclasses.
‡ This leaf class is tied for number of sources with (an)other adjacent class(s) with which it shares a superclass.

The next CCDNH considered beneath "Factor Impacting Asset Vulnerability" is mass movement. As shown in Table 34, the organizational structure of the factors impacting asset mass movement vulnerability is one-to-one with that of the factors impacting asset flood vulnerability. This includes the initial asset split between housing and critical infrastructure, the subsequent relativity-based split, and the introduction of a subclass of structural housing factors which itself possesses subclasses concerning wall and frame characteristics. The justification for each of these subclassing decisions is extrapolated from the evidence used to justify those same decisions in the previous context of floods. As for the delineation of leaf factor classes, the assignment of subclasses to "Wall/ Frame Characteristic Impacting Housing Mass Movement Vulnerability" is based on 'measure quantifying structural state' and borrows directly from formal tabulations in the literature (Papathoma-Köhle, Schlögl, and Fuchs 2019, 4)(Papathoma-Köhle et al. 2007, 771). The same is true for the subclasses assigned to the structural factors impacting housing vulnerability (Dabbeek and Silva 2020, 786-788)(Papathoma-Köhle, Schlögl, and Fuchs 2019, 4)(Papathoma-Köhle et al. 2007, 771) and those assigned to the structural factors impacting critical infrastructure vulnerability (Eidsvig, Kristensen, and Vangelsten 2017, 501). As for the spatial factors, their subclasses are divided on 'measure quantifying spatial state' and for the subdivisions of both housing (Papathoma-Köhle, Schlögl, and Fuchs 2019, 4) and critical infrastructure (Argyroudis et al. 2019, 3) also reflect the literature.

Table 34 shows two influential sources, Papathoma-Köhle, Schlögl, and Fuchs (2019) and Dabbeek and Silva (2020), which also appear in Table 33. In the case of the former, this overlap is accounted for by Papathoma-Köhle, Schlögl, and Fuchs (2019)'s decision to target torrential hazards which, as per Table 3, are considered to be both mass movements and floods (3). In the case of the latter, the authors are addressing multi-hazard vulnerability which they specify includes both landslides (mass movements), floods, and storms (convective hazards) (Dabbeek and Silva 2020, 782).

<u>Table 34</u>: Factor Impacting Asset Mass Movement Vulnerability Summary

Sources *	Factor Impacting Housing Mass Movement Vulnerability					Factor Impacting Critical Infrastructure Mass Movement Vulnerability			
	Structural Factor Impacting Housing Mass Movement Vulnerability †			Spatial Factor Impacting Housing Mass Movement Vulnerability †		Structural Factor Impacting Critical Infrastructure Mass Movement Vulnerability †		Spatial Factor Impacting Critical Infrastructure Mass Movement Vulnerability	
	Wall/ Frame Characteristic Impacting Housing Mass Movement Vulnerability ††	Building Height/ Number of Stories	Position of Openings	Multi-Building Alignment / Block Shape	Building Orientation	Maintenance	Protective Barrier	Slope	Vegetation
	Wall/ Frame Material								
(Argyroudis et al. 2019, 3)									
(Dabbeek and Silva 2020, 786-788)									
(Eidsvig, Kristensen, and Vangelsten 2017, 501)									
(Fuchs et al. 2019, 588, 593)									
(Klaver et al. 2024, 11-12)									
(Luo et al. 2023, 4, 9)									
(Papathoma-Köhle, Schlögl, and Fuchs 2019, 4)									

(Papathoma-Köhle et al. 2007, 771)									

* The selected sources are those which discuss two or more of the nine leaf classes included in the table.
† The two leaf subclasses of this class selected for display are the two most prevalent in the literature (total sources) amongst this class' subclasses.
†† The leaf subclass of this class is the most prevalent in the literature (total sources) amongst this class' subclasses.

"Factor Impacting Asset Convective Hazard Vulnerability" is summarized in Table 35. With only one exception, "Roof Characteristic Impacting Housing Convective Hazard Vulnerability", this class is subclassed using the same approach and justifications as the factors impacting flood and mass movement vulnerability. The class concerning roof characteristics is introduced beneath "Structural Factor Impacting Housing Convective Hazard Vulnerability" and serves to categorize an important set of structural factors with respect to buildings weathering convective hazards. As a result of the high winds characteristic of convective hazards, the aerodynamics and construction of roofs can significantly change their vulnerability to damage (Dabbeek and Silva 2020, 786)(FEMA 2024a, 5-10-5-345-38-5-40).

Once again, the leaf factor class groupings formed in the subclass structure beneath "Factor Impacting Asset Convective Hazard Vulnerability" are each inspired by similar groupings in the literature. The wall and frame characteristics impacting housing convective hazard vulnerability, delineated on 'measure quantifying a structural state', are very clearly tabulated and described by the literature (FEMA 2024a, 4-3-4-15)(Ginger et al. 2007, 217-219). The same delineation measure and relationship to the literature is true for roof characteristics (FEMA 2024b, 5-92-5-93)(FEMA 2024a, 5-38-5-40)(Ginger et al. 2007, 217-219), general structural housing factors (Dabbeek and Silva 2020, 786-788)(Friedland 2009, 37-40, 76)(Pita et al. 2012, 81-84), and structural critical infrastructure factors (FEMA 2024b, 5-254-5-260, 5-267-5-274)(NASEM 2014, 7, 64-65). The spatial housing factors and spatial critical infrastructure factors are both 'measure quantifying a spatial state' delineated. The former grouping is inspired by tabulations from the literature (FEMA 2024b, 5-77-5-79, 5-124-5-125)(Friedland 2009, 76). The latter, however, are only represented in the literature through description, never formal tabulation (NASEM 2014, 47).

Among the spatial critical infrastructure factors, Table 35 displays "Elevation" despite that class having the same prevalence in the literature as "Slope". "Slope" is a factor which is only connected by the literature to the vulnerability of roads. The mechanism of this connection is the increase in vehicle accident vulnerability on higher gradient roadways exposed to convective hazards (Andrey et al. 2003, 334, 337-340). Meanwhile, "Elevation" can be considered relevant to a broader suite of critical infrastructure types through the inundation of low-lying assets (NASEM 2014, 49), leading to its display prioritization in Table 35.

In considering the sources included in Table 35, Dabbeek and Silva (2020) reappear because, as previously mentioned, their multi-hazard includes storms which are interpreted to include convective hazards. The table excludes from display two very influential sources as a result of the source inclusion criteria (clarified below the table) and the minimal overlap between sources treating housing and those treating infrastructure. These are FEMA's Hazus Inventory Technical Manual (FEMA 2024a) which contains extensive classifications of building stocks in relation to convective hazard vulnerability and Pita et al. (2012) who propose an in-depth hurricane damage model with useful tabulations of its input variables.

Table 35: Factor Impacting Asset Convective Hazard Vulnerability Summary

Sources *	Factor Impacting Housing Convective Hazard Vulnerability					Factor Impacting Critical Infrastructure Convective Hazard Vulnerability			
	Structural Factor Impacting Housing Convective Hazard Vulnerability ††			Spatial Factor Impacting Housing Convective Hazard Vulnerability †		Structural Factor Impacting Critical Infrastructure Convective Hazard Vulnerability †		Spatial Factor Impacting Critical Infrastructure Convective Hazard Vulnerability †	
	Wall/ Frame Characteristic Impacting Housing Convective Hazard Vulnerability ††	Roof Characteristic Impacting Housing Convective Hazard Vulnerability ††	Building Height/ Number of Stories	Topography	Elevation	Maintenance	Protective Barrier	Proximity to Water Body	Elevation ‡
	Wall/ Frame Material	Roof Type/Material							
(Alexander 1993, 169-170)	■	■			■				
(Dabbeek and Silva 2020, 786-788)	■	■	■						
(Dawson et al. 2018, 5, 10, 16)						■	■	■	
(FEMA 2024b, 5-91-5-93, 5-95-5-97)	■	■	■						
(Friedland 2009, 17, 37, 39, 76)	■	■	■		■				
(Ginger et al. 2007, 217-219)	■	■		■					
(NASEM 2014, 7, 47, 49)						■	■	■	■

* The selected sources are those which discuss three or more of the nine leaf classes included in the table.
† The two leaf subclasses of this class selected for display are the two most prevalent in the literature (total sources) amongst this class' subclasses.
†† The leaf subclass of this class is the most prevalent in the literature (total sources) amongst this class' subclasses.
‡ "Elevation" and "Slope" are tied for number of sources.

Table 36 presents a summary of the organizational structure of classes representing factors impacting asset wildfire vulnerability. The first two levels of subclassing follow the pattern shown in the previous three tables: an asset-based split between housing and critical infrastructure, a relativity-based split of each between structural factors and spatial factors, and leaf class groupings delineated by ‘measure quantifying structural state’ and ‘measure quantifying spatial state’ respectively. Notably, the structural/spatial split is also performed in the literature (Papathoma-Köhle et al. 2022, 6).

Unlike the previous few tables, Table 36 shows that each of the four resulting branches (structural housing, spatial housing, structural infrastructure, spatial infrastructure) possesses only leaf factor classes as subclasses. As before, these groupings are each inspired by classifications and descriptions in the literature. The subclassing of “Structural Factor Impacting Housing Wildfire Vulnerability” is directly modelled off of Papathoma-Köhle et al. (2022)’s “Physical Vulnerability Index” indicators (6). Papathoma-Köhle et al. (2022)’s set of indicators also includes structural elements like gutters and shutters which are not included in Table 22 on the basis that they, unlike roofs and walls, cannot be generalized globally to all housing structures. The next branch, “Spatial Factor Impacting Housing Wildfire Vulnerability”, has a subclassing is similarly rooted in tabulations of model coefficients and indicators (Syphard et al. 2012, 5-6)(Papathoma-Köhle et al. 2022, 6). As for the structural and spatial factors impacting critical infrastructure wildfire vulnerability, both groupings are sparsely populated with the first containing two subclasses (Argyroudis et al. 2019, 3)(Public Safety Canada 2024, 80) and the second containing only one (NASEM 2014, 6, 45)(Public Safety Canada 2024, 72). This is a result of the infrequency and shallowness of discussions concerning wildfires in the reviewed literature where the assets of interest are critical infrastructure.

Table 36: Factor Impacting Asset Wildfire Vulnerability Summary

Sources	Factor Impacting Housing Wildfire Vulnerability					Factor Impacting Critical Infrastructure Wildfire Vulnerability		
	Structural Factor Impacting Housing Wildfire Vulnerability ††		Spatial Factor Impacting Housing Wildfire Vulnerability †			Structural Factor Impacting Critical Infrastructure Wildfire Vulnerability		Spatial Factor Impacting Critical Infrastructure Wildfire Vulnerability
	Roof Type/ Material	Prefabricated/Mobile	Vegetation	Slope	Building Density/Inter-Building Distance	Material Fire/Heat Resistance	Protective Barrier	Vegetation
(Argyroudis et al. 2019, 3)								
(NASEM 2014, 6, 45)								
(Papathoma-Köhle et al. 2022, 6)								
(Public								

Safety Canada 2024, 72, 75, 80)								
(Syphard et al. 2012, 5)								
(Tedim et al. 2018, 20)								

† The three leaf subclasses of this class selected for display are the three most prevalent in the literature (total sources) amongst this class' subclasses.
†† The two leaf subclasses of this class selected for display are the two most prevalent in the literature (total sources) amongst this class' subclasses.

The next CCDNH for which factors impacting asset vulnerability are represented in the taxonomy of risk factors is drought. Within the reviewed literature, specific factors impacting the vulnerability of housing or critical infrastructure are rare and discussions are sparse. Thus, a summary table is not provided. The structure beneath the class "Factor Impacting Asset Drought Vulnerability" in Table 22 contains only three leaf factor classes: "Building Height/Number of Stories", "Material Desiccation Resistance", and "Vegetation". These leaf classes are organized within the familiar subclassing structure of an asset-based split into housing and critical infrastructure. The housing branch possesses only one subclass, "Structural Factor Impacting Housing Drought Vulnerability", which itself possesses only one subclass "Building Height/Number of Stories" (Alexander 1993, 280). A subclass for spatial factors impacting housing drought vulnerability is excluded because none are discussed in the literature. The critical infrastructure branch follows the expected relativity-based subclassing pattern, possessing the subclasses "Structural Factor Impacting Critical Infrastructure Drought Vulnerability" and "Spatial Factor Impacting Critical Infrastructure Drought Vulnerability". Each is assigned a single leaf factor class, "Material Desiccation Resistance" (Argyroudis et al. 2019, 3) and "Vegetation" (Argyroudis et al. 2019, 3) respectively.

"Factor Impacting Asset Erosion Vulnerability", the sixth subclass of "Factor Impacting Asset Vulnerability", is another class whose subdivision is too sparsely populated to warrant a summary table. The usual asset-based split is applied. In the case of the housing branch, this is followed by a division between structural and spatial factors. The structural factors include the single leaf subclass "Protective Barrier" (Alexander 1993, 294, 296) while the spatial factors include the 'measure quantifying spatial state' delineated leaf subclasses "Proximity to Water Body" (Alexander 1993, 294-296) and "Vegetation" (Alexander 1993, 293-294). "Factor Impacting Critical Infrastructure Erosion Vulnerability" is singly subclassed to possess a subclass for spatial factors but not one for structural factors due to the absence of any such clearly stated factors in the reviewed literature. Only one leaf factor class, "Proximity to Water Body" (Dawson et al. 2018, 10)(Jacobs et al. 2018, 485, 494) is included beneath "Spatial Factor Impacting Critical Infrastructure Erosion Vulnerability" in Table 22.

The next branch of factors impacting asset vulnerability is concerned with snow avalanches and is summarized in Table 37. The table shows that the structure beneath "Factor Impacting Asset Snow Avalanche Vulnerability" returns to the full template wherein an asset-based split is followed by respective relativity-based splits. The first of the resulting classes, the structural factors impacting housing, is divided into just two subclasses delineated by 'measure quantifying a structural state'. These two factors are sources from Alexander (1993)'s description of construction standards aimed to lower building vulnerability to snow avalanche impacts (195-196). The same section also provides the basis for the first three subclasses of “Spatial Factor Impacting Housing Snow Avalanche Vulnerability”, all of which involve the arrangement of buildings relative to each other as well as to a potential avalanche. These subclasses, along with “Topography” (Eckert et al. 2024, 370), each represent a unique ‘measure quantifying a spatial state’. On the side of factors impacting infrastructure, the structural factors once again only possess two concrete leaf factor classes in the literature. This division, based on ‘measure quantifying structural state’, is most directly sourced from the infrastructure risk assessment scenarios set forth by Eidsvig, Kristensen, and Vangelsten (2017) (499-500). Finally, “Topography” (Eckert et al. 2024, 370) is the only leaf-level spatial factor if identified in the reviewed literature as impacting critical infrastructure snow avalanche vulnerability.

Table 37: Factor Impacting Asset Snow Avalanche Vulnerability Summary

Sources	Factor Impacting Housing Snow Avalanche Vulnerability						Factor Impacting Critical Infrastructure Snow Avalanche Vulnerability		
	Structural Factor Impacting Housing Snow Avalanche Vulnerability		Spatial Factor Impacting Housing Snow Avalanche Vulnerability				Structural Factor Impacting Critical Infrastructure Snow Avalanche Vulnerability		Spatial Factor Impacting Critical Infrastructure Snow Avalanche Vulnerability
	Protective Barrier	Wall/ Frame Material	Building Density/Inter-Building Distance	Multi-Building Alignment /Block Shape	Building Orientation	Topography	Protective Barrier	Maintenance	Topography
(Alexander 1993, 189, 193-196)									
(Eckert et al. 2024, 370)									
(Eidsvig, Kristensen, and Vangelsten 2017, 499-500)									

“Factor Impacting Asset Saltwater Intrusion Vulnerability” is another class which possesses too few leaf factor subclasses to justify a summary table. Notably, the reviewed literature never identifies any saltwater intrusion impacts to housing (as shown in Table 12), thus the only direct subclass of “Factor Impacting Asset Saltwater Intrusion Vulnerability” in Table 22 is “Factor Impacting Critical Infrastructure Saltwater Intrusion Vulnerability”. A relativity split is applied to this subclass yielding “Structural Factor Impacting Critical Infrastructure Saltwater Intrusion Vulnerability” and “Spatial Factor Impacting Critical Infrastructure Saltwater Intrusion Vulnerability”. The former is assigned a single subclass, “Material

Saltwater Resistance” (NASEM 2014, 77-78), while the latter is assigned two, “Proximity to Water Body” (Markon et al. 2018, 1202) and “Elevation” (NASEM 2014, 46). This second pair is delineated based on ‘measure quantifying spatial state’.

Permafrost degradation, the next CCDNH for which vulnerability factors are evaluated in Table 22, is similarly too sparingly discussed in the reviewed literature for a summary table to warranted. “Factor Impacting Asset Permafrost Degradation Vulnerability” is first divided by asset of concern. The two resulting classes are each assigned only one subclass which represents the structural factors impacting the permafrost degradation vulnerability of each asset type. Neither is assigned a subclass for spatial factors because none are found in the literature. “Structural Factor Impacting Housing Permafrost Degradation Vulnerability” is singly subclassed to possess only “Foundation Type/Material” (Alexander 1993, 284-285). Meanwhile, “Structural Factor Impacting Critical Infrastructure Permafrost Degradation Vulnerability” is assigned three ‘measure quantifying structural state’ delineated subclasses: “Component Connection Flexibility” (Markon et al. 2018, 1202), “Foundation Type/Material” (Markon et al. 2018, 1197, 1202)(NASEM 2014, 163), and “Maintenance” (Ding et al. 2021, 10)(NASEM 2014, 163). Nowhere in the reviewed literature does there exist a unified discussion of these three structural factors.

While relatively stunted in the breadth of its structure, “Factor Impacting Asset Extreme Precipitation Hazard Vulnerability” gives rise to enough leaf factor classes to justify the creation of Table 38. The table demonstrates that the literature does not include any discussions of extreme precipitation hazard impacts or vulnerability factors with respect to housing. Thus, a single subclass for factors impacting critical infrastructure extreme precipitation hazard vulnerability is introduced. A relativity-based split is applied to this class. The structural branch of the split is subdivided into distinct measures which each quantify a unique structural state and is partially modelled on a tabulation from the literature (NASEM 2014, 77). The spatial branch is subdivided based on ‘measure quantifying a spatial state’ and does not have any precedent in the literature.

Table 38: Factor Impacting Asset Extreme Precipitation Hazard Vulnerability Summary

Sources	Factor Impacting Critical Infrastructure Extreme Precipitation Hazard Vulnerability						
	Structural Factor Impacting Critical Infrastructure Extreme Precipitation Hazard Vulnerability				Spatial Factor Impacting Critical Infrastructure Extreme Precipitation Hazard Vulnerability		
	Drainage	Protective Barrier	Year of Construction	Maintenance	Permeability	Slope	Proximity to Water Body
(Andrey et al. 2003, 334-335, 339-340)							
(Angel et al. 2018, 900-901)							
(Jacobs et al. 2018, 487)							
(NASEM 2014, 76-77, 79)							

The final subclass of “Factor Impacting Asset Vulnerability” is “Factor Impacting Asset Extreme Heat Vulnerability”. This class is not provided a summary table because it only gives rise to three leaf factor classes. Within the literature, no vulnerability factors for housing are ever identified, leading to this class possessing only “Factor Impacting Critical Infrastructure Extreme Precipitation Hazard Vulnerability” as a direct subclass. This subclass is itself divided into structural and spatial factors based on relativity. “Structural Factor Impacting Critical Infrastructure Extreme Heat Vulnerability” possesses two subclasses, “Material Fire/Heat Resistance” (Argyroudis et al. 2019, 3)(Dawson et al. 2018, 12)(Jacobs et al. 2018, 489)(NASEM 2014, 6) and “Year of Construction/Renovation/Refit” (Argyroudis et al. 2019, 3)(Habeeb, Vargo, and Stone 2015, 1662), a subdivision which is most directly inspired by the tabulation of Argyroudis et al. (2019) (3). “Spatial Factor Impacting Critical Infrastructure Extreme Heat Vulnerability” possesses “Vegetation” (Argyroudis et al. 2019, 3) as its only subclass in Table 22.

<u>Factor Impacting Asset Exposure</u>:

“Factor Impacting Asset Exposure” is the third and final subclass of “CCDNH Risk Factor” in the taxonomy of risk factors. This class represents the exposure component of risk (Ettinger et al. 2015, 564)(IPCC AR6 2022, “Risk”)(National Academies of Sciences, Engineering, and Medicine 2014, 56)(Reisinger et al. 2020, 6). As stated in the definition of this class in Table 22, the literature approaches exposure as either a measurement of a quantity of assets or as a measurement of the value of those assets. Throughout the subclasses of “Factor Impacting Asset Exposure”, most leaf factor classes fall into one of those two categories.

The subclassing of this class departs from the norm set by the previous two direct subclasses of “CCDNH Risk Factor”: the factors impacting asset exposure are not subclassed based on individual CCDNH’s. The absence of a CCDNH-based split stems from the literature’s tendency to converge on similar measures of exposure, regardless of the hazard. Instead, the first subdivision applied to the exposure factors is the familiar asset-based split between housing and critical infrastructure.

Table 39 provides a summary of the former, “Factor Impacting Housing Exposure”. The table demonstrates that this class is assigned two subclasses corresponding to an asset quantity based split between single- and multi-building factors impacting housing exposure. This approach of separating exposure factors is present in the literature and is best justified by differences in the scale and data granularity required by each (Joint Research Centre 2017, 54-55). Namely, quantifying the presence and arrangement of buildings, parcels, or properties requires a much lower granularity of data than does the identification of individual building characteristics. “Building Characteristic Impacting Housing Exposure”, the first of the two resulting subclasses, is assigned three subclasses which are delineated by the ‘measure quantifying structural state’ that each represents: “Building Value Measure Impacting Housing Exposure”, “Floor Area/Size of Building”, and “Number of Occupants/Dwellings per Building”. Respectively, these quantify the value, size, and utilization of a structure, a delineation approach that is clearly demonstrated in the literature (Dabbeek and Silva 2020, 794-798)(FEMA 2024a, 6-2-6-3). The class “Building Value Measure Impacting Housing Exposure” is further subdivided based on individual approaches to estimating building value (Merz et al. 2010, 1699-1701). As for the other branch of housing exposure factors concerning multi-building arrangements, two subclasses are assigned based on ‘measure quantifying spatial state’. “Building Density/Inter-Building Distance” influences exposure by providing a measure of the volume of buildings in a given area (Joint Research Centre 2017, 54-55)(Public Safety Canada 2024, 71). Meanwhile, the influence of “Settlement Type” on exposure operates indirectly through its influence on floor areas (Dabbeek and Silva 2020, 798) as well as on building value (Silva et al. 2020, 377).

Table 39: Factor Impacting Housing Exposure Summary

Sources *	Building Characteristic Impacting Housing Exposure						Multi-Building Arrangement Characteristic Impacting Housing Exposure	
	Building Value Measure Impacting Housing Exposure				Floor Area/Size of Building	Number of Occupants/ Dwellings per Building	Settlement Type	Building Density/ Inter-Building Distance
	Replacement/ Repair Cost	Maximum per Unit Area/ Length Damage	Market/ Depreciated Value	Insured Value				
(Armal et al. 2020, 6)								
(Dabbeek and Silva 2020, 794-798)								
(FEMA 2024a, 6-2-6-6, 6-11-6-13)								
(Fuchs et al. 2019, 589-590)								
(Gourevetch et al. 2023, 250-252, 258)								
(Joint Research Centre 2017, 9-10, 54-55)								
(Jongmon, Ward, and Aerts 2012, 830-832)								
(Merz et al. 2010, 1700, 1704-1705, 1718)								
(Public Safety Canada 2024, 23, 71, 75, 96-97)								

(Silva et al. 2020, 375-377)								

* The selected sources are those which discuss three or more of the eight leaf classes included in the table.

The set of classes representing factors impacting critical infrastructure exposure are summarized in Table 40. Their organizational structure follows a pattern similar to that shown in Table 39 with an initial division between factor classes based on asset quantity, between a single or multiple infrastructure assets. Here, characteristics of individual infrastructure assets are differentiated from the leaf factor class "Number of Sites/Assets", the only specific factor from the literature which approaches exposure using multiple assets (Sayers et al. 2015, 25). Beneath "Infrastructure Characteristic Impacting Critical Infrastructure Exposure", two direct subclasses are assigned. Each of these classes is made distinct by its 'measure quantifying structural state', quantifying structural value and capacity respectively. This split applied to infrastructure is not present in the literature. Instead, its use here is extrapolated from its application for housing. The first of these subclasses, "Infrastructure Value Measure Impacting Critical Infrastructure Exposure", is itself given two subclasses representing distinct infrastructure value measurement approaches. Both of these are separately present in the literature but they never compared or split within a source. The second subclass, "Infrastructure Capacity Characteristic Impacting Critical Infrastructure Exposure", is subdivided based on asset function to include subclasses treating the capacity characteristics of emergency facilities, utility sites, and transportation infrastructure (FEMA 2024a, 7-1-10-19). All three of these factor classes are assigned leaf exposure classes which are distinguished based on 'measure quantifying operating capacity'.

Table 40 demonstrates that the FEMA's HAZUS Inventory Technical Manual is the dominant source for factor leaf classes impacting infrastructure exposure. Within the Manual, the connection between many of the factor classes and critical infrastructure exposure is drawn by the use of these factors in calculating replacement costs, which are interpreted here as a measure of exposure.

Table 40: Factor Impacting Critical Infrastructure Exposure Summary

Sources *	Infrastructure Characteristic Impacting Critical Infrastructure Exposure									Number of Sites/ Assets
	Infrastructure Value Measure Impacting Critical Infrastructure Exposure		Infrastructure Capacity Characteristic Impacting Critical Infrastructure Exposure							
			Emergency Facility Capacity Characteristic Impacting Critical Infrastructure Exposure		Utility Site Capacity Characteristic Impacting Critical Infrastructure Exposure			Transportation Infrastructure Capacity Characteristic Impacting Critical Infrastructure Exposure		
	Replacement/ Repair Cost	Maximum per Unit Area/ Length Damage	Population Served	Floor Area/ Size of Building	Power Generating Capacity	Treatment/Pumping Capacity	Station Voltage	Total Length	Number of Lanes/ Tracks	
(FEMA 2024a, 7-5-7-7, 9-12-9-1										

3, 9-15, 10-4-10-11, 10-17)										
(Joint Research Centre 2017, 30-33, 75-76)										
(Sayers et al. 2015, vii-viii, 25)										

* The selected sources are those which discuss two or more of the ten leaf classes included in the table.

Discussion

Conclusion

Bibliography

1. Alexander, David. “Atmospheric and Hydrological Hazards.” In *Natural Disasters*, 1st ed., 120–216. CRC Press, 1993. https://doi.org/10.1201/9780203746080-3.

2. Alexander, David. “Damage and the built environment.” In *Natural Disasters*, 1st ed., 120–216. CRC Press, 1993. https://doi.org/10.1201/9780203746080-5.

3. Alexander, David. “Disasters and the land surface.” In *Natural Disasters*, 1st ed., 120–216. CRC Press, 1993. https://doi.org/10.1201/9780203746080-4.

4. Ali, Sk Ajim, Meriame Mohajane, Farhana Parvin, Antonietta Varasano, Sliman Hitouri, Ewa Łupikasza, and Quoc Bao Pham. “Mass Movement Susceptibility Prediction and Infrastructural Risk Assessment (IRA) Using GIS-Based Meta Classification Algorithms.” *Applied Soft Computing* 145 (2023): 1-27. https://doi.org/10.1016/j.asoc.2023.110591.

5. Allen, John T. "Climate Change and Severe Thunderstorms." *Oxford Research Encyclopedia of Climate Science*. 30 Jul. 2018; Accessed 14 Nov. 2024. https://oxfordre.com/climatescience/view/10.1093/acrefore/9780190228620.001.0001/acrefore-9780190228620-e-62.

6. Andrey, Jean, Brian Mills, Mike Leahy, and Jeff Suggett. “Weather as a Chronic Hazard for Road Transportation in Canadian Cities.” *Natural Hazards* 28, no. 2–3 (2003): 319–43. https://doi.org/10.1023/A:1022934225431.

7. Angel, Jim, Chris Swanston, Barbara Mayes Boustead, Kathryn C. Conlon, Kimberly R. Hall, Jenna L. Jorns, Kenneth E. Kunkel, Maria Carmen Lemos, Brent Lofgren, Todd A. Ontl, John Posey, Kim Stone, Eugene Takle, and Dennis Todey. “Midwest.” In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, edited by Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L.M. Lewis, Thomas K. Maycock, and Brooke C. Stewart, 872–940. Washington, DC, USA: U.S. Global Change Research Program, 2018. https://doi.org/10.7930/NCA4.2018.CH21.

8. Argyroudis, Sotirios A, Stergios A Mitoulis, Mike G Winter, and Amir M Kaynia. 2019. “Fragility of Transport Assets Exposed to Multiple Hazards: State-of-the-Art Review toward Infrastructural Resilience.” *Reliability Engineering & System Safety* 191: 1-22. https://doi.org/10.1016/j.ress.2019.106567.

9. Armal, Saman, Jeremy R. Porter, Brett Lingle, Ziyan Chu, Michael L. Marston, and Oliver E. J. Wing. “Assessing Property Level Economic Impacts of Climate in the US, New Insights and Evidence from a Comprehensive Flood Risk Assessment Tool.” *Climate* 8, no. 116 (2020): 1-20. https://doi.org/10.3390/cli8100116.

10. B. Merz, H. Kreibich, R. Schwarze, and A. Thieken. “Review Article “Assessment of Economic Flood Damage.”” *Natural Hazards and Earth System Sciences* 8 (2010): 1697–1724. https://doi.org/10.5194/nhess-10-1697-2010.

11. Bates, Paul D, Niall Quinn, Christopher Sampson, Andrew Smith, Oliver Wing, Jeison Sosa, James Savage, et al. “Combined Modeling of US Fluvial, Pluvial, and Coastal Flood Hazard under Current and Future Climates.” *Water Resources Research* 57, no. 2 (2021). https://doi.org/10.1029/2020WR028673.

12. Bezgrebelna, Mariya, Kwame McKenzie, Samantha Wells, Arun Ravindran, Michael Kral, Julia Christensen, Vicky Stergiopoulos, Stephen Gaetz, and Sean A Kidd. “Climate Change, Weather, Housing Precarity, and Homelessness: A Systematic Review of Reviews.” *International Journal of Environmental Research and Public Health* 18, no. 5812 (2021): 1-16. https://doi.org/10.3390/ijerph18115812.

13. Blackstock, Cindy. "The emergence of the breath of life theory." *Journal of Social Work Values and Ethics* 8, no. 1 (2011): 1-16.

14. Bloemendaal, Nadia, Ivan D Haigh, Hans de Moel, Sanne Muis, Reindert J Haarsma, and Jeroen C. J. H Aerts. 2020. “Generation of a Global Synthetic Tropical Cyclone Hazard Dataset Using STORM.” *Scientific Data* 7 (1): 40–40. https://doi.org/10.1038/s41597-020-0381-2.

15. Brachman, Ronald J. “What IS-A Is and Isn’t: An Analysis of Taxonomic Links in Semantic Networks.” *Computer* (Long Beach, Calif.) 16, no. 10 (1983): 30–36. https://doi.org/10.1109/MC.1983.1654194.

16. Brutti, Arianna, Antonio Di Pietro, Angelo Frascella, Sonia Giovinazzi, Cristiano Novelli, Gianluca D’Agosta, Stefano Pizzuti, Maurizio Pollino, Ane Ferreiro Sistiaga, Saúl Buitrago, Iñigo Lopez-Villamor, Simone Murazzo, and Gian Marco Revel. “Urban Data Governance: an interoperability-based approach for monitoring natural threats at different geographic scales, through Smart City

Platforms." paper presented at *CRITIS 2024*, September 2024, Rome. https://www.researchgate.net/publication/387994740_Urban_Data_Governance_an_interoperability-based_approach_for_monitoring_natural_threats_at_different_geographic_scales_through_Smart_City_Platforms.

17. Brzev, Svetlana, Charles Scawthorn, Andrew William Charleson, Luke Allen, Marjorie Greene, Kishor Jaiswal, and Vitor Silva. *GEM building taxonomy (Version 2.0)*. no. 2013-02. GEM Foundation, 2013. https://doi.org/10.13117/GEM.EXP-MOD.TR2013.02.

18. Cea, Luís, and Pierfranco Costabile. "Flood Risk in Urban Areas: Modelling, Management and Adaptation to Climate Change. A Review." Hydrology 9, no. 50 (2022): 1-35. https://doi.org/10.3390/hydrology9030050.

19. Collins, L, P Griffioen, G Newell, and A Mellor. "The Utility of Random Forests for Wildfire Severity Mapping." *Remote Sensing of Environment* 216 (2018): 374–84. https://doi.org/10.1016/j.rse.2018.07.005.

20. Cook, Wesley, Paul J Barr, and Marvin W Halling. "Bridge Failure Rate." *Journal of Performance of Constructed Facilities* 29, no. 3 (2015). https://doi.org/10.1061/(ASCE)CF.1943-5509.0000571.

21. Cruden, David M. and David J. Varnes, "Landslide Types and Processes," in *Landslides: Investigation and Mitigation*, ed. Keith Turner and Robert Schuster (Washington D.C: National Academy Press, 1996), 36-75.

22. Dabbeek, Jamal, and Vitor Silva. "Modeling the Residential Building Stock in the Middle East for Multi-Hazard Risk Assessment." *Natural Hazards (Dordrecht)* 100, no. 2 (2020): 781–810. https://doi.org/10.1007/s11069-019-03842-7.

23. Dawson, Richard J, David Thompson, Daniel Johns, Ruth Wood, Geoff Darch, Lee Chapman, Paul N Hughes, et al. 2018. "A Systems Framework for National Assessment of Climate Risks to Infrastructure." *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical, and Engineering Sciences* 376 (2121): 1-19. https://doi.org/10.1098/rsta.2017.0298.

24. de Groot, William J., Alan S. Cantin, Michael D. Flannigan, Amber J. Soja, Lynn M. Gowman, and Alison Newbery. "A Comparison of Canadian and Russian Boreal Forest Fire Regimes." *Forest Ecology and Management* 294 (2013): 23–34. https://doi.org/10.1016/j.foreco.2012.07.033.

25. de Groot, William J., Johann G. Goldammer, Tom Keenan, Michael A. Brady, Tim J. Lynham, Christopher O. Justice, Ivan A. Csiszar, and Kevin O'Loughlin. "Developing a Global Early Warning System for Wildland Fire." *Forest Ecology and Management* 234 (2006): S10. https://doi.org/10.1016/j.foreco.2006.08.025.

26. Ding, Yongjian, Cuicui Mu, Tonghua Wu, Guojie Hu, Defu Zou, Dong Wang, Wangping Li, and Xiaodong Wu. "Increasing Cryospheric Hazards in a Warming Climate." *Earth-Science Reviews* 213 (2021): 1-18. https://doi.org/10.1016/j.earscirev.2020.103500.

27. Eckert, Nicolas, Christophe Corona, Florie Giacona, Johan Gaume, Stephanie Mayer, Alec van Herwijnen, Pascal Hagenmuller, and Markus Stoffel. "Climate Change Impacts on Snow Avalanche Activity and Related Risks." *Nature Reviews. Earth & Environment* 5, no. 5 (2024): 369–89. https://doi.org/10.1038/s43017-024-00540-2.

28. Eidsvig, Unni Marie K, Krister Kristensen, and Bjørn Vidar Vangelsten. 2017. "Assessing the Risk Posed by Natural Hazards to Infrastructures." *Natural Hazards and Earth System Sciences* 17 (3): 481–504. https://doi.org/10.5194/nhess-17-481-2017.

29. Espada, Rudolf, Armando Apan, and Kevin McDougall. "Vulnerability Assessment of Urban Community and Critical Infrastructures for Integrated Flood Risk Management and Climate Adaptation Strategies." *International Journal of Disaster Resilience in the Built Environment* 8, no. 4 (2017): 375–411. https://doi.org/10.1108/IJDRBE-03-2015-0010.

30. Ettinger, Susanne, Loic Mounaud, Christina Magill, Anne-Francoise Yao-Lafourcade, Jean-Claude Thouret, Vern Manville, Caterina Negulescu, et al. 2016. "Building Vulnerability to Hydro-Geomorphic Hazards; Estimating Damage Probability from Qualitative Vulnerability Assessment Using Logistic Regression." *Journal of Hydrology (Amsterdam)* 541: 563–81. https://doi.org/10.1016/j.jhydrol.2015.04.017.

31. FEMA. *Hazus Flood Model Technical Manual*. Washington, DC: U.S. Department of Homeland Security, Federal Emergency Management Agency, 2024c, https://www.fema.gov/sites/default/files/documents/fema_hazus-flood-model-technical-manual-6-1.pdf.

32. FEMA. *Hazus Hurricane Model Technical Manual*. Washington, DC: U.S. Department of Homeland Security, Federal Emergency Management Agency, 2024b, https://www.fema.gov/sites/default/files/documents/Hazus_6.1_Hurricane_Model_Technical_Manual.pdf.

33. FEMA. *Hazus Inventory Technical Manual*. Washington, DC: U.S. Department of Homeland Security, Federal Emergency

Management Agency, 2024a, https://www.fema.gov/sites/default/files/documents/fema_hazus-inventory-technical-manual-6.1.pdf.

34. Fleming, Elizabeth, Jeffrey Payne, William Sweet, Michael Craghan, John Haines, Juliette F. Hart, Heidi Stiller, and Ariana Sutton-Grier. “Coastal Effects.” In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, edited by Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L.M. Lewis, Thomas K. Maycock, and Brooke C. Stewart, 322–352. Washington, DC, USA: U.S. Global Change Research Program, 2018. https://doi.org/10.7930/NCA4.2018.CH8.

35. Friedland, Carol J. “Residential Building Damage from Hurricane Storm Surge: Proposed Methodologies to Describe, Assess and Model Building Damage.” ProQuest Dissertations & Theses, 2009.

36. Fuchs, S, M Keiler, R Ortlepp, R Schinke, and M Papathoma-Köhle. 2019. “Recent Advances in Vulnerability Assessment for the Built Environment Exposed to Torrential Hazards: Challenges and the Way Forward.” *Journal of Hydrology (Amsterdam)* 575: 587–95. https://doi.org/10.1016/j.jhydrol.2019.05.067.

37. Galasso, Carmine, Maria Pregnolato, and Fulvio Parisi. “A Model Taxonomy for Flood Fragility and Vulnerability Assessment of Buildings.” *International Journal of Disaster Risk Reduction* 53 (2021): 1-14. https://doi.org/10.1016/j.ijdrr.2020.101985.

38. Ginger, J D, D J Henderson, C J Leitch, and G N Boughton. “Tropical Cyclone Larry: Estimation of Wind Field and Assessment of Building Damage.” *Australian Journal of Structural Engineering* 7, no. 3 (2007): 209–24. https://doi.org/10.1080/13287982.2007.11464977.

39. Gourevitch, Jesse D, Carolyn Kousky, Yanjun Liao, Christoph Nolte, Adam B Pollack, Jeremy R Porter, and Joakim A Weill. “Unpriced Climate Risk and the Potential Consequences of Overvaluation in US Housing Markets.” *Nature Climate Change* 13, no. 3 (2023): 250–57. https://doi.org/10.1038/s41558-023-01594-8.

40. Habeeb, Dana, Jason Vargo, and Brian Stone. “Rising Heat Wave Trends in Large US Cities.” *Natural Hazards (Dordrecht)* 76, no. 3 (2015): 1651–65. https://doi.org/10.1007/s11069-014-1563-z.

41. Hayhoe, Katharine, Donald J. Wuebbles, David R. Easterling, David W. Fahey, Sarah Doherty, James Kossin, William Sweet, Russell Vose, and Michael Wehner. “Our Changing Climate.” In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, edited by Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L.M. Lewis, Thomas K. Maycock, and Brooke C. Stewart, 72–144. Washington, DC, USA: U.S. Global Change Research Program, 2018. https://doi.org/10.7930/NCA4.2018.CH2.

42. Heneka, P, T Hofherr, B Ruck, and C Kottmeier. 2006. “Winter Storm Risk of Residential Structures – Model Development and Application to the German State of Baden-Württemberg.” *Natural Hazards and Earth System Sciences* 6 (5): 721–33. https://doi.org/10.5194/nhess-6-721-2006.

43. Hoque, Muhammad Al-Amin, Stuart Phinn, Chris Roelfsema, and Iraphne Childs. 2018. “Assessing Tropical Cyclone Risks Using Geospatial Techniques.” *Applied Geography (Sevenoaks)* 98: 22–33. https://doi.org/10.1016/j.apgeog.2018.07.004.

44. Hungr, Oldrich, Serge Leroueil, and Luciano Picarelli. “The Varnes Classification of Landslide Types, an Update.” *Landslides: Journal of the International Consortium on Landslides* 11, no. 2 (2014): 167–94. https://doi.org/10.1007/s10346-013-0436-y.

45. Hungr, Oldrich. “Classification and Terminology.” In *Debris-Flow Hazards and Related Phenomena*, 9–23. Berlin, Heidelberg: Springer Praxis Books, 2005. https://doi.org/10.1007/3-540-27129-5_2.

46. Hunter, Alasdair, David B Stephenson, Theo Economou, Mark Holland, and Ian Cook. “New Perspectives on the Collective Risk of Extratropical Cyclones.” *Quarterly Journal of the Royal Meteorological Society* 142, no. 694 (2016): 243–56. https://doi.org/10.1002/qj.2649.

47. IPCC. “Annex I: Glossary,” edited by Reisinger, Andy, Diego Cammarano, Andreas Fischlin, Jan S. Fuglestvedt, Gerrit Hansen, Yonghun Jung, Chloé Ludden, Valérie Masson-Delmotte, Robin Matthews, Katja Mintenbeck, Dan.J. Orendain, Anna Pirani, Elvira Poloczanskaa, and José Romero. In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Core Writing Team, Hoesung Lee, and José Romero, 119-130. Geneva, Switzerland: IPCC, 2023. https://doi.org/10.59327/IPCC/AR6-9789291691647.002.

48. Jacobs, Jennifer M., Michael Culp, Lia Cattaneo, Paul Chinowsky, Anne Choate, Susanne DesRoches, Scott Douglass, and Rawlings Miller. “Transportation.” In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, edited by Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L.M. Lewis, Thomas K.

Maycock, and Brooke C. Stewart, 479–511. Washington, DC, USA: U.S. Global Change Research Program, 2018. https://doi.org/10.7930/NCA4.2018.CH12.

49. Jay, Alexa, David R. Reidmiller, Christopher W. Avery, Daniel Barrie, Benjamin J. DeAngelo, Apurva Dave, Matthew Dzaugis, Michael Kolian, Kristin L.M. Lewis, Katie Reeves, and Darrell Winner. "Overview." In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, edited by Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L.M. Lewis, Thomas K. Maycock, and Brooke C. Stewart, 33–71. Washington, DC, USA: U.S. Global Change Research Program, 2018. https://doi.org/10.7930/NCA4.2018.CH1.

50. Joint Research Centre: Institute for the Protection and Security of the Citizen, Huizinga, Jan, Hans De Moel, and Wojciech Szewczyk. *Global flood depth-damage functions: Methodology and the database with guidelines*. Luxembourg: Publications Office of the European Union, 2017. https://data.europa.eu/doi/10.2760/16510.

51. Joint Research Centre: Institute for the Protection and Security of the Citizen, Ufuk Hancilar, Fabio Taucer, Georgios Tsionis, and Bijan Khazai. *Guidelines for Typology Definition of European Physical Assets for Earthquake Risk Assessment*. Edited by Ufuk Hancilar, Fabio Taucer, and Bijan Khazai. Luxembourg: Publications Office of the European Union, 2013. https://data.europa.eu/doi/10.2788/68751.

52. Jongman, Brenden, Philip J Ward, and Jeroen C.J.H Aerts. "Global Exposure to River and Coastal Flooding: Long Term Trends and Changes." *Global Environmental Change* 22, no. 4 (2012): 823–35. https://doi.org/10.1016/j.gloenvcha.2012.07.004.

53. Klaver, Niels R, Tom A Dijkstra, Andrew Barkwith, Claire Dashwood, Steven M De Jong, and Rens L. P. H van Beek. "Mass Movement Hazard & Global Climate Change; Physical-Deterministic Modelling Study of the Rest and Be Thankful Pass, Scotland UK." *Geomorphology (Amsterdam, Netherlands)* 446 (2024): 1-20. https://doi.org/10.1016/j.geomorph.2023.108979.

54. Koks, E. E, J Rozenberg, C Zorn, M Tariverdi, M Vousdoukas, S. A Fraser, J. W Hall, and S Hallegatte. "A Global Multi-Hazard Risk Analysis of Road and Railway Infrastructure Assets." *Nature Communications* 10, no. 1 (2019): 2677–11. https://doi.org/10.1038/s41467-019-10442-3.

55. Kuai, X., Zhigang Zhao and Renzhong Guo. 2024 "Smart City Ontology Framework for Urban Data Integration and Governance Applications" Preprints. https://doi.org/10.20944/preprints202410.2577.v1.

56. Luo, H.Y, L.M Zhang, L.L Zhang, J He, and K.S Yin. "Vulnerability of Buildings to Landslides: The State of the Art and Future Needs." *Earth-Science Reviews* 238 (2023): 1-18. https://doi.org/10.1016/j.earscirev.2023.104329.

57. Luo, Xiangang, Feikai Lin, Yihong Chen, Shuang Zhu, Zhanya Xu, Zhibin Huo, Mengliang Yu, and Jing Peng. "Coupling Logistic Model Tree and Random Subspace to Predict the Landslide Susceptibility Areas with Considering the Uncertainty of Environmental Features." *Scientific Reports* 9, no. 1 (2019): 15369–13. https://doi.org/10.1038/s41598-019-51941-z.

58. Markon, Carl J., Stephen T. Gray, Matthew Berman, Laura Eerkes-Medrano, Thomas Hennessy, Henry P. Huntington, Jeremy Littell, Molly McCammon, Richard Thoman, and Sarah Trainor. "Alaska." In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, edited by Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L.M. Lewis, Thomas K. Maycock, and Brooke C. Stewart, 1185–1241. Washington, DC, USA: U.S. Global Change Research Program, 2018. https://doi.org/10.7930/NCA4.2018.CH26.

59. Martinsen, Ole. "Mass movements." In *The Geological Deformation of Sediments*, edited by Maltman, Alex, 127-165. Springer, Dordrecht, 1994. https://doi.org/10.1007/978-94-011-0731-0_5.

60. Maxwell, Keely, Susan Julius, Anne Grambsch, Ann Kosmal, Libby Larson, and Nancy Sonti. "Built Environment, Urban Systems, and Cities." In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, edited by Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L.M. Lewis, Thomas K. Maycock, and Brooke C. Stewart, 438–478. Washington, DC, USA: U.S. Global Change Research Program, 2018. https://doi.org/10.7930/NCA4.2018.CH11.

61. McCarthy, Ian. "Manufacturing Classification: Lessons from Organizational Systematics and Biological Taxonomy." *Journal of Manufacturing Technology Management* 6, no. 6 (1995): 37-.

62. National Academies of Sciences, Engineering, and Medicine. *Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report*. Washington, DC: The National Academies Press, 2014. https://doi.org/10.17226/22473.

63. Nguyen, Viet Nghia, Peyman Yariyan, Mahdis Amiri, An Dang Tran, Tien Dat Pham, Minh Phuong Do, Phuong Thao Thi Ngo, Viet Ha Nhu, Nguyen Quoc Long, and Dieu Tien Bui. “A New Modeling Approach for Spatial Prediction of Flash Flood with Biogeography Optimized CHAID Tree Ensemble and Remote Sensing Data.” *Remote Sensing (Basel, Switzerland)* 12, no. 9 (2020): 1-21. https://doi.org/10.3390/RS12091373.

64. Papathoma-Köhle, Maria, M. Schlögl, C. Garlichs, M. Diakakis, S. Mavroulis, and S. Fuchs. “A Wildfire Vulnerability Index for Buildings.” *Scientific Reports* 12, no. 1 (2022): 1–15. https://doi.org/10.1038/s41598-022-10479-3.

65. Papathoma-Köhle, Maria, Matthias Schlögl, and Sven Fuchs. “Vulnerability Indicators for Natural Hazards: An Innovative Selection and Weighting Approach.” *Scientific Reports* 9, no. 1 (2019): 1–14. https://doi.org/10.1038/s41598-019-50257-2.

66. Papathoma-Köhle, Maria, B. Neuhäuser, K. Ratzinger, H. Wenzel, and D. Dominey-Howes. “Elements at Risk as a Framework for Assessing the Vulnerability of Communities to Landslides.” *Natural Hazards and Earth System Sciences* 6 (2007): 765–79. https://doi.org/10.5194/nhess-7-765-2007.

67. Peduzzi, P, B Chatenoux, H Dao, A De Bono, C Herold, J Kossin, F Mouton, and O Nordbeck. “Global Trends in Tropical Cyclone Risk.” *Nature Climate Change* 2, no. 4 (2012): 289–94. https://doi.org/10.1038/nclimate1410.

68. Pita, G, J.-P Pinelli, S Cocke, K Gurley, J Mitrani-Reiser, J Weekes, and S Hamid. “Assessment of Hurricane-Induced Internal Damage to Low-Rise Buildings in the Florida Public Hurricane Loss Model.” *Journal of Wind Engineering and Industrial Aerodynamics* 104–106 (2012): 76–87. https://doi.org/10.1016/j.jweia.2012.03.023.

69. Pitilakis, K, H Crowley, A. M Kaynia, A.M Kaynia, K Pitilakis, and H Crowley. *SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk : Buildings, Lifelines, Transportation Networks and Critical Facilities. Geotechnical, Geological and Earthquake Engineering*. 2014th ed. Vol. 27. Netherlands: Springer Nature, 2014. https://doi.org/10.1007/978-94-007-7872-6.

70. Public Safety Canada. *National Risk Profile A national emergency preparedness and awareness tool*. 2024. https://www.publicsafety.gc.ca/cnt/rsrcs/pblctns/2023-nrp-pnr/index-en.aspx.

71. Quesada-Ganuza, Laura, Leire Garmendia, and Alessandra Gandini. “2 - A Framework for Risk Assessment.” In *Adapting the Built Environment for Climate Change*, edited by Fernando Pacheco-Torgal and Claes-Göran Granqvist, 17-36. Woodhead Publishing, 2023. https://doi.org/10.1016/B978-0-323-95336-8.00017-2.

72. Reisinger, Andy, Mark Howden, Carolina Vera, et al. *The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions*. Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2020. https://www.ipcc.ch/site/assets/uploads/2021/01/The-concept-of-risk-in-the-IPCC-Sixth-Assessment-Report.pdf.

73. Sang-Jin Park, and Dong-Kun Lee. “Prediction of Coastal Flooding Risk under Climate Change Impacts in South Korea Using Machine Learning Algorithms.” *Environmental Research Letters* 15, no. 9 (2020). https://doi.org/10.1088/1748-9326/aba5b3.

74. Sayers, PB, M Horritt, E Penning-Rowsell, and A McKenzie. *Climate Change Risk Assessment 2017: Projections of Future Flood Risk in the UK*. Research undertaken by Sayers and Partners on behalf of the Committee on Climate Change. London, UK: Committee on Climate Change, 2015. https://www.theccc.org.uk/publication/sayers-for-the-asc-projections-of-future-flood-risk-in-the-uk/.

75. Schwarz, Jochen, and Holger Maiwald. "Damage and loss prediction model based on the vulnerability of building types." In RIMAX Contributions at the 4th International Symposium on Flood Defence (ISFD4). *Deutsches GeoForschungsZentrum GFZ*, 2009. http://dx.doi.org/10.13140/2.1.1358.3043.

76. Schweizer, Juerg, J. Bruce Jamieson, and Martin Schneebeli. “Snow Avalanche Formation.” *Reviews of Geophysics* (1985) 41, no. 4 (2003): 1-25. https://doi.org/10.1029/2002RG000123.

77. Silva, Vitor, Desmond Amo-Oduro, Alejandro Calderon, Catarina Costa, Jamal Dabbeek, Venetia Despotaki, Luis Martins, et al. “Development of a Global Seismic Risk Model.” *Earthquake Spectra* 36, no. 1 (2020): 372–94. https://doi.org/10.1177/8755293019899953.

78. Skidmore, Mark. “A Taxonomy of Natural Disasters.” In *Handbook on the Economics of Disasters*, 13–28. Cheltenham, UK: Edward Elgar Publishing, 2022. https://doi.org/10.4337/9781839103735.00007.

79. Stein, Lina, Francesca Pianosi, and Ross Woods. “Event‐based Classification for Global Study of River Flood Generating Processes.” *Hydrological Processes* 34, no. 7 (2020): 1514–29. https://doi.org/10.1002/hyp.13678.

80. Stephenson, David B. “Definition, Diagnosis, and Origin of Extreme Weather and Climate Events.” In *Climate Extremes and Society*, 11–23. Cambridge University Press, 2008. https://doi.org/10.1017/CBO9780511535840.004.

81. Syphard, Alexandra D, Jon E Keeley, Avi Bar Massada, Teresa J Brennan, and Volker C Radeloff. “Housing Arrangement and Location Determine the Likelihood of Housing Loss Due to Wildfire.” *PLoS ONE* 7, no. 3 (2012): 1-13. https://doi.org/10.1371/journal.pone.0033954.

82. Tarasova, Larisa, Ralf Merz, Andrea Kiss, Stefano Basso, Günter Blöschl, Bruno Merz, Alberto Viglione, et al. “Causative Classification of River Flood Events.” Wiley Interdisciplinary Reviews. *Water* 6, no. 4 (2019): 1-23. https://doi.org/10.1002/wat2.1353.

83. Taxonomy Oversight Group. *Taxonomy Best Practice Evaluation Framework*. London, UK: Office for National Statistics, 2022. https://www.ons.gov.uk/methodology/classificationsandstandards/taxonomybestpracticeframework.

84. Tedim, Fantina, Vittorio Leone, Malik Amraoui, Christophe Bouillon, Michael Coughlan, Giuseppe Delogu, Paulo Fernandes, et al. “Defining Extreme Wildfire Events: Difficulties, Challenges, and Impacts.” *Fire (Basel, Switzerland)* 1, no. 9 (2018): 1-28. https://doi.org/10.3390/fire1010009.

85. Trenberth, Kevin E. “Changes in precipitation with climate change.” *Climate Research* 47, no. 1-2 (2011): 123-138. https://doi.org/10.3354/cr00953.

86. Varnes, David J. “Slope Movement Types and Processes.” In *Landslides: Analysis and Control, Special Report 176*, edited by R.L. Schuster and R.J. Krizek, 11-33. Washington, D.C.: Transportation Research Board, National Academy of Sciences, 1978.

87. Vormoor, Klaus, Deborah Lawrence, Lena Schlichting, Donna Wilson, and Wai Kwok Wong. 2016. “Evidence for Changes in the Magnitude and Frequency of Observed Rainfall vs. Snowmelt Driven Floods in Norway.” *Journal of Hydrology (Amsterdam)* 538: 33–48. https://doi.org/10.1016/j.jhydrol.2016.03.066.

88. Wang, Tianni, Zhuohua Qu, Zaili Yang, Timothy Nichol, Geoff Clarke, and Ying-En Ge. “Climate Change Research on Transportation Systems: Climate Risks, Adaptation and Planning.” *Transportation Research. Part D, Transport and Environment* 88 (2020): 1-17. https://doi.org/10.1016/j.trd.2020.102553.

89. Wilbanks, Thomas J. and Steven J. Fernandez. In *Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report for the U.S. Department of Energy in Support of the National Climate Assessment*, 41-54. Washington, DC: Island Press/Center for Resource Economics, 2014. https://doi.org/10.5822/978-1-61091-556-4_4.

90. Zamuda, Craig, Daniel E. Bilello, Guenter Conzelmann, Ellen Mecray, Ann Satsangi, Vincent Tidwell, and Brian J. Walker. “Energy Supply, Delivery, and Demand.” In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, edited by Reidmiller, David R., Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Kristin L.M. Lewis, Thomas K. Maycock, and Brooke C. Stewart, 174–201. Washington, DC, USA: U.S. Global Change Research Program, 2018. https://doi.org/10.7930/NCA4.2018.CH4.

91. Zhang, Yuehong, Shaohong Wu, Erfu Dai, Dengwei Liu, and Yunhe Yin. “Identification and Categorization of Climate Change Risks.” *Chinese Geographical Science* 18, no. 3 (2008): 268–75. https://doi.org/10.1007/s11769-008-0268-1.

Appendix

Appendix A

Analysis of Terms and Concepts

Appendix B

Class Definition:

With few exceptions, each hazard class within Table 3 is defined according to each of their respective formal definitions in the literature reviewed. The sources cited in the table each provide a full or partial definition of the class to which they are appended. A tabulation of each of these definitions is found in Appendix A and a description of their processing in Appendix B.

There are 2 hazard classes included in the taxonomy which are never mentioned or implied in the reviewed literature. Additionally, there are 8 hazard classes included in the taxonomy which, while never formally defined in the reviewed literature, are implied to exist or used under a different name. All 10 of these classes are included in the taxonomy to aid in organization of the taxonomy and not with the goal of introducing a novel class of hazards.

Treatment of Hazard Class Definitions:

With few exceptions, the definition of each hazard class included in the terms analysis is determined through three steps:

1. For each class, the first step of this process is the tabulation of every instance in which the term or its close analogues appear in the reviewed literature. These instances may take the form of formal definitions, implied definitions, or descriptions of important attributes, characteristics, or behaviors.
2. From these instances, an all-encompassing generalized definition is synthesized. In cases in which conflicting or irreconcilably different definitions appear, multiple generalized definitions may be produced, one for each grouping of irreconcilable instances.
3. Finally, the generalized definition is evaluated against the wider context of the taxonomy in which the class will be introduced. The criteria under consideration include: the ability to be regarded as a member of each of its superclasses; the ability to inherit the description of each its superclasses; the ability of each of its subclasses to possess a variation of its subject; the ability to pass on its description to each of its subclasses. Further explanation of these requirements is provided by the explanation of subClassOf relationships. Upon evaluation, the content or language of the generalized definition may be adjusted in order to better fit the demands of the taxonomy. Any such adjustments made must not significantly alter the practical meaning of the definition. The adjusted definition becomes the definition used for the associated class in the taxonomy. Where multiple generalized definitions are produced, each is evaluated in turn and a single one best able to fit the criteria is selected. After a single generalized definition is selected, any necessary adjustments are made.

Classes Entirely Absent from the Literature:

Among the exceptions to this rule are two classes which, while included in the taxonomy, are never defined, mentioned, or implied in the reviewed literature: “CCDNH Posing a Risk to Housing and/or Critical Infrastructure” and “Water Body-Driven Flood". These classes are introduced as categorization tools for better established hazards which are present in the literature.

The first, “CCDNH Posing a Risk to Housing and/or Critical Infrastructure", arises as the root concept of the taxonomy because it represents the specific scope of this survey in terms of both the risk drivers and at-risk assets of interest. While hazards driven by climate change (Public Safety Canada 2024), hazards considered to be natural (Alexander 1993), hazards posing a risk to infrastructure (Argyroudis et al. 2019), and hazards posing a risk to housing are each relatively prevalent concepts in the reviewed literature, no source reviewed brings together all four of these concepts.

The other classes absent from the literature, “Water Body-Driven Flood", is introduced to group together and emphasize an important category of flood hazards: those driven by the overflowing of an adjacent water body. An application-driven justification for the existence of this category is the importance of understanding the dominant immediate source of flood-water in attempting to model the impacts and risk of a flood hazard. Another justification, organizationally-driven, is to enable the splitting of flood hazards into one of two possible categories: water body-driven or pluvial. This binary facilitates the evaluation of flood hazards against one another.

Classes Absent from, but Implied by, the Literature:

A number of other classes included in the taxonomy are either implied to exist or used under a different name in the reviewed literature: “Hydrospheric Hazard", “Lithospheric Hazard", “Atmospheric Hazard", “Falling Mass Movement", “Sliding Mass Movement", “Flowing Mass Movement", “Convective Hazard", and “Extreme Precipitation Hazard". Each of these hazard classes uses a wording which is not explicitly present in the reviewed literature. In the case of the implied concepts, each possesses close analogues in the reviewed literature from which definitions are borrowed and adjusted. In the case of equivalent but differently named concepts, the definitions from the reviewed literature are reused without adjustment.

Starting with the hazard sphere classes, all three are implied classes. A clear precedent for splitting hazards on the basis of spheres stems from the definition of *extreme events* put forth by Alexander’s 1993 book, *Natural Disasters*:

> “we can define an extreme event as any manifestation in a geophysical system (lithosphere, hydrosphere, biosphere or atmosphere) which differs substantially or significantly from the mean”(5).

This definition of extreme events is presented in the context of a discussion defining natural hazards and disasters. In this way, Alexander indirectly associates the hydrosphere, lithosphere, and atmosphere with natural hazards. Two of the book’s subsequent chapters, “Atmospheric and hydrological hazards” and “Disasters and the land surface", further encourage this association with both their titles and content. While the reviewed literature does not contain any other direct references to the hazard spheres, it does contain many analogues. For hydrospheric hazards, the most common analogue is the use of “hydrological” to describe a group of hazards (Alexander 1993)(Argyroudis et al. 2019)(Dawson, et al.

2018)(Skidmore 2022)(Trenberth 2011)(Vormoor et al. 2016). For atmospheric hazards, the analogues used in the reviewed literature are "meteorological" and "climatological"(Argyroudis et al. 2019)(Skidmore 2022). When combined, "meteorological" and "climatological" hazards can come to encompass most atmospheric hazards (Skidmore 2022). Finally, the analogues to lithospheric hazards used in the reviewed literature are "geological"(Argyroudis et al. 2019) and "geophysical"(Skidmore 2022). Notably, this discussion of hazard spheres excludes "Cryospheric Hazard" because this class of hazards is explicitly presented and defined in the reviewed literature (Ding et al. 2021).

Across all of the direct mentions and analogues of the three implied hazard spheres, the reviewed literature consistently stops short of providing formal definitions. Instead, sources rely on general definitions applicable to all hazards or on lists of the lower level hazards falling under a given sphere or analogue. As a result of the lack of formal definitions in the reviewed literature, the definitions used in Table 3 for these hazard spheres are a synthesis of the available informal definitions. These synthesized definitions conform to the informal definitions of the reviewed literature while also being fitted to the demands of the taxonomy. While the synthesized definitions do not make explicit mention of certain attributes, characteristics, or behaviors from the informal definitions, they are never contradicted.

For example, the definition of "Hydrospheric Hazard" is compatible with the wide variety of criteria set by informal definitions in the literature: it includes floods, storm surges (coastal floods), droughts, mass movements (Skidmore 2022)(Trenberth 2011)(Vormoor et al. 2016); it manifests in a geophysical system, represents extreme (differing substantially from the mean) events, and may affect an urban area (Alexander 1993); it may be characterized by intensity, spatial variability, and probability of occurrence (Argyroudis et al. 2019); it perpetrates climate risk (Dawson et al. 2018). The decision of which of these attributes, if any, to mention explicitly in the definition of "Hydrospheric Hazard" is driven by the rules of the taxonomy, namely, that it should be broad enough to encompass all of its subclasses while remaining consistent with all of the descriptions of its superclass.

The next group of hazard classes are three of the mass movement modes: "Falling Mass Movement", "Sliding Mass Movement", and "Flowing Mass Movement". Each of these classes is renamed from a corresponding mode of movement in Varnes' 1978 *Slope Movement Types and Processes* and its subsequent updates and additions (Cruden and Varnes 1996)(Hungr, Leroueil, and Picarelli 2014). In Varnes' classification system as well as the works that followed, these hazards are referred to as *falls*, *slides*, and *flows* while the terms *falling mass movement*, *sliding mass movement*, and *flowing mass movement* never appear. The names of these categories of hazards were adjusted for use in Table 3 to emphasize their character as types of mass movement and therefore, subclasses of the class "Mass Movement". These new terms are stand-ins and do not introduce new concepts. As such, they take their definitions from the formal definitions of *falls*, *slides*, and *flows* which are found in the reviewed literature.

The fourth mode of mass movement, "Subsiding Mass Movement", is another implied but formally absent class. It represents a rewording of the *subsidence*, a hazard which is repeatedly referenced in the literature (Alexander 1993)(National Academies of Science, Engineering, and Medicine 2014). The rewording allows for the phenomenon to be more closely associated with the other mass movement modes, facilitating comparison across them. Its definition is once again sourced from the formal definitions put for by the literature for *subsidence*.

Finally, “Convective Hazard” and “Extreme Precipitation Hazard” are both hazard classes renamed from equivalent concepts in the reviewed literature. The terms used by the reviewed literature to describe the equivalent concepts are *convective phenomena* (Stephenson 2008) and *extreme precipitation event* (IPCC AR6 2022, “Extreme/heavy precipitation event”), respectively. In both instances, the wording of the concept is changed for use in Table 3 in order to more clearly conform with the need for all classes in the taxonomy to be hazards. The definitions of both “Convective Hazard” and “Extreme Precipitation Hazard” are taken from their equivalent concepts with little adjustment.

subClassOf/superClassOf Relationships:

The requirement that subClassOf/superClassOf relationships exist between every pair of directly connected classes in Table 3 shapes the structure and definitions of the taxonomy. The top-down characteristics of this are clearly demonstrated by considering the influence of the root class, “CCDNH Posing a Risk to Housing and/or Critical Infrastructure”, on the other classes of Table 3. The definition of this root class establishes a subject, natural hazard, and a two part description: it has a frequency and/or magnitude which is increased as a result of climate change, and it has the potential to cause significant negative effects to housing and/or critical infrastructure. Therefore, in following with the subClassOf/superClassOf relationships, every class in Table 3 must be a natural hazard described as having a frequency and/or magnitude increased by climate change and the potential to cause significant negative effects to housing and/or critical infrastructure.

Top-Down Characteristics:

Continuing with the example of the root class, the top-down characteristics of the subClassOf relationship requirement enable the downwards inheritance of descriptions to occur without necessitating the definitions of every class in the taxonomy to explicitly state their shared elements. Provided only subClassOf relationships in which every class is a subclass of its superclass, the transitive nature of the subClassOf relationship ensures that the subject of every class is a variation of the subject of the root class, natural hazard. Ensuring the inheritance of the description of the root classes requires that each non-root class be individually evaluated for compliance with that description. This is accomplished for each class by considering whether or not it has a frequency and/or magnitude that is increased by climate change, and whether or not it has an effect liable to harm housing and/or critical infrastructure.

This exercise of checking the top-down compliance of the classes is not limited to starting from the root class of Table 3. It can be repeated by selecting any non-leaf class and treating it as the root class of a separate taxonomy comprising itself and all of the classes below it.

Bottom-Up Characteristics:

The bottom-up characteristics of the subClassOf relationship requirement can be observed by selecting a leaf class of Table 3 and following the direct lineage leading to the root class. Consider the leaf class “Extreme Heat". The direct lineage from this leaf class to the root class is shown in Figure 1.

Figure 1: Lineage of Extreme Heat

“Extreme Heat”

Subject - *atmospheric hazard*
Description - "results from a temperature maximum, minimum, or average which exceeds a set high percentile of the distribution of available historical data for a certain area and duration of time."
↓
"Atmospheric Hazard"
Subject - *CCDNH posing a risk to housing and/or critical infrastructure*
Description - "results from the interaction of forces and elements in the atmosphere."
↓
"CCDNH Posing a Risk to Housing and/or Critical Infrastructure"
Subject - *natural hazard*
Description - "has a frequency and/or magnitude which is increased as a result of climate change and has the potential to cause significant negative effects to housing and/or critical infrastructure."

Analyzing the subjects in order, the subject of "Extreme Heat" is *atmospheric hazard*, which is also its superclass. The same is true for "Atmospheric Hazard" whose subject, *CCDNH posing a risk to housing and/or critical infrastructure*, also corresponds to its superclass. This pattern confirms that all classes in this lineage are members of the root class.

Analyzing the descriptions in order, "Extreme Heat"'s description, "results from a temperature maximum, minimum, or average which exceeds a set high percentile of the distribution of available historical data for a certain area and duration of time", can be compared against the description of "Atmospheric Hazard", "results from the interaction of forces and elements in the atmosphere." The first description is found to not conflict with the second and, in this case, to even directly conform to the second. Next, "Extreme Heat"'s description can be compared against the description of "CCDNH Posing a Risk to Housing and/or Critical Infrastructure", "has a frequency and/or magnitude which is increased as a result of climate change and has the potential to cause significant negative effects to housing and/or critical infrastructure." Here, "Extreme Heat"'s description does not contradict that of the root class, but it is not immediately evident that it conforms to it. Establishing conformity between the descriptions of the classes with just the information provided by the taxonomy is not required, non-conflict between them is sufficient. The evidence necessary to establish that the frequency and/or magnitude of "Extreme Heat" is increased by climate change readily available throughout the reviewed literature (Habeeb, Vargo, and Stone 2015)(National Academies of Sciences, Engineering, and Medicine 2014)(U.S. Global Change Research Program 2018), and the potential of "Extreme Heat" to harm housing and/or critical infrastructure is established in Table 12. However, thanks to the transitivity of subClassOf/superClassOf relationships, neither of these justifications need to be expounded upon in Table 3.

This same bottom-up lineage tracing test can be applied to any non-root class of Table 3. However, the lineages of many classes are complicated by multiple inheritance which creates several possible lines to the root class. For such classes, the test must be applied separately to each possible lineage.

<u>Multiple Inheritance</u>:

Multiple inheritance is the optionally applied guideline by which individual classes may have multiple superclasses (be the subclass of multiple classes) in the taxonomy. Throughout Table 3, many classes take advantage of the structural flexibility allowed by this rule. This is attributable to the often multi-faceted character of CCDNH mechanisms and drivers. Cases of multiple inheritance in Table 3 are identifiable by two characteristics:

1. The multiply inheriting class appears more than once in the taxonomy, but it is only defined in one location. The undefined appearances of the class direct to the location where the class is defined.
2. The subject of the multiply inheriting class' definition includes each of its superclasses.

One of the levels at which multiple inheritance is most prevalent is in the subclasses of the hazard sphere classes (“Hydrospheric Hazard", “Cryospheric Hazard", “Lithospheric Hazard", “Atmospheric Hazard”). Each sphere has a mechanism generally characterized by forces, elements, or locations. Many CCDNHs in some way fit the mechanisms of multiple spheres. A clear example of this phenomenon is presented by the class “Erosion”. Erosion, as a hazard posing a risk to housing and critical infrastructure, involves the removal and displacement of pieces of rock and sediment and is commonly driven by a wide variety of forces and elements. The mechanism of erosion involves the movement of solid components of the earth's surface, fitting it into the lithosphere. However, this mechanism also involves the detachment and transportation of those solid components by some force and medium such as wind, flowing water, or precipitation. Respectively, these forces are regarded as atmospheric, hydrospheric, and mixed atmospheric/hydrospheric. Thus, “Lithospheric Hazard", “Atmospheric Hazard", and “Hydrospheric Hazard” all fit as superclasses of “Erosion". It is important to note that elements of the cryosphere such as glaciers can also be involved in an erosion mechanism. “Erosion” is not considered to be a subclass of “Cryospheric Hazard” here because glacier-driven erosion is deemed to pose negligible and shrinking risk to housing and critical infrastructure (Alexander 1993, 200-201).

While the hazard spheres are the source of many of the instances of multiple inheritance in Table 3, examples independent of them do exist. One such example is “Flash/Dynamic/Torrential Flood", a class which is determined to inherit descriptions from both “Fluvial Flood” and “Flowing Mass Movement". Flash, dynamic, and torrential floods are all characterized by the overfilling or overflowing of a water channel, usually in a narrow, steep catchment. Also important to this definition is the abnormally high concentration of sediment and other solids that accompany the event. In this way, a flash, dynamic, or torrential flood involves both the flooding of a water channel and the flow-like movement of solid components of the earth's surface. This justifies “Flash/Dynamic/Torrential Flood”'s position as a subclass of both “Fluvial Flood” and “Flowing Mass Movement".

Multiple inheritance has the potential to complicate the requirements of subClassOf/superClassOf relationships. Each superclass added to a class through multiple inheritance creates a new lineage which must be evaluated for compliance with subClassOf/superClassOf. Figure 2 demonstrates this effect for the class “Flash/Dynamic/Torrential Flood". As the subclass of both “Fluvial Flood” and “Flowing Mass Movement", “Flash/Dynamic/Torrential Flood” possesses two possible lineages. With two possible lineages connecting “Flash/Dynamic/Torrential Flood” to the root class, there exist two overlapping but distinct sets of classes. As a member of each of the classes in these sets, “Flash/Dynamic/Torrential Flood” must inherit the description of each.

Figure 2: Alternative Lineages of Flash/Dynamic/Torrential Flood

CCDNH Posing a Risk to Housing or Critical Infrastructure ↓ Hydrospheric Hazard ↓ Flood ↓ Fluvial Flood ↓ Flash/Dynamic/Torrential Flood	CCDNH Posing a Risk to Housing or Critical Infrastructure ↓ Lithospheric Hazard ↓ Mass Movement ↓ Flowing Mass Movement ↓ Flash/Dynamic/Torrential Flood

Exclusion and Truncation:

As repeatedly referenced above, there exists a wide variety of hazards which are present in the reviewed literature but omitted from Table 3. The omission of each of these classes is done through either exclusion or truncation.

Exclusion:

The reviewed literature contains many hazards which are ineligible for inclusion into Table 3 and are therefore excluded. These hazards are made ineligible because they do not meet the requirements necessary to be a subclass of the root class, "CCDNH Posing a Risk to Housing and/or Critical Infrastructure". Examples of such hazards include earthquakes, extreme cold events, blizzards, and dust-devils.

Earthquakes, extreme cold events, and blizzards are all excluded on the basis that their frequency and/or magnitude is not increased by climate change. In the case of earthquakes, the statement that climate change has a negligible effect on its frequency and magnitude is relatively uncontroversial. As for extreme cold events and blizzards, increased climate variability may make the prediction of these hazards more difficult but neither is generally expected to increase in frequency or magnitude (Dawson et al. 2018, 10)(Ding et al. 2021, 4). This contrasts the hazard class "Snow Avalanche". While avalanches are likely to decrease in frequency, their magnitude and the risk they pose to housing and critical infrastructure may increase as climate change pushes up the proportion of wet avalanches (Eckert et al. 2024, 370). Finally, dust-devils are an example of a hazard excluded because of its inability to pose an important risk to housing or critical infrastructure. They are typically short lived and do not possess rotational wind speeds high enough to cause significant damage (Alexander 1993, 176-177).

Truncation:

Throughout Table 3, a number of eligible hazard classes are omitted. Their omissions from the taxonomy are enabled by the adoption of the truncation guideline from Table 2, making possible the construction of a non-exhaustive taxonomy of hazards. Non-exhaustiveness is important for Table 3 because the reviewed literature, while being relatively exhaustive in the breadth of different natural hazards discussed, includes hazards which are not relevant to this survey's approach to urban climate resilience planning. The purpose of Table 3 requires that each eligible class be able to help answer the question "what are the plausible hazards requiring consideration in order to conduct planning in a given location?" Hazard classes which help answer this question comply with two criteria:

1. Has at least one differentiable potential negative impact on housing or critical infrastructure. Differentiability implies that the impact arising from the class is distinct from the impacts of other classes on the basis of the mechanisms giving rise to the impact (pendant column of high winds, abnormally elevated air temperature, salination of normally fresh groundwater, etc…), the unique spatial characteristics of the impact (only occurs in coastal areas, only occurs in between the latitudes of 30° N and 30° S, only occurs in areas with limestone bedrock, etc…), or the temporal characteristics of the impact (most likely to occur during periods of thaw, most likely to occur between the June 1st and November 30th, etc…). A hazard class does not need to have differentiable impacts from its superclasses.

2. Has at least one traceable potential negative impact on housing or critical infrastructure. Traceability implies that the hazard class has been connected with a specific impact on housing or critical infrastructure by the reviewed literature. Every hazard with traceable impacts is cited at least one as a driving hazard of an impact in Table 12.

These criteria are applied to all eligible hazard classes encountered in the literature. Two groups of classes in which truncation is widely used are the hazard classes eligible to be subclasses of "Flood" (flood classes) and the many material-movement mass movement classes which are eligible to be subclasses of "Mass Movement" (mass movement classes). An analysis of each group is provided below.

Flood Classes:

The list of eligible flood classes which are truncated from Table 3 includes: *Estuarine Flood* (Alexander 1993, 120), *Hyper-Concentrated Flow* (Papathoma-Köhle, Schlögl, and Fuchs 2019, 3), *Fluvial Sediment Transport* (Fuchs et al. 2019, 587), *Compound Flood* (Cea and Costabile 2022, 7). All of these flood classes are truncated on the basis that they fail to comply with either or both of the criteria above.

Of these truncated classes, *Compound Flood*, *Hyper-Concentrated Flow*, and *Fluvial Sediment Transport* all fail to be differentiable from other already included hazard classes in Table 3. For *Compound Flood*, its mechanisms, spatial characteristics, and temporal characteristics are made superfluous by a combination of all of the flood classes included in Table 3. In the case of *Hyper-Concentrated Flow* and *Fluvial Sediment Transport* both have mechanisms, spatial characteristics, and temporal characteristics which are shared by "Flash/Dynamic/Torrential Flood" and "Debris Flow". The only truncated flood class which is differentiable from included classes is *Estuarine Flood*. In mechanism and temporal characteristics, *Estuarine Flood* is not differentiable from "Coastal Flood" or "Fluvial Flood". The spatial characteristics of *Estuarine Flood*, however, are unique since estuaries are a specific geographical feature distinct from either rivers or coasts.

As for the second criteria, *Compound Flood* and *Estuarine Flood* both fail to demonstrate traceable impacts in the reviewed literature. Both are mentioned and partially or fully defined but neither of the flood classes is ever connected with a specific impact on housing or critical infrastructure. Meanwhile, *Storm Surge*, *Hyper-Concentrated Flow*, and *Fluvial Sediment Transport* are all able to demonstrate traceable impacts. Both *Hyper-Concentrated Flow* and *Fluvial Sediment Transport* are indirectly associated with impacts in the reviewed literature, primarily on housing (Fuchs et al. 2019)(Luo et al. 2023)(Papathoma-Köhle, Schlögl, and Fuchs 2019).

<u>Movement-Material Mass Movement Classes</u>:

"Mass Movement" is a class with many eligible subclasses to which truncation is liberally applied. The most common type of mass movement class found in the reviewed literature are movement-material mass movement classes. These are classes which are defined using their dominant mode of movement (fall, topple, slide, spread, flow, etc…), and their dominant material type (boulders, debris, silt, clay, sand, mud, etc…). The resulting classes take on names which combine those two elements: *Gravel/Sand/Debris Slide*, *Debris Flood*, *Peat Flow*, etc…. For example, Hungr, Leroueil, and Picarelli (2014) present 32 distinct movement-material mass movement classes, identifying, defining, and tabulating them. This list grows longer when mass movement types from other reviewed sources are added (Alexander 1993)(Varnes 1978)(Cruden and Varnes 1996)(Martinsen, 1994). Almost all of these classes are eligible to be subclasses of both "Mass Movement" and the root class of Table 3, but most fail to meet both of the inclusion criteria.

Of those classes eligible, most meet the first criteria. These classes are made differentiable primarily by their mechanisms. As best exemplified by Hungr, Leroueil, and Picarelli (2014), the reviewed literature provides sufficiently in-depth descriptions of the mechanisms of these classes for each of them to be considered differentiable. The mass movement classes which fail to meet this first criteria do so because they are antiquated or redundant, describing hazards which can be described more aptly by other mass movement classes. One example of this is *Mudslide*, a class which is made redundant by "Earth Flow" (Hungr, Leroueil, and Picarelli 2014, 168). Another such example is *Complex Mass Movement*, an antiquated mass movement class which has been discredited for its lack of uniqueness (Hungr, Leroueil, and Picarelli 2014, 167).

A significant majority of the mass movement classes found to be differentiable by the first criteria are found to not be traceable by the second, leading to their truncation from Table 3. In most cases, the specific movement-material mass movements which make up these classes are never linked by the reviewed literature with specific impacts on housing or critical infrastructure. The movement-material mass movement classes which are found to be traceable are: "Mud Flow"(Argyroudis et al. 2019, 3), "Debris Flow"(Argyroudis et al. 2019, 3)(Jacobs et al. 2018, 489), "Earth Flow"(National Academies of Science, Engineering, and Medicine 2014, 6)(Luo et al. 2023, 5), and "Rock Fall"(Argyroudis et al. 2019, 7). These classes are included in Table 3 while all of the others are truncated.

<u>Other Classes</u>:

The same process of truncation is applied to otherwise eligible classes throughout Table 3. Examples of hazard classes truncated from those hazard sphere classes include *Loose-Snow Avalanche* (Eckert et al. 2024)(Schweizer, Jamieson, and Schneebeli 2003)(Alexander 1993), *Slab Avalanche* (Eckert et al. 2024)(Schweizer, Jamieson, and Schneebeli 2003)(Alexander 1993), *Dry Slab Avalanche* (Alexander 1993)(Eckert et al. 2024), *Wet Slab Avalanche* (Alexander 1993)(Eckert et al. 2024), *Glide*

Slab Avalanche (Alexander 1993), *Sting Jet* (Stephenson 2008), *Waterspout* (Alexander 1993), *Boulder/Debris/Silt Fall* (Hungr, Leroueil, and Picarelli 2014), *Rock Slide* (Hungr, Leroueil, and Picarelli 2014), *Clay/Silt Slide* (Hungr, Leroueil, and Picarelli 2014), *Gravel/Sand/Debris Slide* (Hungr, Leroueil, and Picarelli 2014), *Slope Deformation* (Hungr, Leroueil, and Picarelli 2014), *Precipitation Drought* (Alexander 1993), *Surface Fire* (Alexander 1993), *Ground Fire* (Alexander 1993), *Crown Fire* (Alexander 1993), *Dependent Crown Fire* (Alexander 1993), and *Running Crown Fire* (Alexander 1993). As before, every one of these hazard classes fails to meet one or both of the inclusion criteria and is truncated as a result.

Appendix C:

<u>Class Definition</u>:

As in Table 3, every class in Table 12 is defined such that its subject and description are clear and distinct. However, the class definitions of the taxonomy in Table 12 are marked by a number of peculiarities which separate it from the taxonomy in Table 3. These peculiarities include the approaches used to define these classes as well as the assignment of driving hazards to each.

<u>Definition Approach</u>:

In Table 12, impact classes are defined in one of two ways based on their position within the taxonomy. The first definition approach applies only to the non-leaf classes of the taxonomy. Unlike in Table 3, non-leaf classes and their definitions are included purely as organizational tools used to understand the relationships between the formally established leaf impact classes. These classes may be implied in the reviewed literature, but they frequently are not directly mentioned or defined. As such, most of the definitions provided for these classes in Table 12 are created specifically to conform with the demands placed on them by their position in the taxonomy. Namely, the definition must make clear that each non-leaf impact class complies with its subClassOf/superClassOf relationships.

The second definition approach applies to only the leaf impact classes of Table 12. While all of the leaf impact classes included in Table 12 are present in the reviewed literature, many of the names of the impact classes in Table 12 are never referenced verbatim. In such cases, the reviewed literature refers to the impacts using synonyms or simply descriptions. The majority of the leaf impact classes are also never formally defined. Thus, the definitions of these leaf impact classes are synthesized from their partial definitions or descriptions in the reviewed literature. The synthesis draws upon both the actual wording and wider context of each appearance of the impact.

<u>Driving Hazards</u>:

Appended to the definition of every leaf class of Table 12 is one or more driving hazards. These are a selection of CCDNHs which are cited in the reviewed literature as being able to give rise to the impact to which they are appended. Each of the potential driving hazards references a corresponding class in Table 3's taxonomy of hazards.

The assignment of driving hazards to the impact classes is dependent on the existence of a causal relationship between them in the reviewed literature. This causal relationship is usually implied and not explicitly stated. The statement of these implied relationships may occur on a variety of scales ranging from a single sentence, to a table, to a single section, to an entire paper:

- Two sentence-level examples are provided by the sources which describe a direct causal relationship between the hazard class “Extreme Heat” and the impact class “Reduction in Workable Maintenance Hours”:

“Changes in working hours or other strategies to protect laborers from heat waves”(National Academies of Science, Engineering, and Medicine 2014, 8).

“Protocols that govern worker safety limit construction during heat waves and result in lost productivity”(Jacobs et al. 2018, 489).

Neither of these sentences contains the specific wordings of the hazard and impact classes but both nevertheless imply a causal relationship between the classes. Both of these sources refer to *heat wave* as the driving hazard which, for the purposes of this survey, is considered to be a synonym of class “Extreme Heat”. Similarly, *changes in working hours* and *loss of worker productivity* are both treated as suitable analogues for “Reduction in Workable Maintenance Hours”. Given these synonyms, the causal relationship in each of these sentences is then clear.

- An example of a table-based implied causal connection is provided by “Groundwater Flood” and “Inundation” as subclass of “Physical Impact on Electrical Station”. This connection is sourced from a table which tabulates the percentage of different infrastructure assets in the UK which are at risk of different types of flooding (Dawson et al. 2018, 11). The table lists that 18% of UK power stations are at risk of groundwater sourced flooding. While the driving hazard, “Groundwater Flood", is directly referenced, the impact, “Inundation", is not. The source states that groundwater sourced flooding poses a risk without clarifying a specific impact. In order to complete the connection with “Inundation", an assumption is made: based on explicit connections present elsewhere in the reviewed literature which connect other flood classes with “Inundation” (Cea and Costabile, 2022, 1)(Wilbanks and Fernandez 2014, 51), inundation is assumed to be the most likely mode impact of groundwater sourced flooding on a power station.
- The assignment of “Fluvial Flood", “Flash/Dynamic/Torrential Flood", “Ice Jam Flood", “Pluvial Flood", “Snowmelt Flood", and “Dam Break/Glacial Lake Outburst Flood” as driving hazards of “Partial/Complete Collapse of Building” provides an example of a section-scale causal relationship (Quesada-Ganuza, Garmendia, and Gandini 2023, 28). In this source, a section on “Urban flooding” is opened with a statement of the types of flooding being considered:

“Floods include river (fluvial) floods, flash floods, pluvial floods and derived sewer floods, and can be caused by intense and/ or long-lasting precipitation (pluvial floods), snowmelt, dam break, and reduced conveyance due to ice jams and landslides”(Quesada-Ganuza, Garmendia, and Gandini 2023, 28).

This list of flood types largely conforms with the wordings of flood classes from Table 3, requiring no synonyms. Later in the same section, possible impacts attributable to *floods* are outlined:

> “These direct damages may range from the soiling of basements and lower floors and longterm increases in residual moisture to the collapse of structures due to floodwater force”(Quesada-Ganuza, Garmendia, and Gandini 2023, 28).

Here, the *collapse of a structure* is treated as an analogue of “Partial/Complete Collapse of a Structure". Given the clear description of what the authors of this source consider *floods*, it is reasonable to deduce that any of those flood types from the start of the section could be considered a driver of this impact. Notably, this sentence also provides the evidence used to connect the same set of flood classes with “Inundation of Basement” and “Water Damage to Interior".

- Finally, an example of a driving hazard connection occurring on the scale of an entire paper is demonstrated by the association of “Fluvial Flood", “Pluvial Flood", and “Coastal Flood” with “Depression of Property Value” (Armal et al. 2020). This source establishes its hazard scope early on as including “Pluvial Flood” and “Fluvial Flood” as well as *tidal flood* and *surge surge*, both of which fall under “Coastal Flood”:

> “In 2012, Hurricane Sandy made very clear that communities up and down the New Jersey coast are susceptible to devastating storm surge. However, residents throughout the state face risk from tidal, fluvial, and pluvial flooding as well”(Armal et al. 2020, 4).

In a later section, the authors provide a figure which shows New Jersey’s county-level average property values (Armal et al. 2020, 13). The figure also includes the average annual value of flood-driven losses predicted to be incurred by properties in each county of New Jersey between 2020 and 2050. Property loss estimates are distinct from property values and an increase in loss does not necessarily imply a decrease in property values. However, “higher costs and lower property values”(Fleming et al. 2018, 329) are both stated elsewhere in the reviewed literature to be results of chronic coastal flooding. This evidence is used to justify the assumption that an increase in future loss does put downward pressure on property values, even if the actual property values end up increasing due to other factors like property demand. Thus, increasing losses are used here to represent “Depression of Property Values". While “Pluvial Flood", “Fluvial Flood", and “Coastal Flood” are not explicitly mentioned in relation to the increasing losses, the prior association of all three with New Jersey communities justifies their connection with “Depression of Property Values".

Throughout the taxonomy of impacts, a mix of leaf and non-leaf hazard classes is used. This leads to instances in which the driving hazards of an impact class include both a hazard class and a superclass of that hazard class. This phenomenon occurs because some sources in the reviewed literature identify non-leaf hazard classes as the driving hazards of impacts (i.e. “Flood”, “Mass Movement”, etc…). In a case where a hazard class and one of its superclasses are both identified as driving hazards of the same impact class, the source (or sources) associating that hazard class with the impact is also cited in Table 12 as associating its superclass with the impact.

An example of this is presented by the impact class “Disruption of Water Supply Quality". One source in the reviewed literature states that “Disruption in Water Supply Quality” may result from *floods* without indicating which specific flood leaf classes may give rise to the impact (Wilbanks and Fernandez

2014, 43). As a result, the non-leaf hazard class “Flood” is listed as a driving hazard of “Disruption in Water Supply Quality". Another source in the reviewed literature identifies “Rainfall Flood” as a driving hazard of water supply quality issues (Angel et al. 2018, 878). Given that “Flood” is a superclass of “Rainfall Flood,” the source connecting “Rainfall Flood” with “Disruption of Water Supply Quality” is also cited as associating “Flood” with the impact class.

Another example of this exists among the driving hazards of the impact class “Partial/Complete Collapse of Building” with the hazard classes “Mass Movement”, “Flowing Mass Movement”, and “Flash/Dynamic/Torrential Flood”. “Mass Movement”, the highest level class of the three and superclass of the other two, is associated with “Partial/Complete Collapse of Building” by a source which states that “a building during the landslide may be completely destroyed, partially damaged or it can just experience excessive deformation”(Papathoma-Köhle et al. 2007, 769-770). This statement highlights one of the most prevalent synonym applications used in assigning Table 12’s driving hazards: *landslide* being treated as a synonym of “Mass Movement”. The next hazard cited as a driver of “Partial/Complete Collapse of Building” is “Flowing Mass Movement”, a subclass of “Mass Movement” and a superclass of “Flash/Dynamic/Torrential Flood” (Luo et al. 2023, 7). Lastly, “Flash/Dynamic/Torrential Flood”, a subclass of both “Mass Movement” and “Flowing Mass Movement”, is also connected to “Partial/Complete Collapse of Building” (Ettinger et al. 2016, 572). As a result of the relationship between these three classes, the source for “Flowing Mass Movement” is also cited as a source for “Mass Movement” while the source for “Flash/Dynamic/Torrential Flood” is cited as a source of both “Mass Movement” and “Flowing Mass Movement”.

subClassOf/superClassOf Relationships:

Table 12 complies with the requirement that all inter-class relationships in the taxonomy be subClassOf/superClassOf. This compliance heavily influences the shape of the taxonomy and imparts upon it the same top-down and bottom-up characteristics seen in Table 3.

Top-Down Characteristics:

The clearest top-down characteristic of Table 12 is the inheritance of the root class’ subject, *a direct negative effect of a CCDNH on a physical asset of interest*, and its description, “significantly impedes the ability of the asset to maintain its full intended functionality.” Every subclass of the root class is a variation of the root class’ subject through the transitive nature of the subClassOf relationship. These subclasses also adhere to the root class’ description by possessing a description which does not conflict with the root’s. As in Table 3, this top-down behavior holds for any given non-leaf class when treated as the root class of its own taxonomy composed of itself and all of its subclasses.

This characteristic of the possible sub-taxonomies of Table 12 can be demonstrated by considering the class “Physical Impact on Water Supply/Wastewater Network". Treated as the root class of its own sub-taxonomy, “Physical Impact on Water Supply/Wastewater Network” passes down its subject and description to all six classes below it. All six of its subclasses are examples of *a physical impact on a critical infrastructure network*, and none have descriptions which conflict with the root’s description, “impeding the function of the network supplying clean water to housing or removing and treating wastewater from housing.”

Bottom-Up Characteristics:

The bottom-up characteristics of the taxonomy of impacts are the same as those from the taxonomy of hazards. Any class below the root class of the taxonomy can be selected, and a direct lineage can be traced back up from that class to the root class. The definition of the selected class can be compared against the definition of each class making up its direct lineage, including the root class, following the example shown in Figure 1. Each comparison yields either non-conflict or direct conformity of the selected class' definition with that of the superclass in both subject and description.

Truncation and Non-Truncation Exclusion:

Like in Table 3, truncation is a rule put to use liberally in the taxonomy presented by Table 12. Unlike in Table 3, truncation in Table 12 is largely motivated by the non-exhaustiveness of the reviewed literature instead of by a concern for the urban climate resilience planning relevance. Relevance to urban climate resilience planning is determined based on the ability of a class to help answer the question "what are the impacts of CCDNHs that inhibit the full functionality of housing or critical infrastructure?" In order to help answer this question, an eligible impact class must only meet one criteria:

1. Represents a negative effect of a CCDNH on either housing or critical infrastructure that prevents or lowers the quality of an intended service or function of that asset.

This criteria is broad and, when applied to the eligible impact classes encountered in the reviewed literature, no classes fail to meet it. Thus, the forces driving the truncation of eligible impact classes is dominated by the absence of those classes from the reviewed literature. The classes truncated this way fall into two categories: inferable eligible classes that do not appear in the reviewed literature (known unknowns) and non-inferable eligible classes which do not appear in the reviewed literature (unknown unknowns).

In Table 12, inferable eligible impact classes involve both unaddressed inferable physical assets of interests as well as unaddressed inferable modes of impact. For example, Table 12 is heavily truncated in its inclusion of impacts on components of emergency service networks. Emergency service network components of interest which are inferable but not present in the reviewed literature include paramedic stations and police stations, both of which may conceivably be impacted by CCDNHs. Meanwhile, both the included components of interest (hospitals and fire stations and the unaddressed components of interest (paramedic stations, police stations, etc…) can reasonably be expected to suffer from CCDNH impacts far beyond just inundation. As buildings, hospitals, fire stations, paramedic stations, and police stations can all be inferred to be at risk of many of the impacts as buildings providing housing.

The volume and identities of non-inferable eligible classes are difficult to speculate upon. One approach is to speculate that there exists a large collection of non-inferable physical assets of interest which are components of either housing or critical infrastructure. These assets may be difficult to infer because housing components, infrastructure components, and the interpretation of *critical* with regards to infrastructure may each vary significantly across different cultures, economies, and geographical locations. Another avenue for speculation is through non-inferable CCDNH-driven modes of impact. While such modes of impact certainly exist, they should be more limited in number than the non-inferable physical assets because of their close relationship with relatively predictable concepts like the laws of physics and the materials and elements making up the earth's surface and atmosphere.

<u>Non-Truncation Exclusion</u>:

In addition to the eligible impact classes truncated from Table 12, many ineligible impact classes are excluded on the basis of their ineligibility. There are two primary drivers of ineligibility among impact classes:

1. They impact infrastructure or components of housing which are not critical to the full functionality of housing.
2. They are exclusively driven by hazards that are not considered to be climate change driven.

The first of these drivers of ineligibility is functionally identical to the criteria stated above for the relevance of impact classes to urban climate resilience planning. Their similarity accounts for the fact that none of the impact classes deemed to be eligible fail to meet the relevance criteria. Prominent examples of assets which are deemed to be non-critical to housing in the immediate aftermath of a CCDNH include: oil networks (production, transportation, refining, and distribution), natural gas networks (production and refining), waterway networks, manufacturing infrastructure, and port infrastructure. While each of these grouping of infrastructure plays an important role in western modern economies, none are immediately relevant to the full functionality of housing. As such, CCDNH impacts on these types of infrastructure like flood damage to refineries, drought-driven water shortages for fracking, and reduced oil and gas production capabilities as a result of permafrost degradation (Zamuda, Daniel et al. 2018, 177) are all excluded from Table 12.

An impact class may also be deemed ineligible on the basis that it is exclusively caused by hazards whose frequency or magnitude is not increased by climate change. The most prominent contingent of impact classes rendered ineligible this way are those impacts to housing or critical infrastructure resulting exclusively from earthquakes. Due to the unique forces exerted by earthquakes on human structures, they can be responsible for a number of impacts not included in Table 12. Such impacts include the collapse of tunnels (Argyroudis et al. 2019, 7), the liquefaction of embankments (Argyroudis et al. 2019, 7), the collapse of bridges (Cook, Barr, and Halling 2015, 1), and the uplift of buried services (water, electricity, natural gas) (Koks et al. 2019, 8) among others. While each of these examples impact a physical asset of interest the reviewed literature attributes these impacts only to earthquakes and not a CCDNH. As a result, all are ineligible and excluded from Table 12.