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Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making

Bilal M. Ayyub*

The United Nations Office for Disaster Risk Reduction reported that the 2011 natural disasters, including the earthquake and tsunami that struck Japan, resulted in $366 billion in direct damages and 29,782 fatalities worldwide. Storms and floods accounted for up to 70% of the 302 natural disasters worldwide in 2011, with earthquakes producing the greatest number of fatalities. Average annual losses in the United States amount to about $55 billion. Enhancing community and system resilience could lead to massive savings through risk reduction and expeditious recovery. The rational management of such reduction and recovery is facilitated by an appropriate definition of resilience and associated metrics. In this article, a resilience definition is provided that meets a set of requirements with clear relationships to the metrics of the relevant abstract notions of reliability and risk. Those metrics also meet logically consistent requirements drawn from measure theory, and provide a sound basis for the development of effective decision-making tools for multihazard environments. Improving the resiliency of a system to meet target levels requires the examination of system enhancement alternatives in economic terms, within a decision-making framework. Relevant decision analysis methods would typically require the examination of resilience based on its valuation by society at large. The article provides methods for valuation and benefit-cost analysis based on concepts from risk analysis and management.

KEY WORDS: Community; consequence; infrastructure; measure; measurement; metrics; recovery; resilience; risk; robustness

1. BACKGROUND

The United Nations Office for Disaster Risk Reduction (UNISDR) reported that half of the world's inhabitants, expected by 2025 to increase to roughly two-thirds, and the vast majority of property and wealth are concentrated in urban centers situated in locations already prone to major disasters, such as earthquakes and severe droughts, and along flood-prone coastlines.(1) UNISDR(1) also reported that the 2011 natural disasters, including the earthquake and tsunami that struck Japan, resulted in $366 billion in direct damages and 29,782 fatalities worldwide. Storms and floods accounted for up to 70 of the 302 natural disasters worldwide in 2011, with earthquakes producing the greatest number of fatalities. Average annual losses in the United States amount to about $55 billion. It is anticipated that such disasters would occur in increasing trends of storm rates and disaster impacts because of a combined effect of climate change and increased coastal inventory of assets.(2) Although no population center or a geographic area can ever be risk free from natural or human-caused hazards, communities should strive to enhance resilience to the destructive forces or the impacts of resulting events that may claim lives and damage property. Gilbert(3) provided

Center for Technology and Systems Management, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD, USA.

*Address correspondence to Bilal Ayyub, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742, USA; tel: 301-405-1956 campus; ba@umd.edu, http://www.ctsm.umd.edu.

population-and-wealth-adjusted loss and fatality count trends from 1960 to 2009 to demonstrate that both are about flat without significant slopes; however, it is noted that the United States is becoming more vulnerable to disaster because of increased population concentration in areas prone to natural disasters(4,5) and persisting inadequate condition of infrastructure.(6)

Enhancing system resilience at the structure, network, community, etc. levels could lead to massive savings through risk reduction and expeditious recovery. The rational management of such reduction and recovery is facilitated by an appropriate definition of resilience and associated metrics. Current definitions do not always lend themselves naturally and intuitively to the development of consistent resilience metrics with clear relationships to metrics of the relevant abstract notions of reliability and risk. The objective of this article is to review existing definitions and metrics, and to propose ones that meet logically consistent requirements drawn partly from measure theory. These metrics would provide a sound basis for the development of effective decision-making tools for multihazard environments. Appendix A lists selected urban areas, their respective population sizes, location attributes, and hazards as a summary of the data reported by UNISDR.(1) This summary demonstrates at a global level the extent of exposure to various hazards. The hazard most often listed is flooding, including coastal, and earthquakes.

Resilient systems should be developed to meet sustainability requirements defined by the three pillars of sustainability by reconciling environmental, social equity, and economic demands. These three pillars of sustainability are not mutually exclusive and can be mutually reinforcing. Similar to the long-lived and healthy wetlands and forests, as sustainable biological systems, humans should sustain their long-term well-being in the environmental, economic, and social dimensions and achieve resiliency.

2. RESILIENCE DEFINED

The concept of resilience appears in different domains ranging from ecology to child psychology and psychiatry to infrastructure systems. It was formally introduced in ecology, defined as the persistence of relationships within a system,(7) and measured by the system's ability to absorb change-state variables, driving variables, and parameters and still persist. In discussing the philosophical basis of risk analysis, Starr *et al.*(8) characterized the resilience of a system in agreement with the *Webster's New World Dictionary & Thesaurus*(9) as its ability to bounce or spring back into shape or position, or to recover strength or spirits quickly. The common usage, including technical ones, of the word *resilience* permits some elasticity in its placement in declarative statements, for example, the following are meaningful forms that are structurally identical: (1) infrastructure resilience is desirable and (2) storm resilience is desirable. In the former statement, resilience is an explicit quality of infrastructure, whereas in the latter resilience is an implicit quality of whatever is affected by a storm. Generalizing the latter form to "event resilience is desirable" might imply the event itself is the resilient one, not its subject. This ambiguity in usage is indicative of the elastic nature of the word, and perhaps this elasticity partly explains the confusion in its definition in the literature. Park *et al.*(10) tenuously described some aspects of this ambiguity by describing resilience as an emergent property of what an engineering system does, rather than a static property the system has; therefore, resilience is better understood as the outcome of a recursive process that includes sensing, anticipation, learning, and adaptation, making it complementary to risk analysis with important implications for the adaptive management of complex, coupled engineering systems.

In psychology, resilience is an individual's tendency to cope with stress and adversity. In material science, it is the capacity of material to absorb energy when it is elastically deformed. In engineering, many definitions exist and a succinct definition is the ability of the system to return to a stable state after a perturbation. In systems science, a resilient system returns to an equilibrium state after perturbation, with more resilient systems having multiple equilibrium points. The notion of resilience is used not only for ecological systems, infrastructure, and individuals, but also for economic systems and communities.(11–16)

The use of the term resilience with respect to hazards and disasters is a logical step, as discussed by White and Haas(17) and Mileti,(18) and was used in the 2005 Hyogo Framework for Action by 168 members of the United Nations to enhance its priority for governments and local communities.(19) A substantial number of studies focused on defining the notion of resiliency for infrastructures and the development of resiliency metrics. For example, Bruneau *et al.*(20) defined a resilient system to have reduced failure probability, reduced consequences from failure, and reduced time to recover. Little(21) examined resilience in the context of infrastructure interdependencies in terms of how to react when a disruption occurs. Lebel *et al.*(22) defined resilience as the potential of a particular configuration of a system to maintain its structure and function in the face of disturbance, and the ability of the system to reorganize following disturbance-driven change. Walker *et al.*(23) defined it as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks. Holling and Gunderson(24) identified the rate and speed of return to preexisting conditions after disturbance as key elements for measuring resilience. Fiksel(25) examined resilience relating to infrastructure systems that have rigid operating parameters with intrinsic resistance to stress in some narrow bounds and with vulnerability to small, unforeseen perturbations. He conceptually extended the resilience concept from a process to an enterprise. Hollnagel *et al.*(26) examined resilience in the context of anticipating the changing potential for failure on the basis of plans and procedures. Norris *et al.*(27) and Sherrieb *et al.*(28) described disaster resilience as a process, whereas Kahan *et al.*(29) described it as an outcome. Cutter *et al.*(30) described it as a process and outcome. Colten *et al.*(31) defined it to embrace inputs from the engineering, physical, social, and economic sciences. Gilbert(3) defined it from the perspective of economics as the ability to minimize the costs of a disaster, to return to a state as good as or better than the *status quo ante*, and to do so in the shortest feasible time. He also classified definitions reported in the literature as process-oriented or outcome oriented. This classification appropriately covers and is consistent with the definitions provided in this section.

Several reputable entities defined resilience in their high-impact documents, most notably:

- In the Presidential Policy Directive (PPD-21)(32) on Critical Infrastructure Security and Resilience, the "term *resilience* means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."
- The National Research Council(33) defined resilience as the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events as a consistent definition with U.S. governmental agency definitions (SDR,(34) DHS,(35) and PPD-8(36)) and NRC.(37)
- The ASCE Committee on Critical Infrastructure(38) states that resilience refers to the capability to mitigate against significant all-hazards risks and incidents, and to expeditiously recover and reconstitute critical services with minimum damage to public safety and health, the economy, and national security.
- The National Infrastructure Advisory Council defines infrastructure resilience as the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient system depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.
- The Multidisciplinary Center for Earthquake Engineering Research (MCEER)(39) of the State University of New York at Buffalo lists characteristics of resilience to include robustness, redundancy, resourcefulness, and rapidity.
- UNISDR(19) characterized a resilient city by its capacity to withstand or absorb the impact of a hazard through resistance or adaptation, which enable it to maintain certain basic functions and structures during a crisis, and bounce back or recover from an event.
- The Civil Contingencies Secretariat of the Cabinet Office, London, United Kingdom(40) defined resilience as the ability of a system or organization to withstand and recover from adversity.

Based on these definitions and an understanding of the needs of its broad use ranging from buildings to other structures to infrastructures to networks to communities, an operational definition of resilience should enable its measurement by meeting the following requirements for which metrics are either available or needed:

(1) Building on previous notional definitions and particularly presidential policy directives (PPDs(32,36));
(2) Considering initial capacity or strength, and residual capacity or strength after a disturbance, i.e., robustness;
(3) Accounting for abilities to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events as provided in the NRC(33) definition;

(4) Treating disturbances as events with occurrence rates and demand intensity, i.e., modeling them as stochastic processes;
(5) Enabling the inclusion of different performances based on corresponding failure modes for various things at risk, such as people, physical infrastructure, economy, key government services, social networks and systems, and environment (MCEER,(39) Gilbert(3));
(6) Accounting for systems changes over time, in some cases being improved, in other cases growing more fragile or aging;
(7) Considering full or partial recovery and times to recovery;
(8) Considering potential enhancements to system performance after recovery;
(9) Relatable to other familiar notions such as reliability and risk, i.e., building on the relevant metrics of reliability and risk; and
(10) Enabling the development of resilience metrics with meaningful units.

A proposed resilience definition that builds on the PPD-21(32) and lends itself for measurement by meeting the above requirements is as follows:

> Resilience notionally means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from disturbances of the deliberate attack types, accidents, or naturally occurring threats or incidents. The resilience of a system's function can be measured based on the persistence of a corresponding functional performance under uncertainty in the face of disturbances.

This definition is consistent with the ISO(41) risk definition of the "effect of uncertainty on objectives." The proposed measure includes three key words that offer a basis for quantification. These words are listed in a suggested order for their analysis as follows:

- System's performance defined in terms of requirements or objectives, and examined in the form of output, throughput, structural integrity, lifecycle cost, etc.;
- Uncertainty relating to events such as storms, disturbance, conditions, and system states;
- Persistence examined in terms of enduring the events, recovery, continuance, and/or resumption of performance.

Most resilience definitions do not always lend themselves naturally and intuitively to the development of consistent resilience metrics with clear relationships to the most relevant metrics of the abstract notions of reliability and risk. The use of the operative word of *ability* sometimes has resulted in setting the measurement process on tracks that focus on the abilities rather than the outcomes of these abilities. The primary outcome of these abilities is the continuance of performance of a system, including bouncing back, a characteristic that could be appropriately termed as performance persistence for a particular function of the system. Performance persistence would naturally set measurement in terms of availability of the performance or continuance of system's states of normalcy. Subsequent sections of this article provide metrics based on this definition that meet logically consistent requirements drawn partly from measure theory, and provide a sound basis for the development of effective decision-making tools for multihazard environments.

3. MONOTONE MEASURES FOR RESILIENCE

According to Ayyub and Kilr,(42) a *measure* in the context of mathematics is a function that assigns a number to quantify a *notion* as a *metric* representing a subset of a given set, e.g., size, volume, or probability. Some notions are abstract in nature, such as probability and resilience, whereas others are not, such as distance and volume. Measures, in general, build on the concepts of a universal set (X), a nonempty family C of subsets of X with an appropriate algebraic structure, sets (such as A), and the power set (P_A) to establish a logical measure that can be used to characterize some system attributes of interest, i.e., resilience, probability, uncertainty, belief, etc. Classical measures formulated for a universal set X and a family of subsets C such that if $A_i \in C$, it leads to $A_i \subset X$. The family C is called an *algebra*, if the following conditions are met:

$$C \text{ contain the empty set, i.e., } \phi \in C, \tag{1}$$

$$C \text{ contains the entire set } X, \text{ i.e., } X \in C, \tag{2}$$

$$\text{For any } A_i \in C, \text{ the complementary set } \bar{A}_i \in C, \tag{3}$$

where ϕ is the empty set, $\in$ means belonging, and the $\subset$ means subsethood. The family is called a σ*-algebra* if it has the following additional property:

$$\text{For } A_i \in C,\ i = 1, 2, \ldots, \bigcup_{all\ i} A_i \in C, \tag{4}$$

where $\bigcup$ means the union over all i. In other words, Equation (4) states that the countable union of any family of subsets in C belongs to C.$^{(43,44)}$

A measure μ can be defined in its broadest form as a function that maps C on to the real line (R). This function can be defined mathematically as follows:

$$\mu : C \to R. \tag{5}$$

Of special interest for the purposes of this article is a function that is limited to nonnegative real values (R_+). In probability theory, the probability measure imposes additional requirements on μ consisting of the following:

$$\mu : C \to [0, 1], \tag{6}$$

$$\mu(\phi) = 0, \tag{7}$$

for disjoint $A_{\mathrm{j}} \in C$,

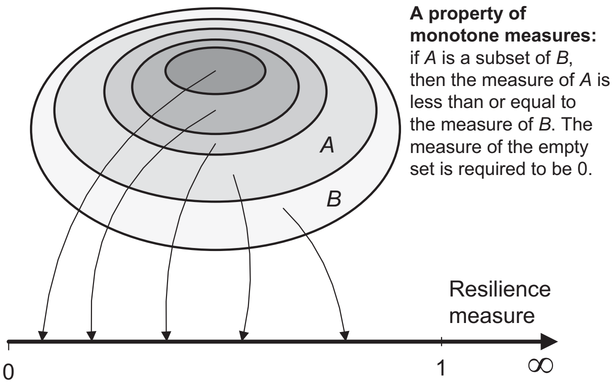
$$i = 1, 2, \ldots, \mu\left(\bigcup_{all\ i} A_i\right) = \sum_{all\ i} \mu(A_i), \tag{8}$$

where any events A_i and A_j meet the following condition:

$$A_i \cap A_j = \phi. \tag{9}$$

Equation (6) limits the mapping to the closed interval of [0,1] with the measure for the null set being zero according to Equation (7). Equation (8) states that the function μ for the union of several disjoint subsets, i.e., with null intersections, is the sum of the measures (i.e., μ values) of these subsets. This *additive property* is unique to this *classical measure* of *probability*. Although the development and evolution of probability theory was based more on intuition rather than mathematical axioms during its early development, an axiomatic basis for probability theory was established and it is now universally accepted.

Generalized measures are employed for representing other than likelihood notions where it makes sense to require that the additivity property of classical measures used in probability theory be replaced with a weaker property of monotonicity with respect to the subsethood relationship. Such measures are called *monotone measures*. Their range is usually the unit interval [0,1], as in probability measures, and it is required that the measure of the universal set be 1. Such measures are called *regular monotone measures*.



A property of monotone measures: if *A* is a subset of *B*, then the measure of *A* is less than or equal to the measure of *B*. The measure of the empty set is required to be 0.

Fig. 1. A monotone measure for resilience.

A *regular monotone measure* can be defined based on a nonempty family C of subsets from P_X (i.e., the power set of X) for a given universal set X, which contains ϕ and X, with an appropriate algebraic structure as a mapping from C to [0,1]. A monotone measure must satisfy the following conditions:

(1) Boundary condition: The monotone measure must meet the following *boundary conditions*:

$$\mu(\phi) = 0 \quad \text{and} \quad \mu(X) = 1. \tag{10}$$

(2) Monotonicity: This property is illustrated in Fig. 1.

$$\text{For all } A_i \text{ and } A_j \in C, \text{ if } A_i \subseteq A_j, \text{ then } \mu(A_i) \leq \mu(A_j). \tag{11}$$

(3) Continuity from below:

$$\text{For any increasing sequence } A_1 \subseteq A_2 \subseteq \cdots \text{ of sets in } C, \text{ if } \bigcup_{all\ i} A_i \in C, \text{ then } \lim_{i\to\infty} \mu(A_i) = \mu\left(\bigcup_{all\ i} A_i\right). \tag{12}$$

(4) Continuity from above:

$$\text{For any decreasing sequence } A_1 \supseteq A_2 \supseteq \cdots \text{ of sets in} C, \text{ if } \bigcap_{all\ i} A_i \in C, \text{ then } \lim_{i\to\infty} \mu(A_i) = \mu\left(\bigcap_{all\ i} A_i\right). \tag{13}$$

Functions μ that satisfy Equations (10), (11), and either Equations (12) or (13) are called *semicontinuous from below and from above*, respectively.

For any pair A_1 and $A_2 \in C$ such that $A_1 \cap A_2 = \phi$, a monotone measure μ is capable of capturing any of the following situations:(42,45,46)

$$\mu(A_1 \cup A_2) > \mu(A_1) + \mu(A_2), \tag{14}$$

called *superadditivity*, which expresses a cooperative action or synergy between A_1 and A_2 in terms of the measured property,

$$\mu(A_1 \cup A_2) = \mu(A_1) + \mu(A_2), \tag{15}$$

called *additivity,* which expresses the fact that A_1 and A_2 are *noninteractive* with respect to the measured property, and

$$\mu(A_1 \cup A_2) < \mu(A_1) + \mu(A_2), \tag{16}$$

called *subadditivity*, which expresses some sort of inhibitory effect or incompatibility between A_1 and A_2 as far as the measured property is concerned.

Probability theory, which is based on the classical measure theory, is capable of capturing only the situation of Equation (15). This demonstrates that the theory of monotone measures provides us with a considerably broader framework than probability theory for formalizing a measure for resilience. The metric for resilience should be consistent with the way mathematical measures are developed by (1) having a state space defined by the desired performances, (2) using real lines for the performance metrics to define appropriate sigma algebra over the state space, and (3) meeting the monotonic property.

4. RESILIENCE MEASUREMENT AND METRICS

In previous sections, a resilience definition of "the persistence of a system's performance under uncertainty in disturbances and its states" is proposed to be consistent with the ISO(41) risk definition of the "effect of uncertainty on objectives." Before proposing metrics for resilience, the article examines other models found in the literature and discusses their purposes and limitations. It should be noted that some of the limitations stem from not only the resilience notion's ambiguous nature but also from its ambiguous definition as an abstract notion. In this section, available metrics are summarized followed by a proposed model.

4.1. Available Resilience Metrics

Bruneau and Reinhorn(20) proposed metrics for measuring resiliency based on the size of expected degradation in the quality of an infrastructure by quantifying robustness, redundancy, resourcefulness, and rapidity to recovery. Garbin and Shortle(47) outline an approach to quantitatively measure the resilience of a network as the percentage of links damaged versus the network performance and the percentage of nodes damaged versus the network performance. Tierney and Bruneau(48) suggested measuring resilience based on observing that resilient systems reduce the probabilities of failure and enhance recovery, and therefore resilience can be measured by the functionality of an infrastructure system after an external shock including the time it takes to return to initial level of performance. They illustrated the concept as shown in Fig. 2 calling it the resilience triangle. Attoh-Okine *et al.*(49) used several potential paths of infrastructure performance during normal operation and cases of unexpected events, for example, a path demonstrating sudden failure as shown in Fig. 2, a path demonstrating decrease in service life, and a path for the normal operation of the system. They used the concept of resilience as illustrated in Fig. 2 to define a resilience index as follows:

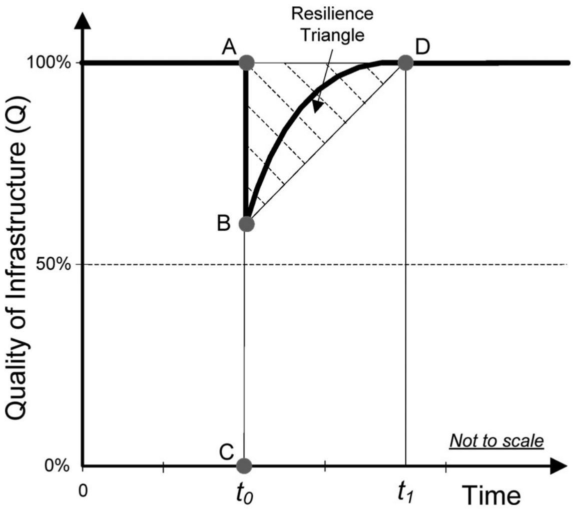


Fig. 2. The resilience properties and triangle.

$$\text{Resilience} = \frac{\int_{t_0}^{t_1} Q(t)dt}{100(t_0 - t_1)}, \tag{17}$$

where Q is the infrastructure quality, or the performance of a system, t_0 is the time of incident or disturbance occurrence, and t_1 is the time to full recovery. According to this model, the units of resilience are performance per unit time, where performance can be measured in percent according to

Table I. Definition of Resilience Properties

Property	Models (Points A, B, C, and D per Fig. 2)	Units	
Robustness	Robustness = B – C	Percentage	(18)
Redundancy	Not defined		
Resourcefulness	Not defined		
Rapidity	Rapidity = $\frac{A-B}{t_0-t_1}$	Average recovery rate in percentage per time	(19)

Equation (17). Equation (17) was also used by the earthquake community$^{(48)}$ with a suggested framework of resilience, called the four "Rs," as follows:

- Robustness as the ability of the system and system elements to withstand external shocks without significant loss of performance;
- Redundancy as the extent to which the system and other elements satisfy and sustain functional requirements in the event of disturbance;
- Resourcefulness as the ability to diagnose and prioritize problems and to initiate solutions by identifying and monitoring all resources, including economic, technical, and social information; and
- Rapidity as the ability to recover and contain losses and avoid future disruptions.

These properties are defined in Table I with reference to Fig. 2 based on models provided by Shinozuka *et al.*$^{(50)}$

Li and Lence$^{(51)}$ refined the resilience index developed by Hashimoto *et al.*$^{(52)}$ by using the performance ratio over two different time periods. Omer *et al.*$^{(53)}$ measure resilience for Internet infrastructure systems as the ratio of the difference in information transmission before, i.e., initial, and after an event divided by the initial information transmission. Attoh-Okine *et al.*$^{(49)}$ also provided formulation of a resilience index of urban infrastructure using belief functions. McGill and Ayyub$^{(54)}$ related resilience concepts to regional capabilities performance assessment for human-caused hazards in homeland security.

Gilbert$^{(3)}$ provides extensive coverage of and mathematical models for recovery after a storm in the context of a disaster cycle consisting of response, recovery, mitigation, and preparedness. He includes in his discussion partial recovery and full recovery including instant urban renewal of population recovery, physical infrastructure, economy, social networks, government services, and environments. He also develops simulation models of recovery and provides validation examples for the Kobe Earthquake.$^{(55)}$ Generally, the recovery trends shown have decreasing slopes as shown in Fig. 2.

4.2. Proposed Resilience Model

Fig. 3 provides a schematic representation of a system performance (Q) with aging effects and an incident occurrence with a rate (λ) according to a Poisson process. At time t_i, it might lead to a failure event with a duration ΔT_f. The failure event concludes at time t_f. The failure event is followed by a recovery event with a duration ΔT_r. The recovery event concludes at time t_r. The total disruption (D) has a duration of $\Delta T_d = \Delta T_f + \Delta T_r$. The figure shows for illustration purposes three failure events: brittle (*f*1), ductile (*f*2), and graceful (*f*3), and six recovery events: expeditious recovery to better than new (*r*1), expeditious recovery to as good as new (*r*2), expeditious recovery to better than old (*r*3), expeditious recovery to as good as new (*r*4), recovery to as good as old (*r*5), and recovery to worse than old (*r*6). These events define various rates of change of performance of the system. The figure also shows the aging performance trajectory and the estimated trajectory after recovery. The proposed model to measure resilience is:

$$\text{Resilience}\,(R_e) = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r}, \tag{20}$$

where for any failure event (*f*) as illustrated in Fig. 3, the corresponding *failure profile F* is measured as follows:

$$\text{Failure}\,(F) = \frac{\int_{t_i}^{t_f} f\,dt}{\int_{t_i}^{t_f} Q\,dt}. \tag{21}$$

Similarly for any recovery event (r) as illustrated in Fig. 3, the corresponding *recovery profile R* is measured as follows:

$$\text{Recovery}(R) = \frac{\int_{t_f}^{t_r} r\,dt}{\int_{t_f}^{t_r} Q\,dt}. \tag{22}$$

The failure-profile value (F) can be considered as a measure of robustness and redundancy, and is proposed to address the notion offered by Equation (18), whereas the recovery-profile value (R) can be considered as a measure of resourcefulness and rapidity, and is proposed to address the notion offered by Equation (19). The time to failure (T_f) can be

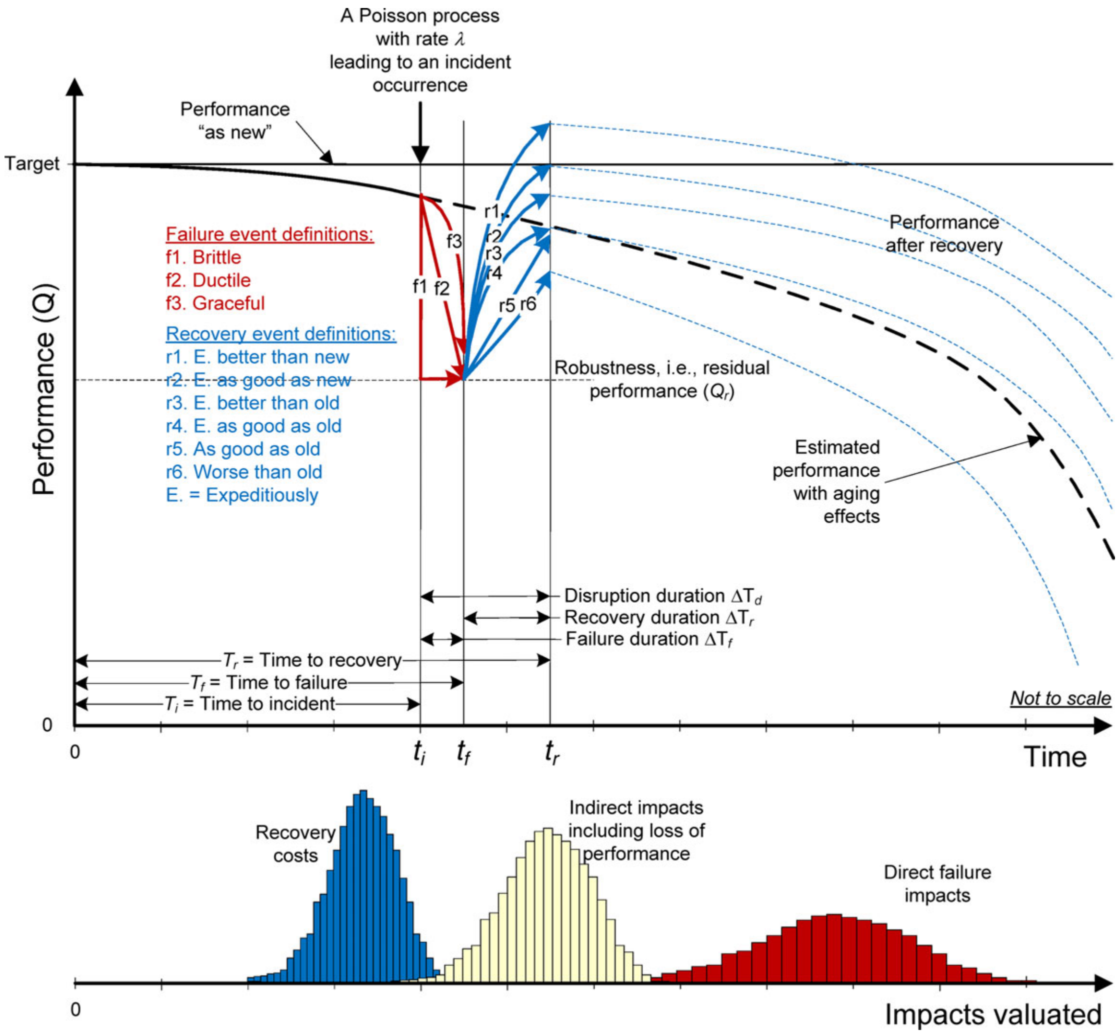


Fig. 3. Proposed definitions of resilience metrics.

characterized by its probability density function computed as follows:

$$-\frac{d}{dt}\int_{s=0}^{\infty}\exp\left[-\lambda t\left(1-\frac{1}{t}\int_{\tau=0}^{t}F_L(\alpha(\tau)s)\,d\tau\right)\right]f_{S_0}(s)\,ds, \tag{23}$$

where Q is defined as the system's performance in terms of its strength (S) minus the corresponding load effect (L) in consistent units, i.e., $Q = S - L$. Both L and S are treated as random variables, with $F_L =$ the cumulative probability distribution function of L, and $f_S =$ the probability density function of S. The aging effects are considered in this model by the term $\alpha(t)$ representing a degradation mechanism as a function of time t. It should be noted that the term $\alpha(t)$ can also represent improvement to the system. Equation (23) is based on a Poisson process with an incident occurrence, such as loading, rate of λ, and is based on Ellingwood and Mori.(56) The probability density function of T_f as shown in Equation (23) is the negative of the derivative of the reliability function.

The proposed model of Equation (20) for measuring resilience meets the set of requirements described in the section on the resilience definition according to the following list of respective items:

(1) The model is consistent with the PPD-21(32) definition.
(2) The model accounts for the initial and residual capacities as noted in Fig. 3 with the performance "as new" and the robustness.

(3) The use of the time to failure and time to recovery accounts for the abilities to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events as provided in the NRC(33) definition.
(4) The disturbances are treated as events with occurrence rates and demand intensity, i.e., modeling them as stochastic processes.
(5) The model permits the use of different performances based on corresponding failure modes for various things at risk, such as people, physical infrastructure, economy, key government services, social networks and systems, and environment.
(6) The model accounts for systems changes over time, in some cases being improved, in other cases growing more fragile or aging.
(7) The model accounts full or partial recovery and times to recovery as illustrated in Fig. 3.
(8) The model accounts for potential enhancements to system performance after recovery.
(9) The model can be related to other familiar notions such as reliability and risk according to Equation (23).
(10) The model requires input with meaningful units, is unit-consistent, and produces results with meaningful units.

The model of Equation (20) also meets the monotone conditions of Equations (6)–(13) by having the following attributes:

$$R_e : (f \cap r) \in C \rightarrow [0, \infty), \tag{24}$$

$$R_e(\phi) = 0. \tag{25}$$

For disjoint $A_i \in C$, $i = 1, 2, \ldots$,

$$R_e\left(\bigcup_{all\ i} A_i\right) = \sum_{all\ i} R_e(A_i). \tag{26}$$

It should be noted that $F{:}f \rightarrow [0, 1]$ and $R{:}r \rightarrow [0, \infty)$. The times T_i, T_f, and T_r are random variables as shown in Fig. 3, and are related to durations as follows:

$$\Delta T_f = T_f - T_i, \tag{27}$$

$$\Delta T_r = T_r - T_f. \tag{28}$$

The disruption duration is given by:

$$\Delta T_D = \Delta T_f + \Delta T_r. \tag{29}$$

4.3. Performance Measurement for Resilience Metrics

The resilience model of Equation (20) can be used for systems, such as buildings, other structures, facilities, infrastructure, networks, and communities. The primary basis for evaluating Equation (20) is the definition of performance (Q) at the system level with meaningful and appropriate units, followed by the development of an appropriate breakdown for this performance, using what is termed herein as performance segregation. The performance segregation should be based on some system-level logic that relates the components of the performance breakdown to the overall performance at the system level as the basis for a system model. This model can be used to aggregate the performance of components to assess system-level performance. Such performance segregation and aggregation analysis is essential for examining the resilience of systems for buildings, other structures, facilities, infrastructure, networks, and communities. The uncertainties associated with the performance components can be modeled as random variables with any necessary performance events to use Boolean algebra and the mathematics of probability to characterize the performance Q in Equation (20).

MCEER(39) proposed the use of resilience index (R_i) in the range $[0, 1]$ for each (the ith) quality of service, and an aggregation model for these resilience indices using an independence assumption. For example, in the case of two indices, the aggregated index is as follows:

$$\text{Resilience}\,(R_{12}) = \frac{R_1 . R_2}{R_1 + R_2 - R_1 . R_2}. \tag{30}$$

Fig. 4 shows a plot of Equation (30) for the case of two identical indices, i.e., resilience components, for the entire range of values of R_i. The figure also shows the effect of increasing the number of components from one to ten. The downward intensification is attributed to the independence assumptions.

The development of such a system-level model relating components' performances to a system performance is beyond the scope of this article. Such a model is domain specific; however, future studies should set meta-methodological requirements for the development of such models. Anthony(57) discussed challenges associated with the treatment of system-level resilience, such as communities, and provided illustrations.

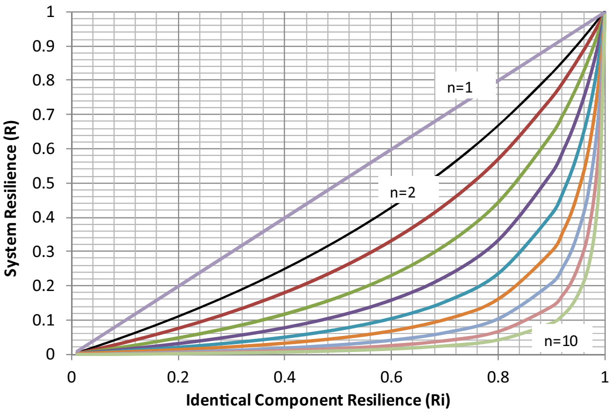


Fig. 4. System resilience aggregate based on two identical resilience components.

Table II. Systems and Performance Measurements

Systems	Performance	Units
Buildings	Space availability	Area per day
Other structures: Highway bridges	Throughput traffic	Count per day
Facilities: Water treatment plants	Water production capacity	Volume per day
Infrastructure: Water delivery	Water available for consumption	Volume
Network: Electric power distribution	Power delivered	Power per day
Communities	Economic output	Dollars
Communities	Quality of life (consumption)	Dollars

The units of performance at the system level vary depending on the system type and the objectives of the analysis. Table II shows examples of performance types and units of measurement for selected systems for demonstration purposes.

5. ECONOMIC VALUATION AND BENEFIT-COST ANALYSIS

Improving the resiliency of a system to meet target levels requires the examination of system enhancement alternatives in economic terms, within a decision-making framework. Relevant decision analysis methods would typically require the examination of resilience based on its valuation by society at large. Methods for the total economic valuation of resilience are needed, and should satisfy the essential requirement of consistency with respect to the definition and metrics of resilience. Concepts from risk analysis and management can be used for this purpose.(58)

Valuation can be approached broadly from philosophy and particularly from ethics to make distinctions among values such as (1) instrumental and intrinsic values, (2) anthropocentric and biocentric (or ecocentric) values, (3) existence value, and (4) utilitarian and deontological values.(59,60) The focus of this section is on economic valuation; however, it is necessary to introduce and discuss these distinctions. An ecosystem is used as an example to discuss these distinctions.

For an ecosystem, the instrumental value is derived from its role as a means toward an end other than itself, i.e., its value is derived from its usefulness in achieving a goal. In contrast, intrinsic value, also called noninstrumental value, is its existence independently of any such contribution defined by usefulness. For example, if an animal population provides a source of food for either humans or other species, it has instrumental value that stems from its contribution or usefulness to the goal of sustaining the consuming population. If it continues to have value even if it were no longer useful to these populations, e.g., if an alternative, preferred food source were discovered, such a remaining value would be its intrinsic value. For example, a national park, such as the Grand Canyon, has an intrinsic value component that exists unrelated or independent of direct or indirect use by humans for recreation or investigation. Such an intrinsic value can also stem from cultural sources, such as monuments and burial grounds.(60)

An anthropocentric value system considers humankind as the central focus or final goal of the universe, human beings as the only thing with intrinsic value, and the instrumental value of everything else is derived from its usefulness in meeting human goals. On the other hand, a biocentric value system, i.e., nonanthropocentric, assigns intrinsic value to all individual living systems, including but not limited to humans, and assumes that all living systems have value even if their usefulness to human beings cannot be determined or can be harmful to human beings.

Existence value reflects the desire of human beings to preserve and ensure the continued existence of certain species or environments to provide for humankind welfare, making it an anthropocentric and utilitarian concept of value and within the domain of instrumental value system. Therefore, utilitarian values are instrumental in that they are viewed as a means toward the end result of increased human welfare as defined by human preferences, without any value judgment about these preferences. The value of particular species or environments comes from generating welfare to human beings, rather than from the intrinsic value of these nonhuman species. This definition permits the potential for substitution or replacement of this source of welfare with an alternative source, i.e., the possibility of a welfare-neutral tradeoff between continued existence of species or environments and other things that also provide the same utility.

The deontological value system is based on an ethical doctrine for assigning worth for an action by its conformity to some binding rule rather than by its consequences. In this case, a deontological value system implies a set of rights that include the right of existence. Something with intrinsic value is irreplaceable and its loss cannot be offset by having more of something else. For example, the death of person is a loss of an intrinsic value because it cannot be offset or compensated by that person having more of something else. The contentious issue is whether this concept should be extended to nonhuman species, for example, animals, either individual animals or species, or all biological creatures, i.e., all plant and animal life, collectively called the biota. In the context of ecosystem valuation, the modern notion of intrinsic value extends the rights beyond human beings. On the other hand, utilitarian values are based on providing utilities.

In this article, the use of a valuation approach with the following characteristics is proposed:

- Anthropocentric in nature based on utilitarian principles.
- Consideration of all instrumental values, including existence value.
- Its utilitarian basis to permit the potential for substitution among different sources of value that contribute to human welfare.
- Individuals' preferences or marginal willingness to trade one good or service for another that can be influenced by culture, income level, and information, making it time and context specific
- Societal values as the aggregation of individual values.

This approach is consistent with NRC(60) and does not capture nonanthropocentric values, e.g., biocentric values and intrinsic values as related to rights. In some decisions, including environmental policy and law, biocentric intrinsic values should be included in agreement with previous practices, e.g., the Endangered Species Act of 1973.

A total economic value (TEV) framework can be constructed based on the above characteristics and using individual preferences and values. The TEV framework is necessary to ensure that all components of value are recognized and included while avoiding double counting of values.(61,62)

Economic valuation, as commonly used in decision analysis, is defined as the worth of a good or service as determined by the market. Economists have dealt with this concept initially by estimating the value of a good to an individual alone, and then extend it broadly as it relates to markets for exchange between buyers and sellers for wealth maximization.

Traditionally, the value of a good or service is linked to its price in an open and competitive market determined primarily by the demand relative to supply. Therefore, goods, property, assets, safety of people, service, etc. are treated as commodities, and if there is no market to set the price of a commodity then it has no economic value. Therefore, the value refers to the market worth of a commodity, which is determined by the equilibrium at which two commodities are exchanged. The limitation herein is in its inability to set a value to things that are not exchanged in markets.

In the labor theory of value, a good or service is associated with the amount of discomfort or labor saved through the consumption or use of it. According to this theory, the exchange value is recognized without recognizing its equivalence to an economic value, i.e., price and value are considered as two different concepts. Accordingly, a value is determined based on the exchange price, which does not necessarily represent its true economic value.

An economic measure of the value of a good or the benefit from a service can be defined as the maximum amount a person is willing to pay for this good or service. The concept of willingness to pay (WTP) is central to economic valuation. An alternate measure is the willingness to accept (WTA) of an amount by the person to forgo taking possession of the good or receiving the service. WTP and WTA produce amounts that are expected to be close; however, generally WTA generated amounts are greater than WTP generated amounts due primarily to income levels and affordability factors.

The economic concept of value, including its exchange value, can be criticized as being stripped from moral and ethical considerations. For example, having an exchange value for a good or a service that is harmful in nature, e.g., markets of illegal drugs or gambling or prostitution or weaponry, have value in some open markets, in some underground markets, and no value in others. Contrarily, not having an exchange value for a good or a service that is good in nature, e.g., volunteer work, might not have a market value but this does not necessarily make it without any value. Accounting for such moral and ethical considerations in economic models can be contentious, and commonly such goods or services are ignored. To perform tradeoff analysis, resilience should be treated in these economic terms.

The valuation of resilience can be based on the savings in potential direct and indirect losses, and cost of recovery as illustrated in Fig. 3. Alternatives for enhancing resilience that can reduce these potential losses can be analyzed using models for benefit-cost analysis, where the benefit (B) is the potential savings in losses and recovery costs because of the implementation of an alternative and the cost (C) is the cost of the alternative. The benefit and costs are treated as random variables.(58) Assuming B and C to be normally distributed, a benefit-cost index ($\beta_{B/C}$) can be defined as follows:

$$\beta_{B/C} = \frac{\mu_B - \mu_C}{\sqrt{\sigma_B^2 + \sigma_C^2}}, \tag{31}$$

where μ and σ are the mean and standard deviation. The probability of cost exceeding benefit can be computed as:

$$P_{f,B/C} = P(C > B) = 1 - \Phi(\beta), \tag{32}$$

where Φ is the standard normal cumulative distribution function. In the case of lognormally distributed B and C, the benefit-cost index ($\beta_{B/C}$) can be computed as:

$$\beta_{B/C} = \frac{\ln\left(\frac{\mu_B}{\mu_C}\sqrt{\frac{\delta_C^2+1}{\delta_B^2+1}}\right)}{\sqrt{\ln[(\delta_B^2+1)(\delta_C^2+1)]}}, \tag{33}$$

where δ is the coefficient of variation. In the case of mixed distributions or cases involving basic random variables of B and C, other reliability methods can be used as described by Ayyub.(58)

6. CONCLUSIONS

Enhancing the resilience of a system, including buildings, infrastructure, network, and communities, could lead to massive savings through risk reduction and expeditious recovery. In this article, a resilience definition is provided that meets a set of requirements with clear relationships to metrics of the relevant abstract notions of reliability and risk. Those metrics also meet logically consistent requirements drawn from measure theory, and provide a sound basis for the development of effective decision-making tools for multihazard environments. The proposed metrics provide a strong basis for the rational management of such reduction and recovery facilitated by an appropriate definition of resilience and associated metrics. Also, the article provides a framework for the valuation of resilience by society at large, methods for benefit-cost analysis based on concepts from risk analysis and management. Although resilience valuation is in its infancy and additional work is necessary along with case studies, this article offers a basis for such efforts.

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APPENDIX A: SELECTED URBAN AREAS AND HAZARDS

Table A1. Selected Urban Areas, Their Respective Population Sizes, Location Attributes, and Hazards as a Summary of the Data Reported by UNISDR[1]

Urban Area and Population	Location Attributes	Hazards
Santa Fe, Argentina 400,000	The flood plain of the Parana and Salada Rivers	Flooding and intense rainfall
Cairns, Australia 164,356	A coastal town in the wet tropics, northern Queensland	Cyclones, flooding, storm surge, and tsunamis
Tyrol Province, Austria 712,077	Western Austria, consisting of nine districts	Flooding and landslides
Thimphu, Bhutan 79,185	Landlocked state in South Asia, east of the Himalayas	Prone to earthquakes, landslides, cyclones, and flooding
North Vancouver, Canada 82,000	Coastal municipality in southwest British Columbia on the mountainsides	Landslides, flooding, and wildfire
Valle de Itata, Chile 80,762	Northwest of the bio region of Chile	Flooding, extreme wind and rain, wildfire, and earthquakes
Baofeng, China 498,000	Henan Province	Drought, flooding, wind, snowstorms, and earthquakes
Siquirres, Costa Rica 59,000	Limon Province, in the plane of the Talamanca mountains	Flooding, landslides
Copenhagen, Denmark 1,213,822	Eastern shore of the island of Zealand, partly on the island of Amager and on a number of natural and artificial islets	Flooding and landslides
Dubai, United Arab Emirates 2,200,000	Southeast of the Persian Gulf on the Arabian Peninsula	Drought, heat waves, sand storms
Quito, Ecuador 2,197,698	Northeast of the country at 2,800 m above sea level	Volcanic hazards, earthquakes, landslides, and flooding
Santa Tecla, El Salvador 200,000	Part of the metropolitan area of the country's capital, San Salvador	Earthquakes, landslide, and flooding risks
Bonn, Germany 300,000	About 25 km south of Cologne on the river Rhine	Flooding from the Rhine and recently extreme heat waves during summer
Bhubaneswar, India 1,000,000	In the Khurda District, Orissa	Earthquakes, flooding, cyclones, heat waves
Pune, India 5,000,000	At the confluence of three rivers: the Mutha, Mula, and Pavana at 560 m above sea level	Flooding
Mumbai, India 19,700, 000	A coastal megacity built on what used to be a group of seven islands, many areas are only 5 m above low tide level	Coastal flooding
Makassar, Indonesia 1,400,000	Southwest coast of the island of Sulawesi, facing the Makassar Strait	Tsunamis and flooding
Jakarta, Indonesia 9,800,000	Situated in the northwest coast of Java, at the mouth of the Ciliwung River on Jakarta Bay, which is an inlet of the Java Sea	Earthquakes and flooding
Mashhad, Iran 2,420,000	850 km east of Tehran at 950 m elevation in the valley of the Kashaf River between two mountain ranges	Flooding, cyclones, earthquakes, and drought
Venice, Italy 263,996	On a group of 118 islands in the Venice Lagoon	Flooding as a result of low (and falling) elevation
Ancona, Italy 100,000	Adriatic coast, south of Venice	Most significant hazard is landslides
Saijo, Japan 114,625	Mountainous terrain in Ehime Prefecture	Extreme rainfall, typhoons, mudslides, landslides, and flooding
Aqaba, Jordan 108,500	Coastal city situated at the northeastern tip of the Red Sea	Drought, heat waves
Narok, Kenya 60,000	Southern side of the Rift Valley and has varied topography, with a predominantly agricultural economy base	Flooding and drought

(*Continued*)

Table A1. Continued

Urban Area and Population	Location Attributes	Hazards
Kisumu, Kenya 200,000	Port city in western Kenya	Flooding
Beirut, Lebanon 1,500,000	On a peninsula at the midpoint of Lebanon's Mediterranean coast	Earthquakes, flooding, wildfires, and landslides
Kathmandu, Nepal 1,000,000	Situated in central Nepal bowl-shaped valley between four major mountains, at high elevation	Earthquakes and landslides
Telica, Quezalguaque and Larreynaga-Malpaisillo, Nicaragua 71,000	Basin of the Leon	Volcanic, seismic, hurricanes, flooding, epidemics, environmental risks linked to gold mining, and monoagriculture
Pakistan 30 cities	Varies	Landslides, flooding, storms, cyclones, earthquake, drought, fire, epidemics, riots, and conflicts
Chincha, Pisco, Cañete, and Ica, Peru 536,000	Peru's Pacific coast	Earthquakes and flooding
Albay, Philippines 1,000,000	Albay Province	Typhoons, storm surge, volcanoes, landslides, tsunamis, and flooding
Amadora, Portugal 175,135	Northwest of the Lisbon metropolitan area	Earthquake, flood, heat wave, land slide, technological disasters
Makati, Philippines 510,383 to 3,700,000 (daytime)	West valley fault system	Earthquakes, flooding, and landslides
San Francisco, Philippines 48,834	Small island within the Camotes Island group and part of the province of Cebu	Flooding and landslide
Quezon City, Philippines 1,700,000	Largest and most populous	Flooding, earthquakes, fire, and epidemic
Cape Town, South Africa 3,700,000	Coastal area	Storm surge, heat wave, flooding, fires, and drought
Johannesburg, South Africa 3,500,000	In the eastern plateau area of South Africa known as the Highveld, at an elevation of 1,753 m	Intense rainfall and flooding
Overstrand, South Africa 76,000	Situated in the Western Cape Province of South Africa	Drought, flooding, and fire
Batticaloa, Sri Lanka 515,857	Situated in the East Province, and the administrative capital of the Batticaloa	Civil unrest in the area (ended in 2009), Indian Ocean tsunami
Colombo, Sri Lanka 647,100	On the west coast of the island and adjacent to Sri Jayawardenapura Kotte	Flooding, typhoons, earthquakes, landslides, fires, and tsunami
Moshi, Tanzania 150,000	A market hub town in northeastern Tanzania at the foot of Mount Kilimanjaro	Drought and flooding
Bangkok, Thailand 9,700,000	Coastal in Southeast Asia	Flooding
Istanbul, Turkey 13,000,000	In northwestern Turkey within the Marmara Region on a total area of 5,343 km^2	Earthquakes
San Francisco, California, USA 805,235	West coast of the United States, at the tip of the San Francisco Peninsula including significant stretches of the Pacific Ocean	Wild fire, tsunami, landslide, heat wave, flooding, earthquake, drought
Chacao, Venezuela 71,000	Mideastern portion of the Caracas Valley, north of the Guaire River	Earthquake and flooding

REFERENCES

1. UNISDR. Making cities resilient: My city is getting ready! A global snapshot of how local governments reduce disaster risk, United Nations Office for Disaster Risk Reduction Report, Geneva, Switzerland, 2012. Available at: www.unisdr.org/campaign.
2. Ayyub BM, Braileanu HG, Qureshi N. Prediction and impact of sea level rise on properties and infrastructure of Washington, DC. Risk Analysis, 2012; 32(11):1901–1918.
3. Gilbert, SW. Disaster Resilience: A Guide to the Literature. NIST Special Publication 1117, Office of Applied Economics, Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, 2010.
4. Burby R (ed). Cooperating with Nature: Confronting Natural Hazards and Land-Use Planning for Sustainable Communities. Washington, DC: Joseph Henry Press, 1998.
5. Berke P, Kartez J, Wenger D. Recovery after disaster: Achieving sustainable development, mitigation and equity. Disasters, 2008; 17:93–109.
6. ASCE. Report Card for America's Infrastructure, Reston, VA: ASCE, 2009.
7. Holling CS. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics, 1973; 4: 1–23.
8. Starr C, Rudman R, Whipple C. The philosophical basis for risk analysis. Annual Review of Energy, 1976; 1:629–662.
9. Webster's New World Dictionary & Thesaurus. New York: Macmillan Publishers, 1998.
10. Park J, Seager TP, Rao PSC, Convertino M, Linkov I. Integrating risk and resilience approaches to catastrophe management in engineering systems. Risk Analysis, 2012; 33(3):356–367.
11. Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM, Shinozuka M, Tierney K, Wallace WA, vonWinterfeldt D. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra, 2003; 19:733–752.
12. Flynn, S. The Edge of Disaster: Rebuilding a Resilient Nation. New York: Random House, 2007.
13. Gunderson, L. Ecological and human community resilience in response to natural disasters. Ecology and Society, 2010; 15(2):18. Available at: http://www.ecologyandsociety.org/vol15/iss2/art18/, Accessed June 25, 2013.
14. Rose A. Economic Resilience to Disasters, CARRI Research Report 8. Community and Regional Resilience Initiative, Available at: http://research.create.usc.edu/cgi/viewcontent.cgi?article=1015&context=published_papers, Accessed June 25, 2013.
15. Cutter SL, Burton CG, Emrich CT. Disaster resilience indicators for benchmarking baseline conditions. Journal of Homeland Security and Emergency Management, 2010; 51: 7(1); DOI: 10.2202/1547-7355.1732.
16. Plodinec MJ, Definitions of Resilience: An Analysis. Community and Regional Resilience Initiative, Oak Ridge, TN, 2009. Available at: http://www.resilientus.org/library/CARRI_Definitions_Dec_2009_1262802355.pdf
17. White GF, Haas JE. Assessment of Research on Natural Hazards. Cambridge, MA: MIT Press, 1975.
18. Mileti D. Disasters by Design: A Reassessment of Natural Hazards in the United States. Washington, DC: Joseph Henry Press, 1999.
19. United Nations Office for Disaster Risk Reduction (UNISDR). Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters. Geneva, Switzerland, 2007. Available at: http://www.unisdr.org/files/1037_hyogoframeworkforactionenglish.pdf, Accessed June 25, 2013.
20. Bruneau M, Reinhorn A. Exploring the concept of seismic resilience for acute care facilities. Earthquake Spectra, 2007; 23(1):41–62.
21. Little RG. Toward More Robust Infrastructure: Observations on Improving the Resilience and Reliability of Critical Systems, in Proceedings of the 36th Annual Hawaii International Conference Hawaii, IEEE, 2003; 1–9.
22. Lebel L, Anderies JM, Campbell B, Folke C, Hatfield-Dodds S, Hughes TP, Wilson J. Governance and the capacity to manage resilience in regional social-ecological systems. Ecology and Society, 2006; 11(1), 19. Available at: http://www.ecologyandsociety.org/vol11/iss1/art19/, Accessed June 25, 2013.
23. Walker B, Holling CS, Carpenter SR, Kinzig A. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society, 2004; 9(2), 5. Available at: http://www.ecologyandsociety.org/vol9/iss2/art5/, Accessed June 25, 2013.
24. Holling CS, Gunderson LH. A working hypothesis for participation: Panarchy, sustainability and panarchies. Pp. 63–102 in Gurdeson LH, Holling CS (eds). Panarchy and Understanding in Human and Natural Systems. Washington, DC: Island Press, 2002.
25. Fiksel J. Designing resilient and sustainable system. Environmental Science and Technology, 2003; 27:5330–5339.
26. Hollnagel E, Woods DE, Levensen N. Resilience Engineering: Concepts and Precepts. Aldershot, UK: Ashgate Publishing, 2006.
27. Norris FH, Stevens SP, Pfefferbaum B, Wyche KF, Pfefferbaum RL. Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. American Journal of Community Psychology, 2008; 41:127–150.
28. Sherrieb K, Norris FH, Galea S. Measuring capacities for community resilience. Social Indicators Research, 2010; 99(2):227–247.
29. Kahan JH, Allen AC, George JK. An operational framework for resilience. Journal of Homeland Security and Emergency Management, 2009; 6(1):1–48. Available at: www.bepress.com/jhsem/vol6/iss1/83, Accessed June 25, 2013.
30. Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J. A place-based model for understanding community resilience to natural disasters, Global Environmental Change, 2008; 18:598–606.
31. Colten CE, Kates RW, Laska SB. Three years after Katrina: Lessons for community resilience. Environment, 2008; 50(5):36–47.
32. Presidential Policy Directive (PPD), Critical Infrastructure Security and Resilience. PPD-21, Released February 12, 2013. Available at: http://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil, Accessed June 25, 2013.
33. National Research Council (NRC). Disaster Resilience: A National Imperative. Washington, DC: National Academies Press, 2013.
34. Subcommittee on Disaster Reduction (SDR). Grand Challenges for Disaster Reduction, Washington DC: National Science and Technology Council, 2005.
35. DHS Risk Steering Committee. DHS Risk Lexicon. Department of Homeland Security, 2008. Available at: www.dhs.gov/xlibrary/assets/dhs_risk_lexicon.pdf, Accessed June 25, 2013.
36. Presidential Policy Directive (PPD). National Preparedness. PPD-8, Released March 30, 2011. Available at: http://www.dhs.gov/xabout/laws/gc_1215444247124.shtm, Accessed June 25, 2013.
37. National Research Council (NRC). National Earthquake Resilience: Research, Implementation, and Outreach. Washington, DC: National Academies Press, 2011.
38. ASCE Policy Statement 518. Available at: http://www.asce.org/Content.aspx?id=8478, Accessed June 25, 2013.

39. MCEER. PEOPLES: A Framework for Defining and Measuring Disaster Resilience. Working Paper, Multidisciplinary Center for Earthquake Engineering Research (MCEER) of the State University of New York at Buffalo, 2010.
40. Civil Contingencies Secretariat of the Cabinet Office, London, UK, 2003. Available at: www.cabinetoffice.gov.uk, Accessed June 25, 2013.
41. International Organization of Standardizations (ISO). Risk Management—Risk Assessment Techniques, ISO Standard IEC/FDIS 31010, iso.org, Geneva, Switzerland, 2009.
42. Ayyub BM, Kilr GJ. Uncertainty Modeling and Analysis in Engineering and the Sciences. New York: Chapman & Hall/CRC, Taylor & Francis Group, 2006.
43. Halmos P. Measure Theory. Princeton, NJ: Van Nostrand, 1950.
44. Royden H. Real Analysis. Upper Saddle River, NJ: Prentice-Hall, 1988.
45. Wang Z, Klir GJ. Fuzzy Measure Theory. New York: Plenum Press, 1992.
46. Klir GJ, Wierman MJ. Uncertainty-Based Information: Elements of Generalized Information Theory. New York: Physica-Verlag, 1999.
47. Garbin DA, Shortle JF. Measuring Resilience in Network-Based Infrastructures, In McCarthy JA (ed). Critical Thinking: Moving from Infrastructure Protection to Infrastructure Resiliency. Fairfax, VA: George Mason University, 2007.
48. Tierney K, Bruneau M. Conceptualized and measuring resilience. TR News, 2007; 250:14–17.
49. Attoh-Okine N, Cooper AT, Mensah SA. Formulation of resilience index of urban infrastructure using belief functions. IEEE Systems Journal, 2009; 3(2):147–153.
50. Shinozuka M, Chang SE, Cheng T-C, Feng M, O'Rourke TD, Saadeghvaziri MA, Dong X, Jin X, Wang Y, Shi P. Resilience of Integrated Power and Water Systems, MCEER Research Progress and Accomplishments: 2003–2004, MCEER-04-SP01, 2004; 65–86, NY. Available at: https://mceer.buffalo.edu/publications/resaccom/04-sp01/06_shino.pdf, Accessed June 25, 2013.
51. Li Y, Lence B. Estimating of water resources systems. Water Resources, 2007; 43:W07422; doi:10.1029/2006WR005636.
52. Hashimoto T, Stedinger JR, Loucks DP. Reliability, resiliency and vulnerability for water resources system performance evaluation. Water Resource Research 1982; 18(1):14–20.
53. Omer M, Nilchiani R, Mostashari A. Measuring the Resilience of the Global Internet Infrastructure System, 2009. 3rd Annual Systems Conference, IEEE, 2009; 156–162.
54. McGill WL, Ayyub BM. Regional capabilities performance assessment for homeland security. IEEE Systems J. 2009; 3(2):192–198.
55. Miles S, Chang S. Urban Disaster Recovery: A Framework and Simulation Model. MCEER, Multidisciplinary Center for Earthquake Engineering Research (MCEER) of the State University of New York at Buffalo, 2003.
56. Ellingwood BR, Mori Y. Probabilistic methods for condition assessment and life prediction of concrete structures in nuclear plants. Nuclear Engineering and Design, 1993; 142:155–166.
57. Anthony L. Community resilience and decision theory challenges for catastrophic risk. Risk Analysis, 2012; 32(11):1919–1934.
58. Ayyub BM. Risk Analysis in Engineering and Economics. New York: Chapman & Hall/CRC, Taylor & Francis Group, 2003.
59. Callicott JB. Explicit and Implicit Values in the ESA. In Davies F, Goble D, Heal G, Scott M (eds.). The Endangered Species Act at Thirty: Retrospect and Prospects. Washington, DC: Island Press, 2004.
60. National Research Council. Valuing Ecosystem Services: Toward Better Environmental Decision-Making. Washington, DC: National Academies Press, 2004.
61. Bishop RC, Boyle KJ, Welsh MP. Toward total economic value of great lakes fishery resources. Transactions of the American Fisheries Society, 1987; 116(3):339–345.
62. Randall A. Total and nonuse values in measuring the demand for environmental quality. In Braden JB, Kolstad CD (eds). Measuring the Demand for Environmental Quality. Amsterdam: Elsevier Science Publishers, 1991.