LA-UR-18-31254
Approved for public release; distribution is unlimited.

Title: Resilience: Concepts from Engineering, Ecology, and the Social Sciences

Author(s): Sims, Benjamin Hayden
Brelsford, Christa

Intended for: Report

Issued: 2018-12-03

Disclaimer:
Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC for the National Nuclear Security Administration of U.S. Department of Energy under contract 89233218CNA000001. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Resilience

Concepts from Engineering, Ecology, and the Social Sciences

Benjamin Sims
Statistical Sciences Group
Los Alamos National Laboratory

Christa Brelsford
Geographic Information Science and Technology Group
Oak Ridge National Laboratory

Revised November 28, 2018
LA-UR-

Table of Contents

Introduction **2**

General Definitions of Resilience *3*

Resilience, Reliability, and Vulnerability *6*

Resilience Concepts and Metrics **6**

Classical Engineering Resilience *7*

Complex Systems Resilience *8*

Community and Regional Resilience *9*

Characteristics of Resilient Systems **11**

References **13**

Acknowledgements **14**

Appendix 1: Detailed Explanation of Ecological Resilience **15**

Appendix 2. Annotated Bibliography **17**

Engineering – Classical *17*

Engineering – Ecological *21*

Ecology *24*

Economics and Public Policy *27*

Introduction

"Resilience" is fast becoming a key word for describing the desired result of the activities we group under the heading of "homeland security." Department of Homeland Security (DHS) Secretary Napolitano has made resilience a key theme in her speeches, highlighting the efforts of DHS to "strengthen the resilience of … infrastructure, computer networks, and of … communities and citizens." She has talked about resilience as "strengthening the ability for our systems, our cities, our towns, and our country to bounce back quickly from an attack or a natural disaster, and to be even stronger than before [1]." The 2009 National Infrastructure Protection Plan (NIPP) emphasizes the dual goals of "protection and resilience," the need to both harden infrastructure against disruption and ensure that it recovers quickly if it is disrupted [2]. In 2009, the National Infrastructure Advisory Council (NIAC) authored a major policy document urging DHS to focus more resources on critical infrastructure resilience [3]. The 2010 Quadrennial Homeland Security Review lists "Ensuring Resilience to Disasters" as one of five core "Homeland Security Missions."

Resilience is also gaining relevance in the wider national security community; the President's 2010 National Security Strategy emphasizes the need to "strengthen security and resilience at home" as well as "enhance the resilience of U.S. forward posture and facilities against potential attacks [4]." In addition, the 2010 Quadrennial Defense Review Report positions "America's resilience" as an "important dimension of our deterrent posture [5]."

The increasing emphasis on resilience in the homeland security community closely follows on its rise in importance as a concept within the disaster research and infrastructure engineering communities. In these fields, resilience has become the dominant framework for assessing the response of both human and technological systems to adverse events, eclipsing the earlier focus on measuring the reliability or vulnerability of these systems.[1]

Why this emphasis on resilience, and why now? One simple answer is that it took time for the concept, as it is currently understood, to migrate from the field of ecology (where it emerged in the early 1970s), to environmental sustainability, to the social sciences and engineering, and into the realm of emergency preparedness and homeland security. Others have suggested that resilience has come forward as a an attractive concept because it is a more action-oriented concept than vulnerability or protection, and focuses on things communities and infrastructure operators can take to improve functioning before a disaster or attack occurs, as well as to respond actively during and after a disaster [6]. In a larger context, resilience is relevant in a post-Cold War, post-9/11 world where the U.S. is seen as vulnerable to attack, but where attacks are likely to have primarily local or regional consequences.

This paper first provides an overview of resilience concepts from U.S. government and academic research sources. It then discusses resilience concepts and metrics from the academic literature in more detail, focusing on three types of resilience: engineering resilience, ecological resilience, and community and regional resilience. Next, it discusses system characteristics that have been associated with increased resilience. Based on this background, we propose a model of the infrastructure resilience

[1] As an indication, a search of the ISI Web of Knowledge indicates that the total number of published scholarly articles with resilience in the title or topic rose from 417 in 1999 to 2,620 in 2009, with most of the articles in engineering and the social and behavioral sciences.

analysis process. We then review LANL capabilities for each process element and indicate areas where capability development opportunities exist. Appendices provide additional information on funding sources and key players in infrastructure resilience, and a more detailed technical explanation of ecological resilience.

General Definitions of Resilience

Resilience can generally be defined as follows:

> ***The resistant characteristics and adaptive capacities of a system that enable it to respond to disruption with lower probability of failure, shorter time to recovery, and/or reduced level of negative impacts.***

This definition derives from the following survey of U.S. government and academic definitions of resilience, and covers the key aspects of resilience that are of interest to LANL. Its meaning, in practice, will depend on how "failure," "recovery," and "negative impacts" are defined and measured.

Resilience is used in many different contexts, but a survey of definitions of the term turns up some common themes. First, resilience almost always refers to the ability of a system to function after some kind of disruption. In a physics or engineering context, resilience is sometimes contrasted with resistance, where "resistance refers to the force required to displace the system from equilibrium, whereas resilience refers to the time required for the system to return to equilibrium once displaced [7]." For example, resistance might refer to the wind speed power lines are designed to withstand without failing, while resilience might refer to how quickly an electric power network is able to reroute power in the event some lines do fail.

Box 1: Official U.S. Government Definitions of Resilience

DHS (Short) [2, 25]

> The ability to resist, absorb, recover from, or successfully adapt to adversity or a change in conditions.

DHS (Extended) [25]

> 1) ability of systems, infrastructures, government, business, and citizenry to resist, absorb, recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance;
> 2) capacity of an organization to recognize threats and hazards and make adjustments that will improve future protection efforts and risk reduction measures.

National Infrastructure Advisory Council [3]

> The ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.

2010 National Security Strategy [4]

> The ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption.

2010 Quadrennial Defense Review [5]

> Robustness, adaptability, and capacity for rapid recovery.

As the definitions in Box 1 indicate, however, resilience is generally defined much more broadly in policy contexts. The ability to recover quickly from a disruption is still the essential feature in these definitions, and serves to distinguish resilience from concepts like reliability that focus more strongly on resistance to disruption. Rather than being seen as a separate concept, however, resistance is typically folded into the overall concept of resilience. In addition, efforts to plan for and anticipate disruptions in advance of an event are seen as key elements of resilience. In these definitions, resilience is fundamentally about the adaptive qualities of a system that enable it to anticipate, resist, and recover from disruption. These definitions are also intended to cover both engineered systems and social systems: they either use phrasing that is neutral about the type of system in question, or explicitly include organizations and communities as key elements of an overall resilience picture.

Box 2: Definitions of Resilience from the Academic Literature

Engineering/sociology [9]

The ability of [a] system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance). More specifically, a resilient system is one that shows the following:

- Reduced failure probabilities
- Reduced consequences from failures, in terms of lives lost, damage, and negative economic and social consequences
- Reduced time to recovery (restoration of a specific system or set of systems to their "normal" level of performance)

Ecology [18]

The capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks.

Geography/sociology [8]

The ability of a social system to respond and recover from disasters and includes those inherent conditions that allow the system to absorb impacts and cope with an event, as well as post-event, adaptive processes that facilitate the ability of the social system to re-organize, change, and learn in response to a threat.

Community psychology [7]

A process linking a set of adaptive capacities to a positive trajectory of functioning and adaptation after a disturbance.

Box 2 provides a cross-section of the numerous definitions of resilience that exist in the academic research literature. As in the policy world, resilience is generally linked to the adaptive capacity of a system, and may include pre-event efforts to anticipate disruptions, resistance to disruption, and ability to effectively recover from disruption. Here, too, resilience can encompass a wide variety of systems, including engineered systems, social systems, and ecological systems. Despite the wide variety of disciplines these definitions come from, it is clear that they are related: resilience is a notably interdisciplinary concept, and researchers from these various fields frequently cite one another. A key distinction among these definitions is between the engineering definition, which focuses on "re-establish[ing] normal performance" and the ecological definition, which indicates that complex systems may not recover to a pre-existing state, but are resilient if they are able to retain their basic structure and functionality.

Resilience, Reliability, and Vulnerability

Resilience is closely related to more established concepts for describing the response of systems to stress, including reliability and vulnerability. In order to understand the meaning and significance of resilience, it is helpful to understand how it differs from these concepts.

In engineering, systems have often been characterized in terms of reliability. Reliability is usually defined in terms of the probability of a system or component being able to perform its intended function under specific conditions over a period of time [15]. A reliability approach is useful primarily for determining the initial impact of a disruptive event on a system, which is related to the resistance of a system to failure. As noted above, resilience is usually understood to include resistance to failure, so reliability is treated as an element of resilience. Resilience goes beyond traditional approaches to reliability by considering system properties that could make a system less likely to fail over a wide range of disruptive conditions, including those that cannot be anticipated in advance [15]. Resilience also places much more emphasis on processes of system adaptation and recovery that occur after an initial disruption.

In the social sciences, the impact of disasters has frequently been discussed in terms of social vulnerability. Social vulnerability is defined in terms of geographic or demographic indicators that are associated with increased impacts from a disruptive event. These indicators may include income, race, age, household characteristics, or geographic location of households. Higher levels of social vulnerability may translate into increased casualties and greater socioeconomic consequences. For example, an isolated poor community may experience greater casualties in a flood of given depth and speed because evacuation is slower due to lack of car ownership, because evacuation would pose a financial hardship, or because decision-makers do not effectively communicate with the community. Like reliability, social vulnerability is primarily concerned with factors contributing to the initial impact of a disruption. The concept of community resilience, by contrast, has been developed to focus more on the recovery process and on the positive social, organizational, and material resources a community can draw on to facilitate it. Social scientists, like engineers, have incorporated resistance to failure into their definitions of resilience, so social vulnerability is often treated as an element of resilience [7,8].

Resilience Concepts and Metrics

Current resilience definitions and analysis methods in engineering, as well as in the social sciences, draw heavily from the ecology literature. Ecology was the first discipline in which system resilience became a central concept, leading to rigorous efforts to define and model resilience beginning in the early 1970s.

In 1973, ecologist C.S. Holling published a paper on resilience that is frequently cited as the foundation for current theories of resilience [10]. In it, he made a distinction between resilience of a system near a stable equilibrium, which he later referred to as “engineering resilience,” and resilience of a complex, adaptive system with multiple, dynamic equilibrium states, which he called “ecological resilience [11].” These ideas have been elaborated on by subsequent generations of ecologists and engineers [12-15].

As Holling and others have extended these ideas, it has become clear that classical engineering approaches to resilience need not be limited to engineered systems, and that a complex systems view of resilience can be applied in many domains outside ecology. Indeed, many ecosystem management

efforts actually treat ecological systems as if they were engineered systems, focusing on single "services" provided by the ecosystem. This can be a good enough approximation in many cases, but in many cases may lead to decisions that support short-term stability while compromising the long-term resilience of the ecosystem. More successfully, ecology-based concepts of resilience have been applied to engineered systems, which themselves may exhibit the complex, emergent behavior found in ecosystems, particularly when combined in "systems of systems" that were not designed in an integrated way from the ground up. Finally, as we will explore in the next section of the paper, both of these concepts of resilience have been applied outside the realms of engineering and ecology, to describe a variety of social, behavioral, and economic systems.

Note on terminology: Although the term "ecological resilience" is often used in an engineering context, we refer to this concept as "complex systems resilience" in the rest of the paper in order to avoid confusion. Also, in order to emphasize that Holling's "engineering resilience" is not the only way engineers see resilience, we use the term "classical engineering resilience" to cover this concept.

Classical Engineering Resilience

Classical engineering resilience is defined as the ability of a system to regain its previous functionality following a disturbance. Engineering approaches to resilience have traditionally viewed systems as performing well-defined functions or services that are always executed through the same set of relationships and processes within the system. Since engineered systems are designed in precisely this way, it is often appropriate to analyze their resilience in terms of degradation of service and time to restore service. When engineered systems break down, the services they provide may degrade or be lost completely, but their fundamental operating principles remain the same, and restoration is simply a matter of repairing components and connections. It is in this sense that engineered systems operate close to a stable equilibrium.

The ideas behind classical engineering resilience initially came from materials science, where resilience was defined as either the amount of force a material could withstand and retain its original shape, or the amount of time it took the material to return to its original shape. However, in engineering, the term has developed a broader definition, and now generally refers to the ability of an engineered structure or system to withstand and recover quickly from damage. This definition has been widely used in the infrastructure engineering community, including in the areas of seismic engineering and information systems engineering.

The typical approach to quantifying engineering resilience is to measure the percentage of service lost due to a disturbance, and the time before it is restored to previous levels or some other steady state. The total functional loss over time, L, can be defined as follows:

$$L = \int_{to}^{t1} [100 - Q(t)]dt$$

Where Q(t) is a measure of the quality of the infrastructure at time t. This might correspond to percentage of households receiving a particular service, or some other measure of system functionality.

Graphically, then, the shaded area in Figure 1 represents the total loss of function of the system. The smaller this area is, the more resilient a system is to the disruption in question.[2]

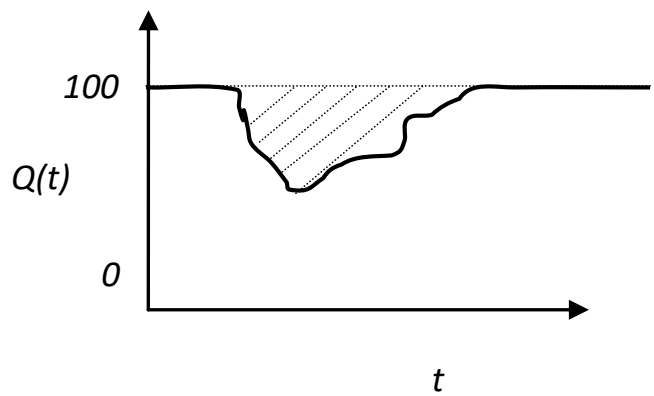

Figure 1. Disruption and recovery of function in an engineered system

In engineering, resilience is sometimes used in another, related sense, to characterize the robustness of a network to disruption of one or more of its components or links. For example, Omer et al. [17] model the resilience of the international trans-oceanic telecommunications cable network in terms of the degradation of its overall function in response to disruption of specific linkages. Using this method, they are able to identify which links are most critical to overall system capacity. In this work, resilience is still measured as loss of function, but instead of focusing on recovery time, there is more emphasis on understanding the internal dynamics of the underlying network as it degrades.

Complex Systems Resilience

The complex systems view of resilience was originally developed to capture features of resilience specific to ecosystems. Ecosystems are complex, emergent structures that do not provide discrete, well-defined functions or services. They tend to have multiple equilibrium states, and those states tend to take the form of dynamic oscillations around a stable attractor, rather than the steady states that are often the goal of engineering design. Each of these dynamic equilibrium states may entail a different set of functional relationships between the entities that make up the system. When pushed out of an equilibrium state, ecological systems may respond not with degradation in performance, but with a shift to a new set of relationships and functions [10], [11], [13], [18]. These shifts may be disastrous for certain elements of the ecosystem, but they maintain the existence of the system as a whole. ***Complex systems resilience is defined as the ability of a system to respond to a disturbance without switching to a new functional equilibrium state,*** particularly one that has negative consequences for valued parts of the system.

[2] Adapted from [9] and [16].

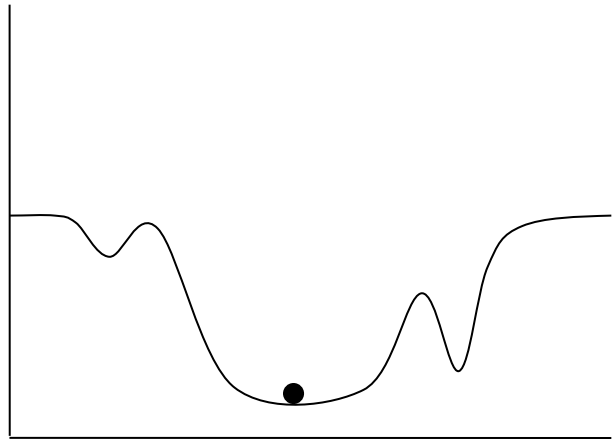

Figure 2. Conceptual representation of a system with multiple equilibrium basins

Figure 2 is a conceptual representation of this view, showing a notional resilience function for an ecological system as a potential energy curve, in which there are several local minima representing equilibrium states of the system, some encompassing a broader range of system dynamics than others, and some with higher thresholds of disruption than others.[3] For additional technical details on ecological resilience, see Appendix 2.

Complex systems approaches are now frequently applied to engineered systems. For example, Wang et al. [19] and Blackmore and Plant [20] examine the resilience of water systems both in terms of time to restore functionality, and by analyzing them as complex systems with multiple equilibrium states. Madni et al. [15] propose an overall view of engineered system resilience that draws on ecological ideas. Hollnagel et al. [21] discuss resilience engineering in terms of complex systems dynamics, even though they do not directly cite the ecological literature. It should be noted that many of the engineers who view resilience in this way do not look at engineered systems in isolation, but as part of larger socio-technical systems that include decision-making processes and organizational dynamics.

Community and Regional Resilience

From ecology proper, the concept of resilience crossed over the fields of ecosystem management and social-ecological interactions [22]. From there, and from engineering sources, the concept migrated into the interdisciplinary disaster research community, which is dominated by engineers and social scientists. Within this field, ideas from engineering and ecological resilience were combined with a focus on human responses to disaster, and the result was the notion of "community resilience."

[3] Adapted from [19] and [18].

One of the earliest formulations of community resilience was by Bruneau et al. [9], which is the source of the definition of engineering resilience provided above, though the authors include a sociologist and a policy analyst as well as engineers. This paper conceives of community resilience to earthquakes in terms of preservation of critical facilities, including "lifeline" infrastructure systems like water and power, as well as hospitals and emergency management organizations. More specifically, it characterizes four dimensions of community resilience, represented by the acronym TOSE: technical, organizational, social, and economic. The technical and organizational dimension comprise the response of infrastructure and key institutions to a disaster, while the social and economic dimensions characterize the extent of the loss, in terms of casualties, social disruption, and economic loss. They define a number of possible metrics for resilience for specific organizational and infrastructure systems, which are generally consistent with the engineering definition of resilience. However, they view overall community resilience as a consequence of interactions between multiple systems interacting through feedback loops, which is similar to ecological resilience. The concepts in this paper have been widely cited and used, particularly within the fields of earthquake engineering and hazards reduction.

Norris et al. [7] link community resilience more closely to concepts of psychological resilience, which look at the psychological characteristics of individuals that make them more or less able to adapt to change and successfully respond to stress. However, they place this in a broad context that includes social and technological resources in the larger community. Like Bruneau et al., they characterize community resilience in terms of four dimensions: information and communication, community competence, social capital, and economic development. These categories are more function-oriented than those proposed by Bruneau et al. Rather than singling out infrastructure as a single dimension, they incorporate it into each dimension of resilience. They propose a simple metric for community resilience, which is the aggregate physical and well-being of the population following recovery from a disruption. This has the advantage of being measurable through community surveys, and creates a scale for measuring impact beyond usual "deaths and dollars" measures.

Cutter et al. [8] conceive of community resilience in terms of a "Disaster Resilience of Place" (DROP) model, which views different indicators of vulnerability and resilience as geographic layers that can be combined to capture the geographic distribution of likely disaster impacts throughout a region. These include ecological, social, economic, and built environment variations.

We propose a generalized view of the elements that go into community resilience, based on the idea that infrastructure is the key interface between natural forces and social processes in modern society [23]. The effects of disasters or attacks are therefore generally mediated by infrastructure: infrastructure disruption is the immediate cause of many of the casualties and much of the social and economic disruption in these events. Infrastructure enables social processes by providing a continuous and widely distributed flow of resources, and is in turn dependent on both natural and social resources for its functionality. This leads to the socio-technical systems view of resilience shown in Figure 3, which incorporates the infrastructural, institutional, social, and individual levels of resilience described above. The institutional level includes economic activity and impacts [24].

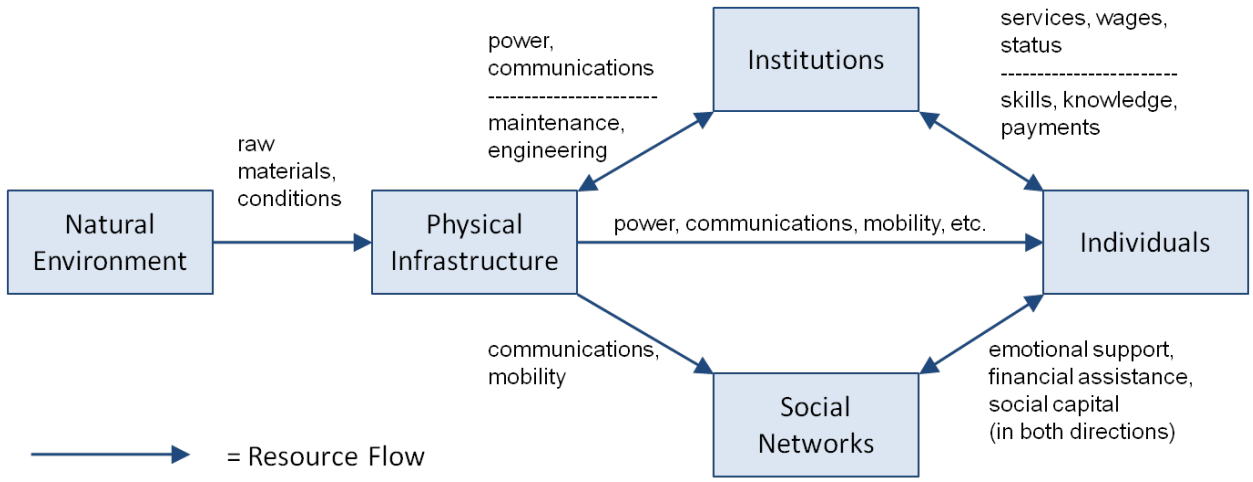

Figure 3. Socio-technical framework for community resilience based on resource flows

Characteristics of Resilient Systems

Although there are relatively well-defined and accepted scales for measuring resilience as an outcome of system response to disruption, there is not significant consensus on what metrics might be appropriate for assessing or predicting the resilience of a system based on its internal characteristics. The metrics that have been proposed often appear to be difficult to apply quantitatively. Bruneau et al. [9], in a formulation that has been widely cited, describe resilience in terms of "4 Rs":

- Robustness
- Redundancy
- Resourcefulness
- Rapidity

Of these, robustness and rapidity are characterized as the ends or goals of resilience improvement efforts: robustness is the "strength" or ability of systems and components to resist breakdown, while rapidity reflects the speed with which functionality can be restored. Redundancy and resourcefulness are characterized as the "means" to these ends. Redundancy reflects the extent to which individual components of a system can substitute for one another, or the degree to which one institution or infrastructure system can substitute for another in terms of the services it provides. Resourcefulness is the ability to set priorities, make decisions, and mobilize resources to meet goals, including the goal of recovery from systemic disruption. This encompasses both the infrastructural and organizational elements needed to successfully mobilize resources.

Madni and Jackson [15], writing from a broad engineering perspective that includes organizational elements, list a number of resilience heuristics that have been suggested in the literature. These include:

- Functional redundancy
- Physical redundancy

- Ability to reorganize
- Human in loop when needed
- Predictability of system behavior
- Complexity avoidance
- Graceful degradation
- Inspectability
- Learning/adaptation

As the diversity of these resilience heuristics suggests, a major challenge for addressing resilience in a quantitative way, and in the context of modeling and simulation, is the need to develop generally applicable metrics for predicting system resilience. There is a significant need for research and development in this area.

References

[1] J. Napolitano, “Remarks as Prepared by Secretary Napolitano to New York City First Responders,” Sep. 2010, http://www.dhs.gov/ynews/speeches/sp_1284133372649.shtm.

[2] U.S. Department of Homeland Security, “National Infrastructure Protection Plan,” 2009, http://www.dhs.gov/xlibrary/assets/NIPP_Plan.pdf.

[3] National Infrastructure Advisory Council, *Critical Infrastructure Resilience: Final Report and Recommendations*, 2009, http://www.dhs.gov/xlibrary/assets/niac/niac_critical_infrastructure_resilience.pdf.

[4] The White House, *National Security Strategy*, 2010, http://www.whitehouse.gov/sites/default/files/rss_viewer/national_security_strategy.pdf.

[5] U.S. Department of Defense, *Quadrennial Defense Review Report*, 2010, http://www.defense.gov/qdr/images/QDR_as_of_12Feb10_1000.pdf.

[6] T.J. Wilbanks, “Remarks at workshop session "Resilience? What's That?," Natural Hazards Research and Applications Workshop, Broomfield, CO, July 9-12, 2010.

[7] F.H. Norris, S.P. Stevens, B. Pfefferbaum, K.F. Wyche, and R.L. Pfefferbaum, “Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness,” *American Journal of Community Psychology*, vol. 41, 2008, pp. 127-150.

[8] S.L. Cutter, L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, and J. Webb, “A Place-Based Model for Understanding Community Resilience to Natural Disasters,” *Global Environmental Change*, vol. 18, 2008, pp. 598-606.

[9] M. Bruneau, S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, and D.V. Winterfeldt, “A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities,” *Earthquake Spectra*, vol. 19, 2003, pp. 733-752.

[10] C.S. Holling, “Resilience and Stability of Ecological Systems,” *Annual Review of Ecology and Systematics*, vol. 4, 1973, pp. 1-23.

[11] C.S. Holling, “Engineering Resilience versus Ecological Resilience,” *Engineering within Ecological Constraints*, National Academies Press, 1996, pp. 31-44.

[12] C. Folke, “Resilience: The emergence of a perspective for social–ecological systems analyses,” *Global Environmental Change*, vol. 16, 2006, pp. 253-267.

[13] L.H. Gunderson, “Ecological Resilience - In Theory and Application,” *Annual Review of Ecology and Systematics*, vol. 31, 2000, pp. 425-439.

[14] D. Ludwig, B. Walker, and C. Holling, “Conservation Ecology: Sustainability, Stability, and Resilience,” *Ecology and Society*, vol. 1, Jul. 2010.

[15] A.M. Madni and S. Jackson, “Towards a Conceptual Framework for Resilience Engineering,” *IEEE Systems Journal*, vol. 3, 2009, pp. 181-191.

[16] C. Wang and J.M. Blackmore, “Resilience Concepts for Water Resource Systems,” *Journal of Water Resources Planning and Management*, vol. 135, 2009, p. 528.

[17] M. Omer, R. Nilchiani, and A. Mostashari, “Measuring the Resilience of the Trans-Oceanic Telecommunication Cable System,” *IEEE Systems Journal*, vol. 3, 2009, pp. 295-303.

[18] C. Folke, S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. Holling, “Regime Shifts, Resilience, and Biodiversity in Ecosystem Management,” *Annual Review of Ecology, Evolution, and Systematics*, vol. 35, 2004, pp. 557-581.

[19] C. Wang, J. Blackmore, X. Wang, K. Yum, M. Zhou, C. Diaper, G. McGregor, and J. Anticev, *Overview of Resilience Concepts, with Application to Water Resource Systems*, Canberra: eWater

Cooperative Research Centre, 2009.
[20] J.M. Blackmore and R.A.J. Plant, "Risk and Resilience to Enhance Sustainability with Application to Urban Water Systems," *Journal of Water Resources Planning and Management*, vol. 134, 2008, p. 224.
[21] E. Hollnagel, *Resilience engineering perspectives*, Aldershot Hampshire England;;Burlington VT: Ashgate, 2008.
[22] M. Janssen, M. Schoon, W. Ke, and K. Borner, "Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change," *Global Environmental Change*, vol. 16, 2006, pp. 240-252.
[23] P.N. Edwards, "Infrastructure and Modernity: Force, Time, and Social Organization in the History of Sociotechnical Systems," *Modernity and Technology*, T.J. Misa, P. Brey, and A. Feenberg, Eds., Cambridge, MA: MIT Press, 2003, pp. 185-225.
[24] B. Sims, "Infrastructure, Social Order, and Community Resilience: A Socio-Technical Perspective," paper presented at the International Research Committee on Disasters Meeting, Broomfield, CO, July 2010.
[25] U.S. Department of Homeland Security Risk Steering Committee, *DHS Risk Lexicon*, Sep. 2010, http://www.dhs.gov/xlibrary/assets/dhs_risk_lexicon.pdf.

Acknowledgements

This paper benefited greatly from the insights of Tim McPherson, Dennis Powell, Stephan Eidenbenz, Brian Edwards, Russell Bent, Rene Leclaire, John Ambrosiano, Sara Del Valle, David Judi, Mary Ewers, Lisa Inkret, Darrin Visarraga, Feng Pan, and Alexander Gutfraind.

Appendix 1: Detailed Explanation of Ecological Resilience

Forty years of studies about ecological resilience have learned a great deal about influencing factors and how ecosystems behave, but have failed to come up with a definition for ecosystem resilience that is general enough to be applicable to a variety of cases, and also specific enough to be quantified.

Holling's original 1973 definition of resilience was narrowly applied, and is specific enough to be quantified. Holling stated that "resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist." This general definition forms the foundation for most definitions of ecological resilience now in use. However, by itself, it is not specific enough to quantify. Without a problem-specific definition of persistence, and what relationships within the system should be persisting, it is impossible to measure what effect changes have on those relationships and system persistence.

The Lotka-Volterra equations, first published in 1920, have been used by ecologists for almost a century to describe the relationship between predator and prey populations. The equations shown below are a pair of differential equations that, depending on the value of the parameters $\alpha,\beta,\gamma,\delta$, can produce oscillations with increasing, constant, or decreasing amplitude. In the case where amplitude is decreasing, eventually a steady state will occur, where population growth in the prey species is exactly balanced by predation, and each predator receives enough food to produce one child. In a system with parameter values such that the amplitude is always increasing, eventually one of the two populations will reach zero. In a real system, populations do not recover once they pass some minimum threshold, so the fundamental rules and relationships of the ecosystem change as a result of the permanent extinction of one species.

1. $\partial x/\partial t = x(\alpha-\beta y)$

2. $\partial y/\partial t = -y(\gamma-\delta x)$

3. $x>\varepsilon$ and $y> \varepsilon$

The variable x is the population level of the prey species, while y is the population level of the predator species. For simplicity, we'll refer to them as rabbits and foxes. Equation 1 shows that the rate of change of the rabbit population is related to two factors: the rabbits' own population growth rate, defined by the parameter α, and the rate at which rabbits are eaten by foxes, determined by the interaction term βxy. This means that the number of rabbits that get eaten depends on both the number of rabbits and the number of foxes. β can represent, roughly, how good the rabbits are at hiding from foxes. Equation 2 shows similar relationships. The term $-y\gamma$ represents the rate at which foxes die from old age and the term δxy defines the rate at which the fox population grows. Its growth rate is assumed to be proportional to its access to its food supply: rabbits.

Equations 1 and 2 provide a quantitative definition of the relationship between the two species. Equation 3 defines persistence in this system. If x_0 and y_0 are initially positive, neither can reach zero, but each can become infinitely small. In reality, an atto-fox cannot exist, so when the population reaches some minimum threshold, ε, it is assumed to become permanently extinct. If we start with initial values for all parameters such that the extinction conditions are never met, then we can measure resilience as the minimum percent change in any combination of the 6 values in equations 1 and 2 (x or y, and α,β,γ

and δ) that leads to an extinction. If we start with initial conditions such that one of the populations goes extinct at time *t*, then resilience could be measured as the percent change in any combination of the variables that leads to a given percent change in time to extinction. There are 63 possible combinations of measured values, and so defining all of them becomes quite complex.

Looking at changes in only one of the measured values leads to intuitive results, but even this simplest index to this simple set of equations is difficult to solve analytically. For more complex systems an analytical solution becomes impossible. Using a numerical approach to explore the effects of changes in population on species persistence is instructive.

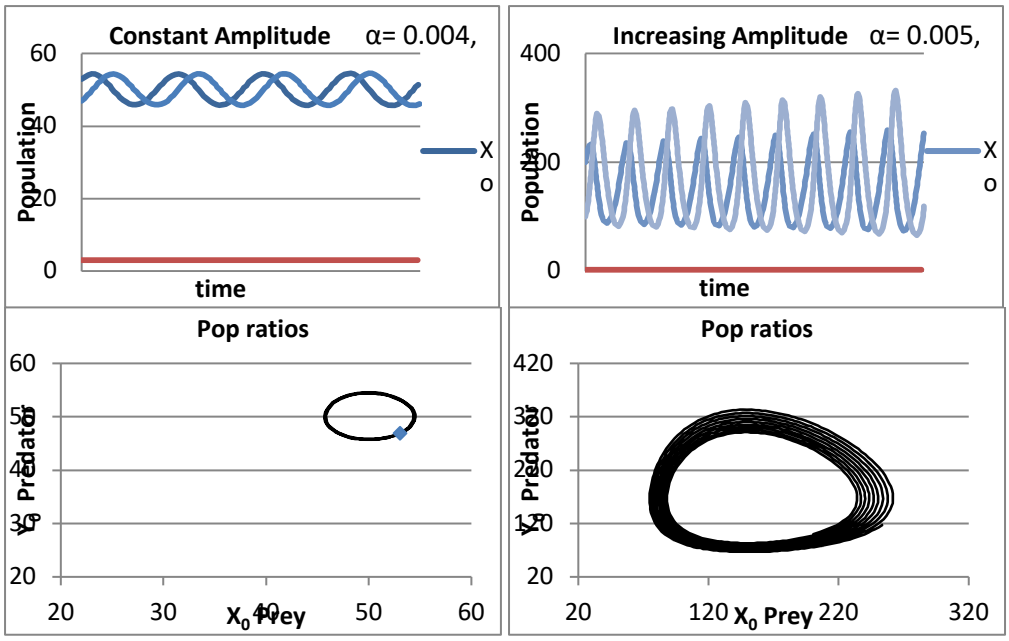

Figure 6. Example equilibrium states for the Lotka-Volterra equations

This example demonstrates the two major challenges associated with a true quantification of ecological resilience: the tension between general applicability and precision in conception of what persistence means in the specific case, as well as the complexity of the systems studied, and the difficulty in determining solutions to even apparently simple metrics. It is feasible to quantify Holling's example because it relies on a single and very precise understanding of what persistence means: the value of both x and y remain greater than ε. However, for more complex systems or less strict values of persistence, it becomes less and less possible to examine the complete changes in initial conditions that lead to changes in resilience. Thus, very precise understanding of the relationships between different aspects of the system and also what persistence means in each case are crucial to quantifying resilience in a meaningful way.

Appendix 2. Annotated Bibliography

Citations and abstracts are in standard font, annotations are in italic.

Engineering – Classical

Sources that implicitly or explicitly rely on the idea of resilience as ability to maintain or return to a single equilibrium state.

Attoh-Okine, N. O., Cooper, A. T., & Mensah, S. A. (2009). Formulation of Resilience Index of Urban Infrastructure Using Belief Functions. IEEE Systems Journal, 3(2), 147-153. doi:10.1109/JSYST.2009.2019148

Most urban infrastructure are interdependent in various ways. A variety of qualitative explanations are presented in the literature to analyze and address resiliency and vulnerability. Unfortunately, most of the explanation do not provide an objective resilience index computation. This paper attempts to develop a resilience index for urban infrastructure using a belief function framework. The belief function framework can handle subjective, independent information and hierarchical data, all of which are characteristics of the inputs required for proper resilience index analyses. The steps of the analyses are presented using a prototype urban highway infrastructure network.

This paper attempts to develop a resilience index for urban infrastructure using a belief function framework. In its definitions of resilience, the paper acknowledges the ecological literature, but starts with a single steady state conception of resilience in each infrastructure system. They then extend this to multiple infrastructures, each with a single steady state. They also used "belief functions " to include imperfect state level knowledge in the system. The paper has an interesting discussion of types of infrastructure interconnections, and types of failures which may be useful. "Resilience engineering is the ability of the system to recover and adapt to external shocks, which include natural intentional and technogenic disasters and failure due to poor design [5]. "

Bonowitz, D. (2009). Resilience Criteria for Seismic Evaluation of Existing Buildings: A Proposal to Supplement ASCE 31 for Intermediate Performance Objectives. In Improving the Seismic Performance of Existing Buildings and Other Structures (pp. 44-44). Presented at the Proceedings of the 2009 ATC & SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures, San Francisco, California. doi:10.1061/41084(364)44

Earthquake resilience, the ability to respond to and recover from a damaging event, is gaining currency as a performance metric even for non-"essential" facilities. Resilience can be measured as the time needed to restore basic operations. Yet our standards for seismic evaluation do not explicitly address recovery time. This paper proposes new evaluation criteria to address questions of resilience. The proposed criteria will help distinguish and prioritize likely seismic deficiencies, grouping them by their impact on recovery time. The criteria use the standard known as ASCE 31 as a platform, building on its procedures and terminology and extending its use to resilience planning.

The author draws from materials resilience, looking at resilience with a single steady state and defining resilience as the time it takes to return to that state, in order to improve seismic engineering.

Crichton, M. T., Ramsay, C. G., & Kelly, T. (2009). Enhancing Organizational Resilience Through Emergency Planning: Learnings from Cross-Sectoral Lessons. Journal of Contingencies and Crisis Management, 17(1), 24-37. doi:10.1111/j.1468-5973.2009.00556.x

After every emergency exercise or actual incident, reports are circulated that usually identify lessons that have been learned from the event. This paper identifies recurring themes from the lessons learned that can be widely applied across sectors. Typically, lessons are expressed in a form that is specific to the actual event that has transpired, the sector in which it has occurred, and the aims of the reporting organization. Reports relating to seven incidents that have occurred in the United Kingdom and internationally, from a range of sectors and with varying parameters, have been reviewed. It is concluded that organizations can become wiser by looking at incidents outside their own sector and by using these recurring themes to explore the resilience of their emergency plans. Recommendations are also made for best practices to improve the learning of lessons within organizations.

This paper looks at the effectiveness of emergency management plans and other management structures in reducing the damage to an organization from low probability but statistically expected failures in complex manufacturing processes, by using several case studies. "To create resilience against potential failures in crisis management. . . . organizations need to believe that failures can happen and need to anticipate the effects of failure."

Huber, S., van Wijgerden, I., de Witt, A., & Dekker, S. W. (2009). Learning from organizational incidents: Resilience engineering for high-risk process environments. Process Safety Progress, 28(1), 90-95. doi:10.1002/prs.10286

For years, safety improvements have been made by evaluating incident reports and analyzing errors and violations. Current developments in safety science, however, challenge the idea that safety can meaningfully be seen as the absence of errors or other negatives. Instead, the question becomes whether a company is aware of positive ways in which people, at all level of the organization, contribute to the management and containment of the risks it actually faces. The question, too, is whether the organization has the adaptive capacity necessary to respond to the changing nature of risk as operations shift and evolve. This article presents the results of a resilience engineering safety audit conducted on a chemical company site. An interdisciplinary team of seven researchers carried out 4 days of field studies and interviews in several plants on this site. This company enjoyed an almost incident-free recent history but turned out to be ill-equiped to handle future risks and many well-known daily problems. Safety was often borrowed from to meet acute production goals. Organizational learning from incidents was fragmented into small organizational or production units without a company-wide learning. We conclude that improving safety performance hinges on an organization's dynamic capacity to reflect on and modify its models of risk as operations and insight into them evolve, for example, as they are embodied in safety procedures and policies.

Similar to the previous paper, looks at results of resilience engineering in a safety audit on a chemical company. They consider safety management procedures in manufacturing.

Klein, R., Nicholls, R., & Thomalla, F. (2003). Resilience to natural hazards: How useful is this concept? Global Environmental Change Part B: Environmental Hazards, 5(1-2), 35-45. doi:10.1016/j.hazards.2004.02.001

Resilience is widely seen as a desirable system property in environmental management. This paper explores the concept of resilience to natural hazards, using weather-related hazards in coastal megacities as an example. The paper draws on the wide literature on megacities, coastal hazards, hazard risk reduction strategies, and resilience within environmental management. Some analysts define resilience as a system attribute, whilst others use it as an umbrella concept for a range of system attributes deemed desirable. These umbrella concepts have not been made operational to support planning or management. It is recommended that resilience only be used in a restricted sense to describe specific system attributes concerning (i) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction and (ii) the degree to which the system is capable of self-organisation. The concept of adaptive capacity, which has emerged in the context of climate change, can then be adopted as the umbrella concept, where resilience will be one factor influencing adaptive capacity. This improvement to conceptual clarity would foster much-needed communication between the natural hazards and the climate change communities and, more importantly, offers greater potential in application, especially when attempting to move away from disaster recovery to hazard prediction, disaster prevention, and preparedness.

This paper looks at the resilience of coastal megacities to natural hazards. It includes a long and useful history of the various definitions of resilience, and eventually concludes that resilience is too vague to be useful. "Yet, there is an unrelenting devotion to using the concept and an unquestioning, almost naïve acceptance that resilience is good and must be promoted, irrespective of the potential risks to society (cf. Handmer and Dovers, 1996*;* Adger, 2000*). The challenge remains to transform the concept into an operational tool for policy and management purposes: a challenge that thirty years of academic debate does not seem to have resolved."*

McManus, S., Seville, E., Vargo, J., & Brunsdon, D. (2008). Facilitated Process for Improving Organizational Resilience. Natural Hazards Review, 9(2), 81. doi:10.1061/(ASCE)1527-6988(2008)9:2(81)

Resilient organizations contribute significantly to resilient communities. However, the task of building more resilient organizations is complicated by an inability to translate the concept of resilience into tangible working constructs for organizations. In addition, resilience is often considered to be a crisis or emergency management issue. The link between creating resilient day-to-day operations and having a resilient crisis response and recovery is typically not well understood by organizations. Resilience for organizations is found to have three principal attributes. Situation awareness, management of keystone vulnerabilities, and adaptive capacity. A facilitated process is introduced that assists organizations to enhance their performance in relation to these attributes. This process is called resilience management and was developed and tested with 10 case study organizations selected specifically to represent a wide range of industry sectors, business types, and sizes in New Zealand. Some of the preliminary resilience issues to arise from this study are also briefly discussed.

Paper has a good description of the history of the use of the term resilience in the academic literature, and discusses in great detail what they mean by organizational resilience. This type of resilience is also critical to managing key infrastructure vulnerabilities, especially in the private sector. They discuss three key factors in organizational resilience: Situation awareness, management of keystone vulnerabilities,

and adaptive capacity all in a complex, dynamic, and interconnected environment. Organizational awareness is defined as an understanding of the multiple parties that make up the organization and how they relate to each other. The definition in this study of the management of keystone vulnerabilities relates to those aspects of an organization, operational and managerial, that have the potential to have significant negative impacts in a crisis situation. Adaptive capacity is defined as the ability of an enterprise to alter its "strategy, operations, management systems, governance structure, and decision-support capabilities" to withstand perturbations and disruptions."

Omer, M., Nilchiani, R., & Mostashari, A. (2009). Measuring the Resilience of the Trans-Oceanic Telecommunication Cable System. IEEE Systems Journal, 3(3), 295-303. doi:10.1109/JSYST.2009.2022570

Resilience is the ability of the system to both absorb shock as well as to recover rapidly from a disruption so that it can return back to its original service delivery levels or close to it. The trans-oceanic telecommunication fiber-optics cable network that serves as the backbone of the internet is a particularly critical infrastructure system that is vulnerable to both natural and man-made disasters. In this paper, we propose a model to measure the base resiliency of this network, and explore the node to node and the overall resiliency of the network using existing data for demand, capacity and flow information. The submarine cable system is represented by a network model to which hypothetical disruptions can be introduced. The base resiliency of the system can be measured as the ratio of the value delivery of the system after a disruption to the value deliver of the system before a disruption. We further demonstrate how the resiliency of the trans-oceanic telecommunication cable infrastructure is enhanced through vulnerability reduction.

Authors measure the ability of a single infrastructure system to cope with shocks and minimize service disruptions. "Resilience is the ability of the system to both absorb shock as well as to recover rapidly from a disruption so that it can return back to its original service delivery levels or close to it."

Reca, J., Martínez, J., Baños, R., & Gil, C. (2008). Optimal Design of Gravity-Fed Looped Water Distribution Networks Considering the Resilience Index. Journal of Water Resources Planning and Management, 134(3), 234. doi:10.1061/(ASCE)0733-9496(2008)134:3(234)

The optimization of looped water distribution networks (WDN) implies achieving the best tradeoff between reliability and cost. Many works have dealt with minimizing the cost, but few have considered both cost and reliability. This paper aims to evaluate the performance of several multiobjective metaheuristics (MOMHs) to optimize the design of looped water distribution networks, taking into consideration two objective functions: Minimizing costs and maximizing the resilience index. The MOMHs used are: Strength Pareto Evolutionary Algorithm 2 (SPEA2), Pareto Archived Evolution Strategy, Pareto Envelope-based Selection Algorithm, Pareto Simulated Annealing, and Multiobjective Simulated Annealing and Tabu Search. These algorithms are tested and compared by applying them to two case studies: The first is a small well-known benchmark network (Hanoi), whereas the second one is a larger looped irrigation network (Balerma). Results of this work show that SPEA2 outperforms the remaining methods in terms of Pareto dominance.

Authors are looking at ways to increase efficiency, reliability and also resilience of water systems.

Reed, D. A. (2009). Multi-Hazard Analysis of Electric Power Delivery Systems. In TCLEE 2009: Lifeline Earthquake Engineering in a Multihazard Environment (pp. 30-30). Presented at the Proceedings of the 2009 ASCE Technical Council on Lifeline Earthquake Engineering Conference, Oakland, California. doi:10.1061/41050(357)30

One of the important challenges facing the US today is the need for resilient networked infrastructure. The electric power delivery system is one of the critical lifelines that comprise the networked infrastructure. Power delivery systems have received a great deal of attention in recent years because most of the other lifelines such as telecommunications, transportation and water supply require power to function properly. In this paper, the resilience of power delivery systems is assessed for wind and seismic loadings using definitions derived by Bruneau (2003) and applied to in-situ post event data for extreme events.

Looking at ability of power systems to meet demand after extreme events.

Reed, D. A., Kapur, K. C., & Christie, R. D. (2009). Methodology for Assessing the Resilience of Networked Infrastructure. IEEE Systems Journal, 3(2), 174-180. doi:10.1109/JSYST.2009.2017396

In this paper, we outline a method to characterize the behavior of networked infrastructure for natural hazard events such as hurricanes and earthquakes. Our method includes resilience and interdependency measures. Because most urban infrastructure systems rely on electric power to function properly, we focus on the contribution of power delivery systems to post-event infrastructure recovery. We provide a brief example of our calculations using power delivery and telecommunications data collected post-landfall for Hurricane Katrina. The model is an important component of a scheme to develop design strategies for increased resilience of urban infrastructure for extreme natural hazard scenarios.

Looking at resilience of the electric power system in the classic engineering single steady state model, and then looking at the effect of linked infrastructures and interdependencies, each with single steady state.

Engineering – Ecological

Papers that implicitly or explicitly consider the more ecological definition of resilience in an engineering context.

Blackmore, J. M., & Plant, R. A. J. (2008). Risk and Resilience to Enhance Sustainability with Application to Urban Water Systems. Journal of Water Resources Planning and Management, 134(3), 224. doi:10.1061/(ASCE)0733-9496(2008)134:3(224)

Many cities in water-stressed environments are seeking sustainable alternatives to traditional solutions such as supply augmentation and water restrictions. One alternative is to upgrade urban water systems in an integrated manner. Design of an integrated urban water system (IUWS) requires an understanding of the risk of the IUWS failing to deliver sustainable outcomes. We present a rationale for enhancing well-established risk assessment and management tools with concepts of ecosystem resilience. Although traditional risk assessment focuses on the states of controls that operate on specific system

components and the likelihood and consequences of control failure, resilience theory addresses whole-of-system behavior. In identifying critical controls, risk management focuses on the ability to prevent failure and stabilize a certain system state, whereas resilience focuses on the "uncontrollable" to identify pathways for managing system adaptation to change. Based on conceptual analysis of two key resilience metaphors, the "stability landscape" and the "adaptive cycle," we investigate pathways toward risk-based IUWS design and management that explicitly include system resilience as an overarching measure of sustainability. Areas for future research include development of methodologies for measuring system adaptive capacity, and identifying and quantifying emerging thresholds. The challenge for the risk assessment community is to reconsider what "risk" is: In a resilience context, events traditionally seen as risky are not necessarily bad, and may become opportunities. The challenge for the resilience community is to identify thresholds and the system's proximity to them.

This paper discusses an extension of existing risk management tools used in water infrastructure to include ideas of ecological resilience. Presents a comprehensive survey of the literature discussion the evolution of ecological resilience. Focuses on idea of adaptive capacity, and uses concepts of multiple steady states.

Boin, A., & McConnell, A. (2007). Preparing for Critical Infrastructure Breakdowns: The Limits of Crisis Management and the Need for Resilience. Journal of Contingencies and Crisis Management, 15(1), 50-59. doi:10.1111/j.1468-5973.2007.00504.x

Modern societies are widely considered to harbour an increased propensity for breakdowns of their critical infrastructure (CI) systems. While such breakdowns have proven rather rare, Hurricane Katrina has demonstrated the catastrophic consequences of such breakdowns. This article explores how public authorities can effectively prepare to cope with these rare events. Drawing from the literature on crisis and disaster management, we examine the strengths and weaknesses of traditional approaches to crisis preparation and crisis response. We argue that the established ways of organising for critical decision-making will not suffice in the case of a catastrophic breakdown. In the immediate aftermath of such a breakdown, an effective response will depend on the adaptive behaviour of citizens, front-line workers and middle managers. In this article, we formulate a set of strategies that enhance societal resilience and identify the strong barriers to their implementation.

Dealing with conceptions of multiple cascading infrastructure failures, and how to increase societal resilience to multiple system infrastructure failure. The rely on idea that in true catastrophe, first responders and citizens can have an effect, top down management cannot respond quickly enough to make a tangible difference. Looks at infrastructure failure, but the outcomes measured are social.

Comfort, L. K., Sungu, Y., Johnson, D., & Dunn, M. (2001). Complex Systems in Crisis: Anticipation and Resilience in Dynamic Environments. Journal of Contingencies and Crisis Management, 9(3), 144-158. doi:10.1111/1468-5973.00164

Confronted with increasing risk and uncertainty from disruptive change, public managers seek methods to strengthen the capacity of their interdependent organizations to anticipate risk and demonstrate resilience in response to threat. The problem intensifies for public organizations that interact with private and nonprofit organizations to protect a community at risk from natural or technological disasters. It reflects the constraints placed upon human decision processes in complex environments by

limited cognitive capacity, and illustrates the persistent difficulty in achieving coordination among multiple organizations with different responsibilities in different locations in serving the public interest. This article summarizes current research on the design and development of an interactive, intelligent, spatial information system (IISIS) for decision support in the mitigation of, and response to, risk from hazardous materials for a university community. Appropriate uses of the IISIS prototype are expected to increase both the technical and organizational capacity to manage timely, accurate information exchange within and among organizations, thus increasing coordination in action.

This paper discusses some general ideas about resilience, and then develops a technological tool aimed at increasing the resilience of a particular system (a university) to threat. The definition stated is more closely related to the material science definition of resilience, but the conception of resilience as applied to a social construct - a university, is more related to the ecological conception. "Resilience meant a flexible response to actual danger, demonstrating an ability to `bounce back' after a damaging event."

Hollnagel, E. (2008). Resilience engineering perspectives. Aldershot Hampshire England;;Burlington VT: Ashgate.

This book focuses on the idea of engineering with the understanding that failure is part of normal system behavior. The resilience definitions draws from single state ideas, although it includes concept of drift and development, without reference to other literature that discusses it. "A resilient system is defined by its ability to effectively adjust its functioning prior to or following changes and disturbances so that it can continue its functioning after a disruption or mishap and in the presence of continuous stresses."

Madni, A. M., & Jackson, S. (2009). Towards a Conceptual Framework for Resilience Engineering. IEEE Systems Journal, 3(2), 181-191. doi:10.1109/JSYST.2009.2017397

As systems continue to grow in size and complexity, they pose increasingly greater safety and risk management challenges. Today when complex systems fail and mishaps occur, there is an initial tendency to attribute the failure to human error. Yet research has repeatedly shown that more often than not it is not human error but organizational factors that set up adverse conditions that increase the likelihood of system failure. Resilience engineering is concerned with building systems that are able to circumvent accidents through anticipation, survive disruptions through recovery, and grow through adaptation. This paper defines resilience from different perspectives, provides a conceptual framework for understanding and analyzing disruptions, and presents principles and heuristics based on lessons learned that can be employed to build resilient systems.

Briefly, the authors define resilience in complex systems management as how to keep small and incremental decisions from accumulating to effect long term safety. "In resilience engineering, failures do not imply a breakdown or malfunction of a normal system. Rather, they represent an inability of the system to adequately adapt to perturbations and changes in the real world given finite resources and time."

Ratick, S., Meacham, B., & Aoyama, Y. (2008). Locating Backup Facilities to Enhance Supply Chain Disaster Resilience. Growth and Change, 39(4), 642-666.

The use of emergency backup and storage facilities to supplement existing facilities in response to the potential effects of various natural and anthropogenic hazards (e.g., floods, fires, outages, and acts of malice) can be an effective way of reducing vulnerability and enhancing the resilience of supply chain and other logistics functions. Although there can be additional costs associated with utilizing emergency backup and storage facilities, they can be a particularly attractive and cost-effective alternative in those cases where long-term disruptions can, or should, be expected. In this paper, we use set cover location modeling as a decision to determine the number of backup facilities to locate under varying cover, anticover, and complementary anticover distances. We then add the flexibility of allowing existing facilities to serve as backup facilities and explore the interrelationships among hazards, vulnerability, and location. Finally, these model formulations are applied to an example data set over 900 cities and towns in New England and New York.

Authors are looking at ways to think about and increase ability of supply chains to cope with disaster, in the context of lost nodes and links. Resilience means ability of supply chain to meet demand, even if demand changes rapidly or some facilities are lost.

Ecology

Berkes, F., & Folke, C. (2000). *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. Cambridge University Press.

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, *16*(3), 253-267. doi:10.1016/j.gloenvcha.2006.04.002

The resilience perspective is increasingly used as an approach for understanding the dynamics of social–ecological systems. This article presents the origin of the resilience perspective and provides an overview of its development to date. With roots in one branch of ecology and the discovery of multiple basins of attraction in ecosystems in the 1960–1970s, it inspired social and environmental scientists to challenge the dominant stable equilibrium view. The resilience approach emphasizes non-linear dynamics, thresholds, uncertainty and surprise, how periods of gradual change interplay with periods of rapid change and how such dynamics interact across temporal and spatial scales. The history was dominated by empirical observations of ecosystem dynamics interpreted in mathematical models, developing into the adaptive management approach for responding to ecosystem change. Serious attempts to integrate the social dimension is currently taking place in resilience work reflected in the large numbers of sciences involved in explorative studies and new discoveries of linked social–ecological systems. Recent advances include understanding of social processes like, social learning and social memory, mental models and knowledge–system integration, visioning and scenario building, leadership, agents and actor groups, social networks, institutional and organizational inertia and change, adaptive capacity, transformability and systems of adaptive governance that allow for management of essential ecosystem services.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. (2004). Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*, *35*(1), 557-581. doi:10.1146/annurev.ecolsys.35.021103.105711

We review the evidence of regime shifts in terrestrial and aquatic environments in relation to resilience of complex adaptive ecosystems and the functional roles of biological diversity in this context. The evidence reveals that the likelihood of regime shifts may increase when humans reduce resilience by such actions as removing response diversity, removing whole functional groups of species, or removing whole trophic levels; impacting on ecosystems via emissions of waste and pollutants and climate change; and altering the magnitude, frequency, and duration of disturbance regimes. The combined and often synergistic effects of those pressures can make ecosystems more vulnerable to changes that previously could be absorbed. As a consequence, ecosystems may suddenly shift from desired to less desired states in their capacity to generate ecosystem services. Active adaptive management and governance of resilience will be required to sustain desired ecosystem states and transform degraded ecosystems into fundamentally new and more desirable configurations.

Gunderson, L. H. (2000). Ecological Resilience – in Theory and Application. *Annual Review of Ecology and Systematics*, *31*(1), 425-439. doi:10.1146/annurev.ecolsys.31.1.425

In 1973, C. S. Holling introduced the word resilience into the ecological literature as a way of helping to understand the non-linear dynamics observed in ecosystems. Ecological resilience was defined as the amount of disturbance that an ecosystem could withstand without changing self-organized processes and structures (defined as alternative stable states). Other authors consider resilience as a return time to a stable state following a perturbation. A new term, adaptive capacity, is introduced to describe the processes that modify ecological resilience. Two definitions recognize the presence of multiple stable states (or stability domains), and hence resilience is the property that mediates transition among these states. Transitions among stable states have been described for many ecosystems, including semi-arid rangelands, lakes, coral reefs, and forests. In these systems, ecological resilience is maintained by keystone structuring processes across a number of scales, sources of renewal and reformation, and functional biodiversity. In practice, maintaining a capacity for renewal in a dynamic environment provides an ecological buffer that protects the system from the failure of management actions that are taken based upon incomplete understanding, and it allows managers to affordably learn and change.

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*, 1-23.

Individuals die, populations disappear, and species become extinct. That is one view of the world. But another view of the world concentrates not so much on presence or absence as upon the numbers of organisms and the degree of constancy of their numbers. These are two very different ways of viewing the behavior of systems and the usefulness of the view depends very much on the properties of the system concerned. If we are examining a particular device designed by the engineer to perform specific tasks under a rather narrow range of predictable external conditions, we are likely to be more concerned with consistent nonvariable performance in which slight departures from the performance goal are immediately counteracted. A quantitative view of the behavior of the system is, therefore, essential. With attention focused upon achieving constancy, the critical events seem to be the amplitude and frequency of oscillations. But if we are dealing with a system profoundly affected by changes external to it, and continually confronted by the unexpected, the constancy of its behavior becomes less important than the persistence of the relationships. Attention shifts, therefore, to the qualitative and to questions of existence or not.

Holling, C. S. (1996). Engineering Resilience versus Ecological Resilience. In P. Schulze (Ed.), *Engineering within Ecological constraints* (pp. 31 -45). National Academy Press.

Janssen, M., Schoon, M., Ke, W., & Borner, K. (2006). Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change. *Global Environmental Change*, *16*(3), 240-252. doi:10.1016/j.gloenvcha.2006.04.001

This paper presents the results of a bibliometric analysis of the knowledge domains resilience, vulnerability and adaptation within the research activities on human dimensions of global environmental change. We analyzed how 2286 publications between 1967 and 2005 are related in terms of co-authorship relations, and citation relations. The number of publications in the three knowledge domains increased rapidly between 1995 and 2005. However, the resilience knowledge domain is only weakly connected with the other two domains in terms of co-authorships and citations. The resilience knowledge domain has a background in ecology and mathematics with a focus on theoretical models, while the vulnerability and adaptation knowledge domains have a background in geography and natural hazards research with a focus on case studies and climate change research. There is an increasing number of cross citations and papers classified in multiple knowledge domains. This seems to indicate an increasing integration of the different knowledge domains.

Lotka, A. (1920). Analytical Note on Certain Rhythmic Relations in Organic Systems. *Proceedings of the National Academy of Sciences*, *6*, 410-415.

Periodic phenomena play an important role in nature, both organic and inorganic.

Ludwig, D., Walker, B., & Holling, C. (n.d.). Conservation Ecology: Sustainability, Stability, and Resilience. *Ecology and Society*, *1*(1). Retrieved from http://www.ecologyandsociety.org/vol1/iss1/art7/

The purpose of this essay is to define and refine the concepts of stability and resilience and to demonstrate their value in understanding the behavior of exploited systems. Some ecological systems display several possible stable states. They may also show a hysteresis effect in which, even after a long time, the state of the system may be partly determined by its history. The concept of resilience depends upon our objectives, the types of disturbances that we anticipate, control measures that are available, and the time scale of interest.

Peterson, G., Allen, C. R., & Holling, C. S. (1998). Ecological Resilience, Biodiversity, and Scale. *Ecosystems*, *1*(1), 6-18. doi:10.1007/s100219900002

We describe existing models of the relationship between species diversity and ecological function, and propose a conceptual model that relates species richness, ecological resilience, and scale. We suggest that species interact with scale-dependent sets of ecological structures and processes that determine functional opportunities. We propose that ecological resilience is generated by diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales, thereby

reinforcing function across scales. The distribution of functional diversity within and across scales enables regeneration and renewal to occur following ecological disruption over a wide range of scales.

Economics and Public Policy

Alberola, E., & Serena, J. M. (2008). Reserves, Sovereign Wealth Funds and the Resilience of Global Imbalances. *Economic Notes*, *37*(3), 315-343.

Reserves and sovereign wealth funds (SWFs) assets should be jointly considered for the assessment of global imbalances, hence their denomination as sovereign external assets (SEAs): both are public capital outflows from developing to developed countries, both hinder adjustment in current account surplus and deficit countries and, therefore, both contribute to sustain global imbalances. They represented 135 percent and 50 percent of net and gross US financing needs, respectively, in 2007. Reserves contribute 80 percent and SWFs 20 per cent. They will go on providing resilience to the global imbalances, and the relative importance of SWFs is set to increase if commodity prices stay high.

Badia-Miro, M., Tello, E., Valls, F., & Garrabou, R. (2010). The Grape Phylloxera Plague as a Natural Experiment: The Upkeep of Vineyards in Catalonia (Spain), 1858-1935. *Australian Economic History Review*, *50*(1), 39-61.

This paper analyses the impact in Catalonia of the grape Phylloxera plague in Europe (1865-90). A statistical model is used to analyse the economic resilience of 35 districts in Catalonia to this external ecological and economic shock, and to explain why districts in the provinces of Barcelona and Tarragona resumed growing wine grapes after the plague, in contrast to districts in Girona and Lleida provinces. The opportunity cost of labour, the demand pull of Barcelona's commercial growth, and the agro-climatic suitability of land for growing grapes are used to explain the differing capacities of districts to endure the Phylloxera plague in Catalonia.

Resilience is used in passing to describe why some regions survived a plague and others didn't.

Comfort, L. K., Oh, N., & Ertan, G. (2009). The Dynamics of Disaster Recovery: Resilience and Entropy in Hurricane Response Systems 2005-2008. *Public Organization Review*, *9*(4), 309-323.

The challenge for policy makers and disaster managers is to achieve a balance between two dynamics--resilience and entropy--in order to develop sustainable risk reduction. Achieving an appropriate balance between resilience and entropy in any given community requires a systematic exploration of both dynamics. The recent hurricanes that struck Louisiana, Hurricane Katrina on August 29, 2005 and Hurricane Gustav, on September 1, 2008, offer an unusual opportunity to assess the degree to which both dynamics operated following Hurricane Katrina.

Davoudi, S. (2009). Scalar Tensions in the Governance of Waste: The Resilience of State Spatial Keynesianism. *Journal of Environmental Planning and Management*, *52*(2), 137-156.

There has been a heightened interest in the 'region' as a key site of economic activities. While regionalisation is often explained as part of the wider process of state scalar strategy in response to global economic restructuring, less attention has been paid to the role of the region in rescaling of environmental governance. This paper aims to fill the gap by drawing on the changing governance of municipal waste planning in the UK. Such a focus demonstrates that key elements of 'spatial Keynesianism' have been carried through, rather than superseded, in 'the new metropolitan reform'. Following a brief summary of the municipal waste problem and the influence of the EU regulatory measures in changing waste policy in the UK, the paper situates the regional institution building for waste planning in its historical and conceptual context. It then discusses the key rationales for regionalisation of waste in order to substantiate the central argument of the paper which is: the resilience of some of the key features of spatial Keynesianism in the new wave of metropolitan reforms. The final part of the paper unpicks the inherent tensions in state rescaling strategy and outlines the key factors that undermine the capacity of the state's reconfigured regional institutions to achieve their prescribed goals.

Duval, R., & Vogel, L. (2008). Economic Resilience to Shocks: The Role of Structural Policies. *OECD Journal: Economic Studies*, *2008*, 201-238.

Cyclical fluctuations in economic activity have moderated over time but the extent and dynamics of volatility remain different across OECD countries. A reason behind this heterogeneity is that countries exhibit different degrees of resilience in the face of common shocks. This paper traces divergences in resilience back to different policy settings and institutions in labour, product and financial markets. Using pooled regression analysis across 20 OECD countries over the period 1982-2003, the paper identifies the impact of policy settings on two dimensions of resilience: the impact effect of a shock and its subsequent persistence. Policies and institutions associated with rigidities in labour and product markets are found to dampen the initial impact of shocks but to make their effects more persistent, while policies allowing for deep mortgage markets lower persistence and thereby improve resilience. Combining these two dimensions of resilience, the paper then uses the estimated equations to derive indicators of resilience for the OECD countries concerned, based on their current or recent policy settings. Three groups of countries emerge. In English-speaking countries, simulations suggest shocks have a significant initial effect on activity but this impact then dies out relatively quickly. By contrast, in many continental European countries the initial impact of shocks is cushioned but their effect linger for longer, with the cumulated output loss tending to be larger than in English-speaking countries. Finally a few, mostly small, European countries combine cushioning of the initial shock with a fairly quick return to baseline.

Economic resilience may be loosely defined as the ability to maintain output close to potential in the aftermath of shocks. Hence, it comprises at least two dimensions: the extent to which shocks are dampened and the speed with which economies revert to normal following a shock.

Gaillard, J. C. (2010). Vulnerability, Capacity and Resilience: Perspectives for Climate and Development Policy. *Journal of International Development*, *22*(2), 218-232.

In the decades since the terms vulnerability, capacity and resilience became popular in both the disaster and development literatures, through natural and social science discourses, the terms have been applied to many development- and disaster-related policies and have been the subject of much debate

and interpretation amongst various schools of thought. An illustrative review of the use of these terms is given followed by a critique of the main discourses, especially regarding the development and disaster policy advantages and disadvantages. Recommendations are given at different scales for closing some of the gaps identified, especially regarding the policy usefulness of certain theoretical approaches.

Discussion of uses of the terms resilience, vulnerability, adaptation. "The United Nations International Strategy for Disaster Reduction (2002) adopted this approach in its definition of resilience as 'the capacity of a system, community or society to resist or change in order that it may obtain an acceptable level of functioning and structure."

Lentzos, F., & Rose, N. (2009). Governing Insecurity: Contingency Planning, Protection, Resilience. *Economy and Society*, *38*(2), 230-254.

How should we understand the politics of security today? This article addresses this question from one particular perspective, that of 'biosecurity'. It examines contemporary strategies for managing biorisks in three European states: France, Germany and the United Kingdom. We suggest that the framing of threat and response differs, even within Europe, and that one can identify three different configurations: contingency planning, protection and resilience. Each of these embodies a significantly different way of reconciling fundamental imperatives for those who would govern a liberal society today--the imperative of freedom and the imperative of security.

Its aim is to improve UK 'resilience' – that is to say, the ability to handle any disruptive challenges that can lead to, or result in, crisis (not just terrorism but also eventualities like flood and fuel crisis).

Ranjan, R., & Athalye, S. (2009). Drought Resilience in Agriculture: The Role of Technological Options, Land Use Dynamics, and Risk Perception. *Natural Resource Modeling*, *22*(3), 437-462.

Sustained droughts coupled with increasing pressure from urbanization severely test the ability of farmers to continue in agriculture. Understanding farmers' resilience to such pressures is increasingly becoming a significant policy concern. In this paper, a new measure of resilience to severe and sustained droughts in agriculture is derived as the ability to continue farming by saving and carrying forward water through the adoption of water efficient technology. In addition, the role of behavioral factors--such as subjective risk perception over the probability of droughts, of the probability of land getting urbanized, and of resistance to revising beliefs over water scarcity situation--in determining farmers' resilience to droughts is explored. Findings highlight the key role played by behavioral factors in influencing the decision to adopt when the economic factors, such as the price of water, do not capture the true opportunity costs of water. The range of available technological options is found to be crucial too, as marginal improvements in technology do not encourage adoption. An empirical application to the case of lettuce farming in Western Australia reveals that in the presence of speculative benefits from land rezoning, technological adoption is done only for enhancing profits in agriculture and not for improving resilience to droughts. Land rezoning possibilities may further distort technology adoption decisions, thereby, reducing resilience to droughts.

Resilience is the number of years a farmer can withstand drought before exiting agriculture.

Treado, C. D., & Giarratani, F. (2008). Intermediate Steel-Industry Suppliers in the Pittsburgh Region: A Cluster-Based Analysis of Regional Economic Resilience. *Economic Development Quarterly*, *22*(1), 63-75.

The experience of intermediate steel-industry suppliers in the Pittsburgh region offers valuable insight into how traditional industrial clusters can serve as a source of economic resilience in regions like Pittsburgh, where a "signature" industry contracts or relocates. The authors find that intermediate steel-industry suppliers in Pittsburgh remain an important part of the region's economic base, serving as a significant source of export income from national and international markets. Survey results offer a description of the cluster's characteristics. An important subset of firms in this cluster relies on key contacts in the region such as suppliers, partners, and business networks for collaboration on product development or marketing. By recognizing and supporting local linkages of these kinds, policy initiatives can help to strengthen such clusters and contribute to a region's economic resilience.