Building Adaptive Capacity to Climate Hazard Scenarios through Use of the Sustainable Resilience Framework

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To my family, Skye and Magnus (my amazing Bebu)

and

To my mom, dad, and Ryan

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CHAPTER I
Introduction

Overview

The terms resilience and adaptive capacity are gaining traction across disciplinary boundaries as a means of potentially realizing a community's capability, based on assessment of its performance, to survive and remain viable under changing and uncertain conditions. As complex systems, communities are subject to a variety of hazards in the form of acute shock and chronic stress. Hazards can result in immediate harm, as well as longer-term harm due to disruption of critical community functions that can threaten survival, well-being, and long-term viability. While it is expected that disruption of some kind will inevitably occur, there is increasing uncertainty regarding the frequency, severity, and duration of future hazards, as well as uncertainty regarding where, when, how, and to whom harm will occur. Changes in population, urbanization, climate, and potential interactions exacerbate uncertainties, making it difficult for communities to effectively operationalize assessment practices that can lead to sound planning and prioritization of actions required to safeguard a community's future. This dissertation seeks to address gaps in current knowledge regarding key concepts that affect community performance (vulnerability, resilience, sustainability, and adaptive capacity), determine how they may be combined to better assess current community states and future trajectories, and provide an example by which this process can be operationalized for use by a community.

In general terms, a community is a complex, social-environmental system, consisting of groups of people and necessary life-supporting systems, sub-systems, and networks in a place often defined by boundaries, where common interests are linked to collective action. Life-supporting systems can be seen as the set of critical resources (social, economic, and environmental capital) that makeup and maintain societal function and integrity over space and time. As there is no single definition of a community, there is also no formally accepted definition of what constitutes a resilient, sustainable, or adequately adaptive community. However, literature provides evidence that the concepts of vulnerability, resilience, sustainability, and adaptive capacity are firmly linked. Each concept can be generalized as follows:

- vulnerability - the likelihood of experiencing loss due to hazard as a function of exposure, sensitivity, and adaptive capacity;
- resilience – ability to resist disruption, recover, adapt, and/or transform given a hazardous event in order to maintain desired system performance;
- sustainability - long-term ability to operate without failure through balanced management of critical social, economic, and environmental capital; and
- adaptive capacity - the ability to cope with, recover from, and adapt/transform in response to hazardous events.

While it is clear that the concepts are related (e.g., resilience can be constrained by adaptive capacity, which in turn, can be restrained by lack of sustainability capital), there is general confusion and lack of consensus on the nature of causal relationships between concepts and how they collectively respond to change over time to determine performance. Both natural hazard and climate adaptation literature appear to recognize adaptive capacity as a common and critical factor in achieving resilience and sustainability, yet, there is no dominant framework that links all of the constituents together in a dynamic setting. This is an apparent gap in the collective ability to understand and measure what it means to achieve desired community performance outcomes implied by each concept, making the act of planning for and achieving outcomes an increasingly uncertain task with many unknowns for communities already encumbered by prioritization of limited resources needed to address known challenges. Gaps in resilience and adaptive capacity research continue to frustrate efforts to bring greater understanding of assessment processes into mainstream practice. The most predominate of these gaps include: i) continued confusion about the conceptual relationships between vulnerability, resilience, sustainability, and adaptive capacity; ii) lack of an assessment framework that can account for multi-scalar and dynamic processes related to all of these interdependent concepts, iii) lack of consolidation and classification of existing indicators and metrics for measuring performance related to resilience and adaptive capacity of communities, and iv) lack of validation of community-based case studies to operationalize concepts and practices.

It is important for communities to understand how interactions between vulnerability, resilience, sustainability, and adaptive capacity can create possible trajectories for states of performance over time. Analysis of how these concepts can be combined to better assess and make decisions regarding current and possible future community states is needed. Additionally, communities need an integrated framework that allows for dynamic monitoring of significant shifts in critical components to help inform decision making processes such as policy, planning, and resource allocation efforts. The use of such a framework should not be limited to researchers, but should be operationalized for use by practitioners within any community jurisdiction. In order to operationalize the assessment process, means of measurement need to be made more understandable and accessible to the public. This requires review, consolidation and structuring of indicators and metrics, definition of relationship to an assessment framework, and access to information to aid indicator selection and application. Finally, the concepts and framework should be applied within an appropriate context to a community (or community system) to determine impacts to sustainable resilience under risk scenarios and thresholds. In this research, the context of flooding under extreme precipitation conditions shall be applied to flood protection infrastructure (subject system) within the City of Nashville, and local thresholds will be used to determine possible impacts to the sustainable resilience of the subject system within this community.

This dissertation contributes to the state-of-the-art by addressing the four gaps mentioned above. The primary goal of this research is to develop and demonstrate methods that enable the assessment and validation of qualities that influence the survivability, well-being, and long-term preparedness of communities subject to climate hazards in order to provide communities with strategic tools to improve adaptive capacity and resilience. As a secondary benefit, this research will build theory on adaptive capacity and resilience, providing information relevant to evaluation of current and future states of community performance through a robust policy lens in order to gain comfort in dealing with uncertainties associated with possible climate futures and potential hazards. The methods employed to develop worst-case scenarios for evaluating future sustainable resilience are not meant to predict or to represent the probability of extreme events, but to demonstrate the plausibility of such events in future planning horizons. While this research focuses on a single community (Nashville, TN) and a specific hazard (hydrologic events and impacts on flood protection infrastructure), the methods developed can be generalized and applied to any type of system, hazard, or risk-based environment to better understand performance over time.

The tools and methods provided herein are a starting point intended to increase understanding and access to needed definitions, an assessment framework, a set of indicators and metrics, a new way of looking at data to elicit plausible risk scenarios, and illustration of how each of these items may be employed. The intended audience for tools and methods provided is one that has sufficient information and understanding regarding how to employ and constructively use information and processes, or an audience that can be educated sufficiently to employ them. Ideally, it is hoped that any audience desiring to understand the concepts provided can have access to both the tools and the training needed to operationalize resilience assessment.

Outline of Dissertation

The format of the dissertation is a compilation of peer-reviewed papers that build upon one another to achieve a full set of objectives. Chapters 2-5 are individual papers as submitted in manuscript form. Each paper contains its own literature review and set of conclusions. For this reason, the review of literature appears sequentially in the progression of papers with a final set of references at the end of the document. Each paper builds from the prior paper as follows: chapter 2 creates the conceptual foundation for sustainable resilience (a new concept developed in this work) needed to build the novel assessment framework; chapter 3 develops the assessment framework for sustainable resilience and explains how it can be used; chapter 4 identifies and organizes indicators and metrics from literature using a novel classification system that is specific to sustainable resilience, and provides a non-duplicative set of indicators and associated metrics for use in assessing sustainable resilience for communities; and chapter 5 provides an assessment of flood protection infrastructure (dams and levees) in the U.S. and implications for future sustainable resilience, where results are applied to a specific levee in Nashville, TN using both local data and General Circulation Models (GCMs) via CMIP5 under a worst-case scenario (RCP 8.5) to develop recommendations to increase sustainable resilience and adaptive capacity of the affected community. Each of these chapters is summarized below.

Chapter 2:

Gillespie-Marthaler, L., Nelson, K. S., Baroud, H., Kosson, D. S., & Abkowitz, M. (2018). An Integrative Approach to Conceptualizing Sustainable Resilience. *Sustainable and Resilient Infrastructure,* DOI: 10.1080/23789689.2018.1497880.

> “Vulnerability, resilience, and sustainability are three concepts commonly used in assessing the quality of a variety of systems. While each can be applied independently when performing risk analysis, there is growing interest across

> multiple disciplines in understanding how these concepts can be integrated when considering complex adaptive systems, such as communities. In this paper, we identify issues related to the use of these respective concepts in assessing complex adaptive systems, and describe how these issues may produce imbalanced results and maladaptive outcomes. We identify five critical areas where alignment and integration across concepts can lead to improved system assessment. As a result, we introduce a new paradigm, sustainable resilience, in which these concepts are integrated to enable alignment of adaptation and transformation strategies with desired resilience outcomes. This work provides the foundation for the development of an integrated assessment framework to help guide informed risk-based decision making for sustainable and resilient systems."

Chapter 3:

Nelson, K. S., Gillespie-Marthaler, L., Baroud, H., Abkowitz, M., & Kosson, D. S. (2019). An Integrated and Dynamic Framework for Assessing Sustainable Resilience in Complex Adaptive Systems. *Sustainable and Resilient Infrastructure,* DOI: 10.1080/23789689.2019.1578165.

> "Growing awareness of climate change and resulting impacts to communities have generated increasing interest in understanding relationships between vulnerability, resilience, sustainability, and adaptive capacity, and how these concepts can be combined to better assess the quality of complex adaptive systems over time. Previous work has described interactions between these concepts and the value-added should they be integrated and applied in a strategic manner, resulting in a new understanding of system quality defined as sustainable resilience. However, a framework for explicitly integrating vulnerability, resilience, and sustainability assessment to develop understanding of system sustainable resilience has yet to be proposed. This paper presents a high-level, integrated and dynamic framework for assessing sustainable resilience for complex adaptive systems. We provide a set of functional definitions, a description of each step in the proposed assessment process, and walk through an example application of the framework, including a discussion of preliminary analyses, technical methodologies employed, and suggested future advances."

Chapter 4:

Gillespie-Marthaler, L., Nelson, K. S., Baroud, H., Abkowitz, M. (2019a). Selecting Indicators for Assessing Community Sustainable Resilience. *Risk Analysis* (Submitted following second review)

> "Communities are complex systems subject to a variety of hazards that can result in significant disruption to critical functions. Community resilience assessment is rapidly gaining popularity as a means to help communities better prepare for, respond to, and recover from disruption. Sustainable resilience, a recently developed concept, requires communities to assess system-wide capability to

> maintain desired performance levels while simultaneously evaluating impacts to resilience due to changes in hazards and vulnerability over extended periods of time. To enable assessment of community sustainable resilience, we review current literature, consolidate available indicators and metrics, and develop a classification scheme and organizational structure to aid in identification, selection, and application of indicators within a dynamic assessment framework. A non-duplicative set of community sustainable resilience indicators and metrics are provided that can be tailored to a community's needs, thereby enhancing the ability to operationalize the assessment process."

Chapter 5:

Gillespie-Marthaler, L., Baroud, H., Abkowitz, M. (2019b). Failure Mode Analysis and Implications for Sustainable Resilience of Flood Protection Infrastructure in the U.S. (Submitted to *Safety Science*)

> "Root cause (failure mode) analysis is conducted to identify primary and secondary modes of failure for 779 dam and 1,160 levee failures. Overtopping and breach due to an extreme hydrologic event is determined to be the most significant cause for flood protection infrastructure failure (dams and levees) in the U.S., presenting a threat to sustainable resilience for both infrastructure and communities. High risk scenarios based on most significant failure modes are developed and examined to aid in understanding implications for future sustainable resilience of flood protection infrastructure. Use of local data and General Circulation Models (GCMs) via CMIP5 under a worst-case scenario (RCP 8.5) suggests that extreme hydrologic events (in the form of precipitation at or greater than the 95th percentile) are likely to increase in both frequency and magnitude over the remainder of the century. Results are applied to a local community and compared to a record flood event to demonstrate potential impacts to sustainable resilience for flood protection infrastructure and communities under the projected worst case."

Chapter 6 is the conclusion of the document, providing a summary of contributions resulting from the collective effort and directions for new research. These contributions include both those from each of the individual efforts, as well as cumulative contributions to the state of research in fields of resilience, sustainability science, natural hazard mitigation, and community planning. Future research ideas to further expand the concept of sustainable resilience and its use are also discussed.

CHAPTER II

An Integrative Approach to Conceptualizing Sustainable Resilience

Introduction

There is increasing focus on understanding individual and combined impacts of environmental stress, extreme events, and human development on communities and the environment. As collective understanding of the dynamic nature of human impacts on the environment and environmental impacts on human society has grown, greater effort has been placed on engineering systems that are able to maintain quality, withstand change, and minimally impact the surrounding environment. Vulnerability, resilience, and sustainability are three concepts that have emerged from ecological, engineering, and social science disciplines as criteria to meet these goals.

Each of these concepts is suited to assessing different aspects of system quality (e.g., exposure to harmful events, ability to resist disruption, expected lifetime of a current system state based on critical resources), each concept is typically utilized at different points in planning and decision making processes. Yet, these concepts ambiguously share many terms and attributes associated with a common foundation in risk assessment, management, and communication. Identification of gaps and linkages across each concept, and their relationships to the ability of current and future systems to adapt and/or transform are therefore needed (Adger, 2006; Bahadur et al., 2010; Upadhyaya et al., 2014; Bocchini et al., 2014; Minsker et al., 2015).

To date, there has been a paucity of literature devoted to how these concepts are used to assess dynamic system quality (Adger, 2006; Fiksel, 2006; Turner, 2010; Engle, 2011; Ahern, 2011; Miller et al. 2010; and Bocchini et al., 2014; Minsker et al., 2015). Moreover, while approaches for combining aspects of resilience and vulnerability (Cutter et al., 2008; Cutter et al., 2014; Frazier et al., 2014; Lam et al., 2015; Mayunga, 2007; Manyena, 2006), or resilience and sustainability (Ashley and Carney, 1999; Turner et. al., 2003; Wilhelmi and Hayden, 2010; O'Connell et al., 2015; Minsker et al., 2015) frameworks have been developed, to our knowledge, a framework explicitly combining all three concepts based on critical evaluation of framework linkages and interactions has yet to be proposed.

In this paper, we review the individual concepts of vulnerability, resilience, and sustainability, as well as existing efforts to develop integrative frameworks. We then identify and illustrate critical linkages among concepts, and provide analysis of value added through strategic alignment. We then introduce a new concept to achieve this alignment that reflects the desired end-state for dynamic integrated system assessment, which we term “sustainable resilience.” This work forms a necessary foundation upon which a framework for dynamic assessment of sustainable resilience can be formed. Critical concepts and terminology used in the analysis are italicized within the text and defined in Appendix A.

Background and Literature Review

Risk

Decision making under uncertainty is an inherent part of any *complex adaptive system*, where a range of outcomes are possible. In the context of this paper, we define a *system* as a collection of components that provide specific and related functions that are combined to serve a common purpose (Bossel, 2001). Across all lifecycle phases of social, engineered, or *coupled systems*, decisions are made that result in impacts across time and space, creating a set of dependent responses that ultimately affect quality and performance (e.g., the system’s ability to serve society). The term *social-environmental system* is used in this paper to describe linkages between humans, human systems (engineered and/or social), and the surrounding environment (built and/or natural). This term is intended to include socio-technical systems, a term widely used within the literature. Our intent is to encompass linkages and interactions between humans, natural systems, engineered (built) systems, socio-technical (technology & infrastructure) systems, and socio-economic systems.

Risk differs from *uncertainty* through inherent association with the concept of harm and resulting consequences (Kaplan & Garrick, 1981). It can be argued that the concepts of *vulnerability*, *resilience*, and *sustainability* all fall under the umbrella of risk management as each involves the identification and characterization of potential performance degradation and mitigation opportunities to reduce negative consequences. To better understand goals associated with each concept and how they relate to varying applications of risk, a review of each concept is provided below.

Vulnerability

Vulnerability is described as the extent to which a system is likely to experience losses from a *hazard* (impactful event), and as such, it is a universally negative quality (Turner et al., 2003). *Vulnerability assessment* has evolved along two dominant tracks in the natural hazards community and the social science community. In the natural hazards literature, vulnerability employs a risk-hazard model, where vulnerability is defined as the combination of a risk factor and the potential for loss in the system at risk (Turner et al., 2003; Eakin & Luers, 2006). In the social science community, vulnerability traditionally focuses on inequities in *sensitivity* and *exposure* (social equity), resulting from social-structural characteristics such as socioeconomic and/or political status; governance; and community cohesion (Adger, 2006; Cutter et al., 2003; Turner et al., 2003; Eakin & Luers, 2006). Here, less emphasis is placed on physical damage incurred by a specific hazard while a greater emphasis is placed on identifying who is vulnerable and why they are vulnerable. Foundational application of the social sciences approach (Adger, 2006; Cutter 2003; Eakin & Luers, 2006) remains widely used in current applications within literature (Cutter, 2016a; Cutter, 2016b). In both cases (risk-hazard and social science applications), imbalanced assessment can occur through over-emphasis of either the physical or social aspects of vulnerability, leading to an incomplete understanding of system vulnerability.

A more recent approach to defining vulnerability attempts to merge both perspectives by defining vulnerability as the, "state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt," (Adger, 2006). We defer to this definition, which includes three components: exposure, sensitivity, and *adaptive capacity*. Exposure is the magnitude and extent to which a disruption (hazard event) or stress is experienced, sensitivity is the expected degree of impact from a disruption or stress given exposure, and adaptive capacity is the ability to prepare for and respond to disturbance and is dependent upon the ability to effectively access and use necessary resources (Adger & Vincent, 2005; Adger, 2006; Engle, 2011).

Despite the breadth in definition, little consensus exists on the appropriateness of different methods for measuring or characterizing vulnerability across social-environmental systems. This is in part due to continuing challenges in the ability to operationalize different components of vulnerability and how to account for differences between short-term and long-term vulnerability (Engle, 2011; Gallopin, 2006; Fekete, 2012; Fussel, 2007; Eakin & Luers, 2006; Hinkel, 2011).

For example, it has been noted that overlap exists between sensitivity and adaptive capacity, as an indicator of sensitivity at one time scale (e.g., poverty may be an indicator of sensitivity during an active emergency as fewer resources are immediately available to respond to the crisis at hand), yet may be an equally valid indicator of adaptive capacity at another time scale (e.g., poverty may also be an indicator of adaptive capacity as fewer resources are available to adequately prepare for future emergencies) (Frazier et al., 2014). Differences in operationalizing vulnerability are also obvious when considering the numerous variations in defining adaptive capacity, examples of which include coping capacity, coping ability, and capacity of response (Gallopin, 2006). In some cases, these terms refer to characteristics that exist before a harmful event occurs and impact outcomes in the short-term, while in others they refer to processes such as social learning that produces impacts in the long-term (Adger et al., 2004; Fussel, 2007; Gallopin, 2006; Keck and Sakdapolrak, 2013; Turner, 2003).

Vulnerability assessments are often used as a pre-event planning tool or for post-event analysis, and are typically conducted using indices that represent various attributes and properties of sub-systems or system components in order to evaluate exposure to harm and possible distribution of impacts. There are few examples of vulnerability assessment that adequately balance all aspects of social-environmental system components (e.g., human, engineered systems, social systems, natural systems) and consider their cross-scalar interactions (Engle, 2011; Adger, 2006; Fussel, 2007). Difficulties in addressing multi-scalar interactions may reflect the typical micro-scale lens employed in vulnerability assessments. While analysis at this scale can be a strength when identification of critical sub-systems/components or social justice issues within a system is needed, emphasis on the micro-scale can provide an incomplete picture of impacts at the system level (Miller et al., 2010). Current frameworks for vulnerability assessment do not adequately address dynamic temporal changes in vulnerability, critical *thresholds*, and/or multi-scalar interactions (Engle, 2011; Hinkel, 2011; Fekete, 2012; Miller et al., 2010; Frazier et al., 2014). As a result, imbalanced vulnerability assessment can provide discrepant and/or contradictory conclusions which may lead to adoption of inefficient and/or ineffective strategies to improve system quality and performance.

Resilience

The concept of *resilience* originates from ecological science, where it was defined as a system's ability to, "absorb changes of state variables, driving variables, and parameters, and still persist" (Holling, 1973). Resilience in this sense is a property that results in a system's level of persistence. A commonly accepted definition of resilience is the, "capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks" (Folke, 2006). This definition considers both system persistence and adaptability within the context of complex system interactions such as cross-scale dynamics, dependency, multiple equilibria, and feedback loops (Folke, 2006; Turner et al., 2003).

Recent definitions of resilience associated with social and economic systems incorporate the concepts of coping, adaptive, and transformative capacities (Engle, 2011; Keck & Sakdapolrak, 2013), and the ability to adapt or reconfigure to achieve strategic goals (Martin, 2012). For example, a community that is able to minimize physical flooding, has proactive emergency communication systems and sufficient emergency response infrastructure, and that is able to learn from flood events and take action to improve the outcomes of future flood events could be considered to be resilient. Doorn et al. (2018) go a step further and combine resilience with a capability approach that links social justice and well-being to infrastructure damage and recovery, highlighting interactions between social and physical coping and recovery processes. Resilience can also be viewed as a process that includes planning, preparation, monitoring, and learning to respond to change in order to achieve desired long-term goals (Godschalk, 2003; Ahern, 2011; Davoudi et al., 2012; Wilkinson, 2012; Desouza & Flanery, 2013; Sharifi & Yamagata, 2014; Arup and The Rockefeller Foundation, 2014) that are often associated with urban planning.

Among these resilience definitions are a number of common attributes: i) most refer to the ability of a system to absorb and adapt to disruptive events, ii) recovery from disturbance is considered a critical component, iii) some require a return to a steady or pre-disturbance state, while others allow for system degradation or the possibility of an enhanced or transformed state, iv) many include emphasis on *preparedness* and *recovery* activities (Hosseini et al., 2016; Koliou et al., 2018), and v) the attainment of resilience is often linked to achieving desired levels of system performance (Bruneau et al., 2003). In the case of social, engineered, or coupled systems, resilience is typically associated with attaining some combination of achieving social health and wellbeing and infrastructure/environmental stability and function (Keck & Sakdapolrak, 2013, Meerow et al., 2016a).

Defining resilience is an ongoing process as systems characterization and risk identification evolve. *Resilient systems* are also characterized by system attributes that impact different components of resilience, such as *robustness*, *redundancy*, *reliability*, preparedness, *rapidity*, risk, vulnerability, sustainability, and adaptive capacity (Bruneau et al., 2003; Rose, 2009; Keck & Sakdapolrak, 2013; Hosseini et al., 2016). The terms preparedness, rapidity, and *recovery* are often associated with community and infrastructure resilience, and are related to the ability to anticipate, plan for, and respond to disruption in ways that minimize injury and loss and allow for timely recovery of functions (Godschalk, 2003; Vale & Campanella, 2005; NIAC, 2009; Bozza et al., 2015; Minsker et al., 2015). Recovery itself is a complex term, especially for communities and associated infrastructure systems, where prevention of future loss and injury may require significant change or *transformation* involving multiple subsystems, objectives, and tradeoffs (replace, retreat, or relocate) rather than a return to pre-disturbance conditions (Vale, 2014). Uncertainty is also an important attribute associated with resilience, requiring an uncertainty-robust adaptation approach to manage lack of homeostasis and the need for flexibility when considering strategies for climate change (Wardekker et al., 2010).

Growing appeal and multiple definitions make resilience susceptible to criticism and point to a need for caution in its application. Davoudi et al. (2012) warn practitioners to carefully translate the use of resilience from one discipline to another and to avoid creation of a catch-all approach that is so malleable as to be “indefensible”. Meerow & Newell (2016b) also caution against a “one-size-fits-all” approach by emphasizing a need to question how resilience is to be applied, or more specifically, “resilience of what, to what, for whom, where, when, and why?” The nature and specificity associated with these questions is intended to avoid inconsistent, unintended, or maladaptive outcomes that can be associated with improperly scaled or incompletely informed decisions and associated trade-offs in planning processes to achieve resilience.

In contrast to vulnerability assessment, *resilience assessments* are often conducted in a dynamic way at multiple stages within a system planning and/or event response and recovery process, seeking to evaluate performance-based measures in response to systemic stress and disruption. Resilience assessments are often applied to relatively short-term events, one exception being the assessment of resilience to climate variability, which can cover a much longer temporal horizon. Complex coupled systems often require identification and use of indicators and metrics to represent specific performance objectives and use of statistical methods or network models to evaluate assessment outcomes (Baroud et al., 2014; Bozza et al., 2015; Linkov et al., 2014; Lam et al., 2015).

The exact nature of relationships between resilience, its multiple components, and various system attributes are often variable and not well defined. For example, Doorn (2017) provided a review of resilience in disaster management and found that different disciplines use varying definitions and relationships to describe resilience and vulnerability, and that distributive issues (e.g., access to resources, harmful impacts, etc.) are not well addressed in the literature, making it challenging to determine standards for social equity both before and after a disaster. As a result, difficulties can arise in aggregating measures across coupled systems where components or sub-systems may have differing levels of resilience, while taking into account the linkages between different system characteristics. Inadequacies in resilience assessment can lead to: i) short-term solutions that give the appearance of resilience, ii) poor strategies for reducing the severity of anticipated impacts and inadequate recovery planning that can lead to rebuilding the same set of conditions that resulted in system failure in the first place, and 3) failure to effectively use available resources and adaptation strategies (Vale, 2005; Masterson et al., 2014). For this reason, it is not always desirable to return to a pre-disturbance state, but rather to consider achieving an altered or transformed state through incremental adaptation, partial transformation or complete transformation.

In today’s world, physical, social, and economic systems are increasingly interconnected, resulting in complex interactions, which impact system performance in the presence of disruption. Koliou et al., 2018 provides a timely review of applications in resilience assessment for a variety of complex system types. The review finds a general lack of resilience assessment frameworks that are able to consider the multi-functional dynamics of complex systems (natural, built, social, and economic components and their interdependencies), and states that attempts to aggregate results from single-system analyses has contributed to confusion and inconsistency in the collective ability to understand and apply concepts (Koliou et al., 2018). While static levels of resilience may appear high (based on immediate availability of resources for response and recovery), long-term resilience is driven by sustained levels of availability and access to resources needed to fuel adaptation/transformation strategies. Current definitions and analytical frameworks do not account for all of these aspects, resulting in potential discrepancies in the assessment of resilience to inform decision making for critical resource allocation before, during, and after a disruptive event (Hosseini et al., 2016; Minsker et al., 2015).

Sustainability

Much of current *sustainability* literature defers to the Brundtland Report definition of *sustainable development* that includes trans-generational (long-term) equity by requiring that development be able to meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). The concept of recognizing present and future needs is related to understanding the interdependence between critical human-centric and ecological-centric resources (coupling), as well as overall social dependence upon both types of resources necessary to sustain development over time. In the literature, a sustainable social-environmental system is sometimes characterized as a system with the ability to provide sufficient resources to the human population without endangering the viability of the natural system, it is essentially concerned with addressing "threats to provisioning society and to maintaining life support systems," (Turner, 2010) through management of critical resource capital. Critical resource capital, or s*ustainability capital*, must be managed strategically over appropriate spatial and temporal scales to ensure future viability (Berkes & Folke, 1998; Kates et al., 2001; Marcotullio, 2001; Fiksel, 2006; Dietz & Neumayer, 2007). This includes managing both risk and opportunity to provide desired outcomes and overall system performance (Pope et al., 2004).

In this sense, "capital" refers to the quality and abundancy of a critical resource (social, economic, or environmental) that may be available at a point in time (Alberti & Susskind, 1996; Pickett et al., 2004; Mayunga, 2007; Wilson, 2010; Bettencourt & West, 2010; Mori & Christodoulou, 2012; Hiremath et al., 2013; Vanegas, 2003). These can broadly be described as follows:

- *social* - people, skills, health, and broad governance (provision of services, political capacity, law, and justice, among others);
- *economic* - employment, income levels, market diversity, tax base, business growth, and internal/external funds, among others.; and
- *environmental* – (natural and built) air, land, water, food, energy, ecosystem health, facilities, and infrastructure systems, sub-systems, and supporting networks.

Sustainability seeks to achieve environmental equity, long-term allocative efficiency, and distributive efficiency (Bithas & Christofakis, 2006) across sustainability capital in order to maintain system viability and well-being. Issues of finite supply, non-substitutability, and tipping points are also encompassed in the concept of sustainability. The concept of "strong" sustainability prohibits substitution of one capital for another (e.g., economic growth for environmental health or social equity) (Finco & Nijkamp, 2001; Dietz & Neumayer, 2007), as opposed to "weak" sustainability, where some trade-offs are allowable in order to maintain a combined capital stock under general limits of growth and capacity (Nourry, 2008). Growth is ultimately limited by the availability of capital and the capacity for assimilation of waste through sinks across various systems (with overriding limitations imposed by planetary carrying capacity) (Berkes & Folke, 1998; Fischer et al., 2007; Rockstrom et al., 2009). Without sufficient quality and quantity of critical resources (e.g., skilled labor, money, water, land, energy, etc.), referred to herein as sustainability capital, or the ability to change to address deficits in sustainability capital, system quality may be challenged. An understanding of thresholds and limitations at various scales (global, regional, local) is necessary in order to manage and employ capital when and where it is needed to enable resilience through capacity for change (Folke et al., 2002; Folke et al., 2003; Longstaff et al., 2010; Engle, 2011).

The challenge in seeking and maintaining sustainability lies in the balance between trade-offs among capital and the ultimate risk of exceeding acceptable thresholds for consumption and degradation, resulting in the possibility of irreversible damage or failure (Moldan et al., 2012; Botero et al., 2015). Like resilience, sustainability (or more specifically, sustainable development) can also be viewed as a process, in addition to a normative state, and can require iterative steps of assessment, planning, monitoring, and re-assessment to achieve desired long-term goals linked to system integrity, livelihood sufficiency, opportunity, resource maintenance, and adaptation (Adger et al., 2005; Gibson, 2006; Rosales, 2011; Boyko et al., 2012). Recent planning goals to achieve sustainable cities have been developed within the U.S. and abroad (UN, 2015; NAS, 2016).

In contrast to traditional use of vulnerability and resilience assessment, *sustainability assessments* are typically carried out prior to system development and are not often reassessed throughout a system's lifetime. Sustainability assessments typically focus on risk in terms of a system's impact upon its critical resources (sustainability capital), in order to achieve a long-term balance between the availability (access to needed quality and quantities) of resources and the system’s ability to provide desired services to society. Assessments can be conducted proactively based on desired achievement of sustainability goals and objectives for a future system (reduce risk and associated consequences), or reactively to assess sustainability for existing systems relative to an established baseline and future goals/objectives. Timing of assessments can impact the degree of trade-offs that may be possible when considering impacts to different sustainability capital categories, with greater constraints placed on reactive assessments (Pope et al., 2004).

When used to characterize system quality, sustainability assessment without adequate consideration of changes to sub-system/component vulnerability and system resilience can lead to sub-optimal system performance (Minsker et al., 2015). Where specific applications of sustainability assessment may require that a system is optimized to reduce material flows, the same system may also require an increase in materials to achieve decreased vulnerability and/or increased resilience through protective measures such as increasing *robustness* and adaptability (Bozza et al., 2015; Ahern, 2011; Bocchini et al., 2014). This is especially true over time and under changing circumstances that may not have been fully anticipated, or may not be fully definable without a high degree of uncertainty (Linkov et al., 2014; Minsker et al., 2015), such as climate change. Current analytical frameworks do not adequately address these issues by broadening the scope and objectives to account for critical system properties such as its vulnerability and resilience that are not included in typical sustainability assessments (Bocchini et al., 2014). While sustainability is inherently multi-generational in scope, typical sustainability assessments offer only a snapshot in time related to a specific set of resource trajectories (Mori & Yamashita, 2015). In addition, current frameworks do not adequately address dynamic system changes and resulting sustainability impacts over time (Minsker et al., 2015). This does not allow for evaluation of long-term sustainability. Such limitations highlight the need for iterative and multi-scenario approaches to assessing system sustainability.

Adaptive Capacity

Each of the aforementioned concepts (vulnerability, resilience, and sustainability) are related to a system’s ability to adapt and/or transform. The concept of adaptive capacity, as previously stated, is commonly understood as the ability to prepare for and respond to disturbance (Adger et al. 2004; Adger, 2006; Engle, 2011). This concept is less developed than the concepts of vulnerability, resilience, and sustainability, and not widely utilized by practitioners in the form of assessment techniques. However, it is gaining traction in social-environmental system assessment as it is commonly recognized as playing a vital role in both vulnerability and resilience concepts (Engle, 2011). In addition, it is widely recognized that the adaptive capacity of a system is dependent upon the resources available to that system, critically linking it to the concept of sustainability via availability and use of sustainability capital to affect positive change (Adger et al., 2004; Adger & Vincent, 2005; Engle, 2011; Turner, 2010). Whereas sustainability relates to the balanced management and interactions between forms of capital, adaptive capacity relates to the ability to effectively apply forms of capital to realize desired change (reduce harm, increase benefit), often through social structures and governance processes (Folke et al., 2002).

While the concept of adaptive capacity is not one of the primary concepts commonly used in complex system assessment today, it is implicit within any assessment oriented towards understanding the quality and performance of adaptive systems, and plays a key role in linking the three aforementioned concepts of vulnerability, resilience, and sustainability (Engle, 2011). Much work remains to be done to understand the nature of interactions between vulnerability, resilience, sustainability, and adaptive capacity, and how to avoid maladaptive outcomes over time and space (Romero-Lankao et al., 2016).

Used independently, each type of assessment discussed above produces a characterization of risk from an internal or external perspective over varying spatial and temporal scales that can be used to inform future actions to increase system quality and performance. However, when applied independently, they may not effectively or efficiently account for dynamic interactions across varying perspectives (impacts to systems or by systems), scales (temporal and spatial), and dependent systems (social, ecological, engineered, and coupled social-environmental). In recognition of limitations in using only a single concept to assess system quality and performance, efforts have been made to combine aspects of concepts with varied results. For example, the Disaster Resilience of Place (DROP) model (Cutter et. al., 2008), and SERV (Spatially Explicit Resilience-Vulnerability) model (Frazier et al., 2014) both integrate vulnerability and resilience yet lack robust consideration of sustainability. On the other hand, the Resilience Adaptation Transformation Assessment and Learning Framework (RAPTA) integrates concepts of resilience and sustainability yet does not explicitly account for vulnerability (O’Connell et al., 2015). While there are examples of frameworks that integrate two concepts explicitly and the third concept implicitly, to our knowledge, no framework has yet been described that explicitly accounts for all three concepts (vulnerability, resilience, & sustainability) with appropriate linkages to adaptive capacity, and associated interactions between concepts.

Materials and Methods

Evaluation of Concepts

A review of existing efforts point to a need to strengthen areas of perceived weaknesses in the ability to assess complex system quality absent consideration of all three assessment types. In this section, we examine these weaknesses in the context of suggesting areas of added value that could be produced by more comprehensive integration of the concepts. For the purpose of this discussion, we utilize the following definitions, i) vulnerability is the likelihood of experiencing loss due to hazard as a function of exposure, sensitivity, and adaptive capacity; ii) resilience is the ability to resist disruption, recover, adapt, and/or transform given a hazardous event in order to maintain desired system performance; and iii) sustainability is the long-term ability to operate without failure through balanced management of critical social, economic, and environmental capital. Additionally, adaptive capacity is defined as the ability to cope with, recover from, and adapt/transform through effective use of available sustainability capital in response to a hazardous event at a point in time.

Table 1 below, presents a summary of strengths and weaknesses of individual concept application in complex systems assessment. Differences in perspective and scale across individual concepts produce strengths and weaknesses, and imply a need for further analysis regarding areas of convergence and divergence that help to identify where and how integration may lead to greater understanding of system quality. In the following section, we examine the relationships between concepts through comparison of goals, focal lens, scale (spatial & temporal), and metrics to identify linkages and interactions among concepts.

	Strength of Individual Concept	Weaknesses (Gaps) in Current Application
Vulnerability	Identification and assessment of sub-system/component: • Risks • Weakest points • Means to reduce severity of harmful impacts to specific sub-systems/components within current system constraints	• Balance across social-environmental components (human, engineered systems, social systems, natural systems, among others) • Consideration of interactions with and impacts on, sustainability capital and long-term viability • Sub-system/component interactions with system-wide performance and quality, particularly in relation to critical thresholds
Resilience	Identification and assessment of system-wide: • Performance related risks • Plans for reduction of harmful impact and severity • Recovery and adaptation strategies • Transformation needs associated with system operations	• Balance across social-environmental components • Consideration of sub-system/component level variations and their impact on system-wide performance and quality over time • Consideration of impacts on sustainability capital resulting from implementation of adaptation or transformation strategies and resulting changes in adaptive capacity
Sustainability	Identification and evaluation of multi-scalar critical resource capital: • Deficiencies and/or opportunities • Long-term system-wide viability and wellbeing	• Consideration of critical system and sub-system/component properties given hazardous event scenarios • Consideration of dynamic system changes over time, including the impact of adaptation or transformation strategies

Table 1. Strengths and Weaknesses (Gaps) of Individual Concept Application in Complex Systems Assessment

Divergence, Convergence, and Interactions

Depending upon the framework used and the context of application, the concepts of vulnerability and resilience can be seen as inversely related, interdependent, or intersecting (e.g., vulnerability as a part of resilience or resilience as part of vulnerability) (Engle, 2011; Turner 2010, Lam et al., 2015, Gallopin, 2006; Bahadur et al., 2010). In some cases, a direct decrease in vulnerability is considered to be an approach to increasing resilience (Sahely et al., 2005, Cutter et al., 2008; Bahadur et al., 2010). Whereas some argue that resilience is a subset of vulnerability, and therefore increasing resilience can be seen as a way of decreasing vulnerability (Gallopin 2006, Turner et.al. 2003; Adger, 2006), others consider vulnerability a subset or factor in resilience metrics (Henry & Ramirez-Marquez, 2012; Baroud et al., 2014). In other cases, resilience is characterized as a component of, or contributor to, sustainability, where sufficient ability to resist disruption is required to ensure self-regulated operation over multiple generations (Fiksel, 2003;

Mayer, 2008).

Increasing adaptive capacity is considered a means of both increasing resilience and decreasing vulnerability (Burch & Robinson, 2007; Engle, 2011; Romero-Lankao et al., 2016). Through "sustainability science," resilience and vulnerability are regarded in a manner which implicitly links adaptive capacity to the availability and effective use of resources (Turner, 2010). While it is sometimes assumed that increasing resilience and/or decreasing vulnerability will increase sustainability and vice-versa, this is not necessarily the case. The focal lens of each concept, if improperly balanced, can lead to superficial consideration of related concepts and a failure to examine trade-offs, resulting in seemingly competing or misaligned goals and unsustainable outcomes (Mori & Yamashita, 2015).

In addition, dynamic environmental conditions, such as changes in climate, resource availability, and underlying control variables that impact system risk, lead to increased uncertainty in maintaining long-term resilience and sustainability. A system's ability to remain viable in the long-term is a function of its ability to adapt over time to changing circumstances. In this respect, system performance needs to be re-examined within and across interdependent systems using not only averages, but with consideration of extremes, infrequent events with severe consequences (Minkser et al., 2015). Whereas a conventional sustainability assessment may seek to minimize resource consumption in the development and operation of a system, this effort can undermine essential components of robustness and redundancy that are critical to resilience. Likewise, a conventional vulnerability or resilience assessment may not assess impacts to critical resources at spatial and temporal scales necessary to identify possible shortfalls in future availability of resources needed to support sustainability and fuel adaptive capacity (Mori & Yamashita, 2015). Analysis across all three concepts, perspectives, and scales is necessary to determine sufficiency in resource use and restoration/replenishment, as well as trends in increasing community performance over time (Milman & Short, 2008; Upadhyaya et al., 2014).

We assert that improved understanding of the nature of linkages and interactions is critical to enabling strategic integration of concepts, rather than a simple combination of terms. A detailed understanding of the interactions between concepts can highlight areas where a strategic approach to balanced integration and alignment of vulnerability, resilience, and sustainability goals may lead to an improved method for assessing the performance of any complex system (including communities), as well as improved ability to strategically build adaptive capacity, thereby strengthening long-term sustainability and resilience. The review of in-practice and conceptual literature on vulnerability, resilience, and sustainability presented earlier reveals at least five critical areas where conceptual interactions exist between assessment types: goals, focal lens, scale (spatial & temporal), and key measurement and practice terms. Table 2 presents a comparison of each concept across these critical areas.

From examination of the Conceptual Definition Terminology and Key Measurement and Practice Terms in Table 2, it can be seen below that economic considerations (cost, effectiveness, efficiency) are common across the concepts; considerations of equity-related diversity and susceptibility are common across sustainability and vulnerability concepts; aspects of system performance such as robustness, reliability, and thresholds are common across sustainability and resilience concepts; the abilities to cope/resist and adapt in response to disruption are key components of both vulnerability and resilience; and sensitivity is a common concern (although at different levels) across all three concepts. Comparison of the scale of assessment indicates that shared consideration of the ability to cope/resist or adapt across vulnerability and resilience occurs at the component-scale for vulnerability, while resilience is reflective of coping/resisting and adaptation capability within and across linked systems. In addition, terms such as exposure and sensitivity can be seen to be key components of conceptual definitions of vulnerability, but not of resilience. However, measurement of sensitivity and exposure are common in resilience assessment, suggesting that the conceptual components of resilience are dependent on exposure and sensitivity. Consideration of terms such as resourcefulness and preparedness in vulnerability and resilience assessment imply that levels of coping/resisting and adaptive capacity over time depend on availability of sustainability capital, where long-term coping and adaptive capacity are dependent on the equitable distribution of resources over system lifetimes or generations.

	Focal Lenses	Goals	Spatial and Temporal Scale	Conceptual Definition Terminology	Key Measurement and Practice Terms
Vulnerability	• What can happen to the system? • What is the impact to the system? • How equitably are the impacts distributed?	Mitigate impacts to the system and improve survivability and/or well-being of entities within the system under the influence of stress and/or shock.	Spatial: Micro (sub-system/ component). Temporal: Short to mid-term.	• Adaptive Capacity • Coping/Response • Exposure • Sensitivity	• Cost • Density • Diversity • Extent • Duration • Effectiveness • Efficiency • Preparedness • Resourcefulness • Susceptibility • Impact
Resilience	• How did the system respond? • How will the system recover?	Maintain system performance and functionality in the presence of change, minimize periods of disruption, and recover as well as adapt or transform.	Spatial: Meso (system-wide). Temporal: Mid-term (operational lifetime).	• Absorb/Resist/Cope • Recover • Adapt • Transform	• Cost • Effectiveness • Efficiency • Exposure • Rapidity • Threshold • Performance • Coping/Response • Redundancy • Reliability • Resourcefulness • Robustness • Sensitivity
Sustainability	• How will the system impact its surrounding environment (across social, economic, and environmental systems and sub-systems)? • Will impacts to critical resources modify system viability?	Identify and manage impacts to connected resource systems and sustainability capital in order to maintain indefinite system viability and well-being.	Spatial: Meso (system) with macro (beyond system boundaries) connectivity. Temporal: Long-term or strategic (life-time and beyond).	• Equity • Long term resource availability (in terms of social, economic, and environmental capital) • Resource quality and quantity	• Access • Cost • Diversity • Effectiveness • Efficiency • Redundancy • Reliability • Resource Demand • Resource Supply • Robustness • Sensitivity • Susceptibility • Performance • Threshold

Table 2. Vulnerability, Resilience, and Sustainability Assessments - Conceptual Linkages and Interactions

From the areas of divergence and potential linkages across concepts presented in Table 2, we further identify specific areas where *strategic* integration of concepts can be expected to result in greater understanding of system quality over time, which we refer to as "value-added" in Table 3. A summary of areas of value-added through focused integration of concepts, time-scales, systems, and resources is provided in Table 3 below.

	Gaps (from Table 1)	**"Value-Added" through Integration to Address Gaps**
Vulnerability	• Balance between social-environmental components • Consideration of interactions and impacts on sustainability capital and long-term viability • Consideration of sub-system/component interactions with system-wide performance and quality, particularly in relation to critical thresholds	• Greater consideration of ecosystem and physical infrastructure effects • Greater consideration of constraints on adaptive capacity imposed by sustainability capital • Improved consideration of threshold conditions; • Improved consideration of impacts to system-wide performance • Improved consideration of impacts to system sustainability capital
Resilience	• Balance between social-environmental components • Consideration of sub-system/component level variations and their impact on system-wide performance and quality over time • Consideration of impacts on sustainability capital resulting from implementation of adaptation or transformation strategies and resulting changes in adaptive capacity	• Greater consideration of socio-economic and socio-political effects • Improved understanding of how to reduce severity of harmful impacts • Improved identification and consideration of sub-systems/components critical to maintenance of system-wide performance • Improved identification of adaptation and/or transformation strategies that can be effectively implemented • Improved consideration of effects on system sustainability capital in order to maintain long-term system viability
Sustainability	• Consideration of critical system and sub-system/component properties given hazardous event scenarios • Consideration of dynamic system changes over time, including the impact of adaptation or transformation strategies	• Greater consideration of changes in the availability of sustainability capital • Improved consideration of effect of sustainability capital on adaptive capacity

Table 3. Areas of "Value-Added" through Focused Integration of Concepts, Time-Scales, Systems, and Resources

Conceptual Linkages & Interactions

While the exact nature of the linkages and interactions between individual assessment types is currently debated, it is evident that causal relationships are present at the sub-system/component and system-wide level in relation to measurements for vulnerability, resilience, and sustainability over time. Conceptual linkages and interactions identified in earlier Tables (1-3) are further illustrated in Figure 1 below.

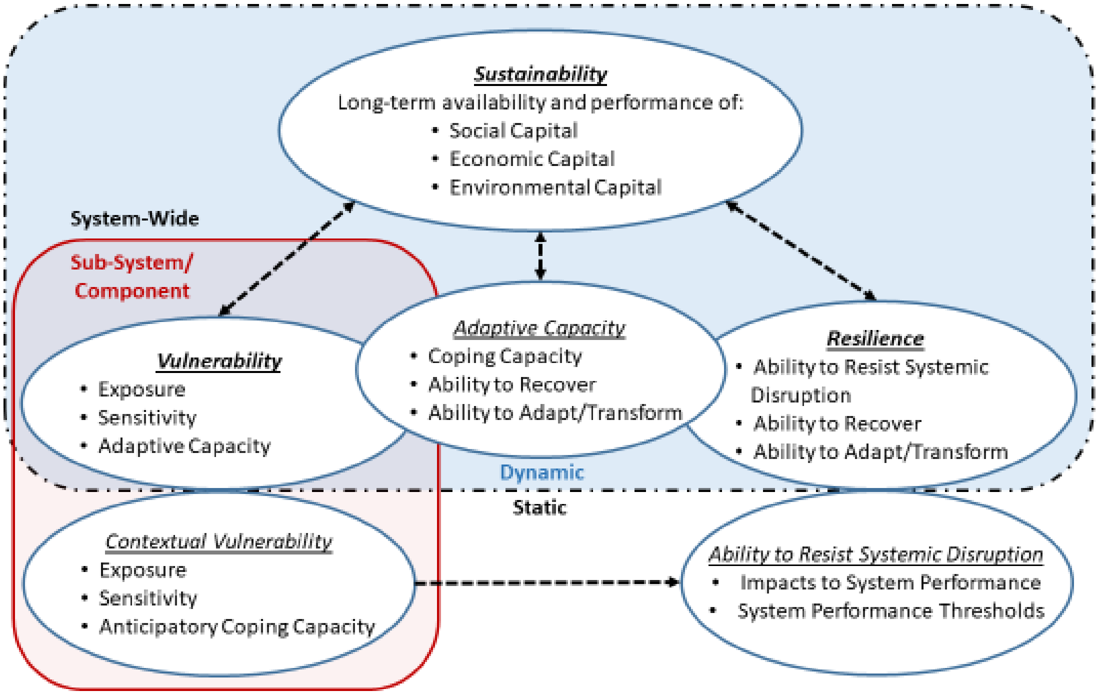

Figure 1. Assessing System Quality - Conceptual Linkages and Interactions

Overlapping areas indicate strong interdependence between primary and contributing concepts (e.g., adaptive capacity is a key component, or contributing concept, to both vulnerability and resilience). Primary concepts are represented by bold font. Dashed arrows indicate interdependence between concepts. For example, the quality and availability of sustainability capital (and ability to harness it to create change) impacts adaptive capacity. In turn, as resources may be utilized to create change, sustainability capital may also be impacted based on the degree of utilization and impacts to capital stocks. Over-utilization or lack of balanced management can render sustainability capital inadequate or inaccessible, thereby impacting vulnerability, adaptive capacity, and system resilience to varying degrees. Areas within the blue background refer to dynamic interpretations of concepts, while those outside refer to static interpretations of vulnerability and resilience that exist at a given point in time. The static state of vulnerability has a direct impact upon the static state of resilience within a system, and these static states contribute strongly to dynamic levels of system resilience. Changes in dynamic states are realized over time (through adaptation strategies, or lack thereof) via changes in and interactions between sustainability capital, vulnerability, and adaptive capacity as described below.

Within social-environmental systems, vulnerability assessment is typically applied to the component/sub-system scale of analysis (Miller et al., 2010). While resilience assessment is sometimes carried out for smaller scales of analysis, within the social-environmental system literature resilience assessment is typically conducted at the system-wide scale (Miller et al., 2010). Vulnerability and resilience are evaluated in both static and dynamic contexts in the literature (Cutter et al., 2008; Gallopin, 2006; Frazier et al., 2014).

Static characterization of vulnerability, termed here as *contextual vulnerability* in Figure 1, is defined as a pre-existing/current state of the system that takes into account exposure, sensitivity, and existing plans or capabilities that improve the effectiveness and range of actions available in response to a hazardous event (Cutter et al., 2008; Gallopin, 2006; Turner, 2003). This static form of adaptive capacity is herein referred to as *anticipatory coping capacity*, a component of contextual vulnerability (Figure 1). The resilience counterpart to contextual vulnerability is termed the *ability to resist systemic disruption* (Figure 1). This ability is based on the expected level of impact to critical sub-systems/components given their contextual vulnerability and interactions between those components that result in a systemic impact, where the overall system ability to either resist or succumb to disruption is also dependent on critical system performance thresholds.

As contextual vulnerability includes consideration of exposure, sensitivity and, through anticipatory coping, adaptive capacity, it can be deduced that the ability to resist systemic disruption is also dependent on these components (although considered at a different scale and in reference to performance thresholds). Since the ability to resist systemic disruption is a subset of resilience, this suggests that resilience is also dependent on exposure, sensitivity, and anticipatory coping capacity. These relationships imply that the concepts of vulnerability and resilience are also interdependent, and as formulated, are composed of the same basic building blocks. Despite this, differences in the scale, resolution, and unit of comparison that define the lenses of vulnerability and resilience mean that these concepts are not simple inverses of each other.

In addition, both vulnerability and resilience are dependent upon sustainability capital and its ability to promote or constrain adaptive capacity through availability and effective use of critical resources. The quality and quantity of capital on hand at any time can impact the ability of a system to harness needed capital in anticipation of, preparation for, or recovery from disruption. Therefore, adaptive capacity essentially functions as a moderator in determining levels of vulnerability and system resilience through availability of sustainability capital needed to realize change (Engle, 2011).

Lastly, sustainability is seen to be dependent upon the ability of the system to resist systemic disruption, recover, adapt, and transform, which we define as resilience, as these abilities directly impact deposits and withdrawals from sustainability capital; suggesting that sustainability and resilience are interdependent. Sustainability is also seen to be dependent upon vulnerability, as hazard impacts not directly related to system performance are still expected to directly influence deposits and withdrawals from sustainability capital. This again suggests that sustainability and vulnerability are interdependent.

Sustainable Resilience

In understanding and assessing the quality of complex adaptive systems over time, with the aim of reducing adverse impacts (disruption) to the system over its lifetime, we suggest resilience as the focal point for assessment integration. This does not presume that one concept is more important than another; rather it requires consideration of balance and alignment across concepts to achieve the capacity for long-term resilience. The evaluation of concepts and illustration of linkages and interactions as developed and presented (Figure 1), lead us to conclude that changes in sustainability capital and sub-system vulnerability can increase or decrease system-wide resilience over time through moderation of adaptive capacity.

As it is currently difficult to measure changes in adaptive capacity over time across complex systems, we propose that it is therefore critical to monitor significant shifts in both sustainability capital and sub-system/component vulnerability over time, and in conjunction with development and implementation of adaptation/transformation strategies in order to assess, and ultimately manage, current trends and possible future trajectories for system resilience. Given the discussed conceptual linkages and the suggested use of resilience as a system assessment focal point, we define *sustainable resilience as the ability of a system to maintain desired system* *performance by changing in response to expected and unexpected challenges over time, while simultaneously considering intra-system and inter-generational distribution of impacts and sustainability capital.* Vulnerability is represented within this definition by consideration of the intra-system distribution of impacts that result from varying levels of vulnerability within the system over time, and sustainability is represented by consideration of distribution of sustainability capital over the life of the system.

Discussion

Critical areas of interaction exist between vulnerability, resilience, and sustainability that suggest the need for an integrated assessment framework to better understand and measure the quality of complex adaptive systems. However, current literature does not provide a solid foundation on which to base integration of these concepts or an obvious focal point for assessment. In response to this need, we provide an analysis of linkages and dependencies between the concepts of vulnerability, resilience, and sustainability and their relationship(s) with adaptive capacity, and identify the value added that integration of concepts might provide to system assessment processes. We further develop the concept of sustainable resilience to better communicate the need for balance and alignment across concepts to achieve the capacity for long-term resilience.

A detailed framework to assess vulnerability, resilience, and sustainability in an integrated manner that can be adapted to fit a variety of systems and ultimately operationalized has yet to be described in the literature. We suggest that an integrated framework for assessing sustainable resilience based on the linkages and interactions between the concepts of vulnerability, resilience, and sustainability, as described in this paper, could fill this gap and result in improved ability to:

- Identify or anticipate significant changes in, or the need to alter, availability of sustainability capital through management practices (maintenance, withdrawals, and investments) over time;
- More effectively use sustainability capital to reduce critical sub-system vulnerability and improve resilience outcomes through successive monitoring and/or scenario development aimed at evaluating the impact of adaptation strategies; and
- Identify or anticipate when to consider system transformation (adaptation is no longer feasible, and transformation strategies may lead to new systems and objectives).

To further advance the concept of sustainable resilience, forthcoming work will describe a dynamic assessment framework for sustainable resilience that can be adapted to fit a variety of systems and that adds value to overall system characterization through recognition of key interactions across assessment types.

CHAPTER III

An Integrated and Dynamic Framework for Assessing Sustainable Resilience in Complex Adaptive Systems

Introduction

From a human-centric perspective, the quality of an engineered system can be defined as a measure of its ability to serve society. The concepts of vulnerability, resilience, sustainability, and adaptive capacity are frequently used to frame assessments related to system quality and are frequently invoked within the literature on coupled social-environmental systems (Adger, 2006; Folke, 2006; Turner et al., 2003; Minsker et al., 2015). It is widely recognized that these concepts are interrelated, and that system assessments that do not consider each of these concepts have limitations that may lead to decision-making and planning that result in negative, unintended consequences (Gillespie-Marthaler et al., 2018). However, to date, little progress has been made in developing operational assessment frameworks that integrate more than two of these concepts (Gillespie-Marthaler et al., 2018). Integration of the concepts of vulnerability, resilience, sustainability and adaptive capacity in an operational assessment framework has been hampered by issues of complexity and conceptual confusion. While definitions and usage of these concepts will undoubtedly continue to evolve, the conceptual relationships proposed by Gillespie-Marthaler et al. (2018) that are based on current general understandings of vulnerability, resilience, sustainability, and adaptive capacity, help to identify potential points of integration.

In this paper, we introduce a high-level assessment framework based on the conceptual relationships described by Gillespie-Marthaler et al. (2018) that explicitly integrates vulnerability, resilience, and sustainability assessment within an adaptive cycle. The proposed framework is intended to enable the characterization of sustainable resilience, which we define as the ability to maintain system performance by changing in response to expected and unexpected challenges while simultaneously considering intra-system and inter-generational distribution of impacts and sustainability capital. We include a detailed explanation of the framework and assessment process to show how sustainable resilience is impacted by changes in vulnerability, sustainability, and resulting adaptive capacity at multiple scales and time points through a series of interdependent relationships. We further provide a set of functional definitions and an example of an application of the framework for an urban community with high flood risk. Key concepts and terminology used in the analysis are italicized within the text and defined in Appendix B.

Background

Several examples of frameworks for system assessment that attempt to integrate sustainability and resilience, or vulnerability and resilience, appear in the literature (Cutter et al., 2008; O'Connell et al., 2015; Lam et. al., 2015; Mayunga, 2007; Manyena, 2006; Henry & Ramirez-Marquez, 2012; Baroud et al., 2014; Turner et. al 2003; Minsker et al., 2015). For example, the Resilience Adaptation Transformation Assessment and Learning Framework (RAPTA) integrates concepts of resilience and sustainability by defining *system objectives* that guide resilience assessment in terms of sustainability goals through a modular and iterative process involving multi-stakeholder collaboration within the Resilience-Assessment-Transformation Assessment Framework (RATA) (O'Connell et al., 2015). This framework provides a valuable way of integrating sustainability and resilience concepts in a single assessment process focused on adaptation and transformation, and does allow for some consideration of vulnerability. However, the generality of the framework can obscure linkages between concepts and make operationalization difficult.

Spatial analysis is emphasized as a means of identifying and measuring social vulnerability within a resilience frame by Frazier et al. (2014) through use of the SERV (Spatially Explicit Resilience-Vulnerability) model, and by Cutter et al. (2014) via BRIC (Baseline Resilience Indicators for Communities). These tools tend to emphasize social aspects (age, income, access, etc.) in relation to the built environment (often infrastructure systems) without balanced consideration of natural systems and processes, thereby providing the potential for an incomplete assessment of system quality by failing to account for all critical sustainability capital (Sharifi, 2016).

The Disaster Resilience of Place (DROP) model provides a different way of approaching resilience assessment, proposing a framework for quantification of resilience through a serial assessment process with feedback loops that integrates vulnerability and resilience concepts, but with less overt focus on sustainability and environmental concerns (Cutter et. al., 2008). Whereas, Lam et al., (2015) take yet another approach and integrate resilience, vulnerability, and adaptive capacity concepts by measuring current resilience as a ratio of the other two concepts in the Resilience Inference Measurement (RIM) model without fully addressing relationships between adaptive capacity and sustainability.

The Sustainable Livelihoods Framework focuses on improving capital assets in order to enhance disaster resilience (Ashley and Carney, 1999; Wilhelmi and Hayden, 2010). While the conceptual application of this framework is appealing due to its flexibility, operationalization remains challenging with respect to defining and measuring progress due to the possible need for multiple, dynamic trade-off analyses based on identification of what should be sustained to maintain economic viability. Methods like the Driver-Pressure-State-Impact-Response (DPSIR) or enhanced DPSIR frameworks have been shown to aid in decision making by helping to structure problems in terms of pressures and responses, and organize indicators in multi-disciplinary settings. While the framework has been used to help describe problems in social-environmental settings by the Organization for Economic Cooperation and Development (OECD), it does not directly address the concepts of vulnerability, resilience, and sustainability (Kristensen, 2004; Niemeijer & de Groot, 2008; Tscherning et al., 2012).

These and other approaches provide valuable ways of conceptualizing and interpreting, and in some cases operationalizing, complex concepts and their intersections as they apply to solving social-environmental system problems. However, there continues to be a call for improving the translation of conceptual understanding into operational assessment methods and improving the universal ability to practically apply principles of resilience, vulnerability, and sustainability (Miller et al., 2010; Biggs et. al., 2012; Minsker et al., 2015; Romero-Lankao et al., 2016). Miller et al. (2010) suggest that a first step towards improving operationalization would be to develop integrated vulnerability and resilience assessments, whereas Minsker et al. (2015) advocate continued effort towards integrating sustainability and resilience. While some of these frameworks integrate two concepts explicitly and may consider the third concept implicitly, to our knowledge, no framework has yet been described that explicitly accounts for all three concepts (vulnerability, resilience, and sustainability), their interdependencies, and their linkages to adaptive capacity.

Examination of the conceptual relationships between vulnerability, resilience, sustainability, and adaptive capacity proposed by Gillespie-Marthaler et al. (2018) (Figure 2) suggests that one possible focal point for operationalization of integrated system assessment centers on the evaluation of resilience as it relates to changes in vulnerability and sustainability.

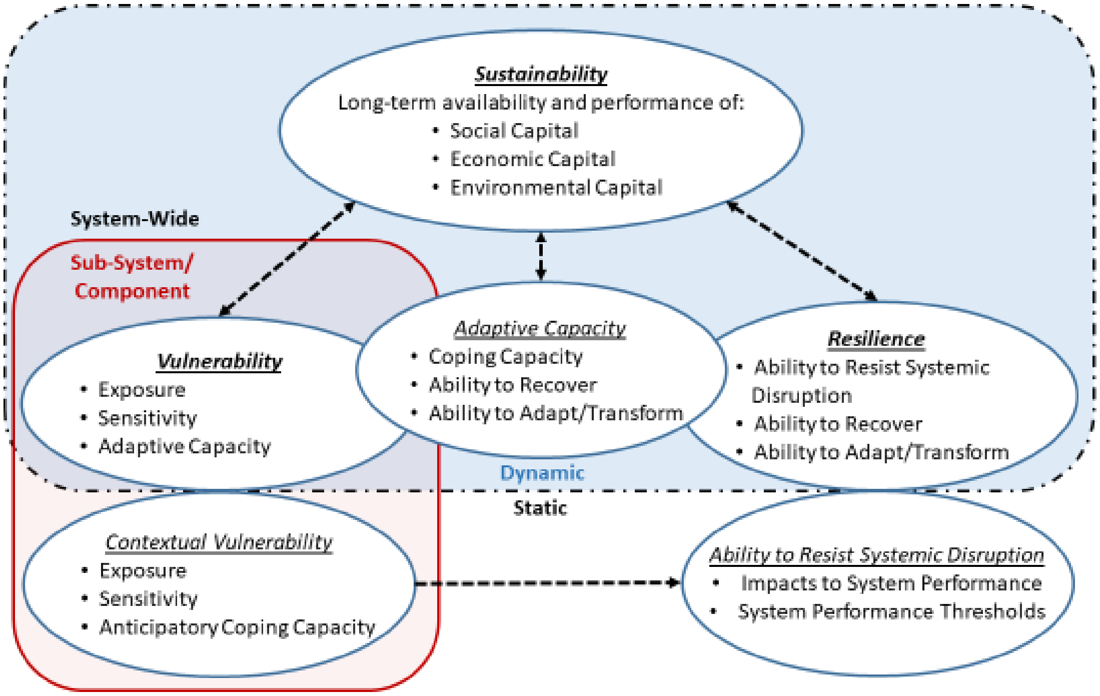

Figure 2. Assessing System Quality - Conceptual Linkages and Interactions (reproduced from: Gillespie-Marthaler et al., 2018)

Changes in *sustainability capital* may result in changes to system-wide adaptive capacity, which can alter the vulnerability of critical sub-system and components. This, in turn, can impact system-wide resilience over time and further impact development and selection of *adaptation/transformation strategies* needed to reduce harmful impacts associated with *hazards* and enable avoidance of *systemic disruption* and/or *systemic failure*. We suggest that it is necessary to monitor shifts in both sustainability capital and vulnerability as they relate to resilience in order to assess and manage the sustainable resilience of social-environmental systems (Gillespie-Marthaler et al., 2018). Below, we present a framework that integrates the aforementioned concepts via a dynamic assessment process, in order to characterize sustainable resilience.

Methodology

Overview of the Sustainable Resilience Assessment Framework

The sustainable resilience assessment framework is intended for application to *complex adaptive systems*, specifically *social-environmental systems*. Like any system, social-environmental systems are defined by both their function and structure. As complex adaptive systems, social-environmental systems are expected to be subject to multi-scalar relationships between the system, sub-systems, and external systems, where direct and indirect causal relationships, both physical and non-physical in nature, can result in impacts to overall system performance. Complex, coupled social-environmental systems undergo adaptive cycles, where change is triggered by disruptive events (Adger, 2006; Engle, 2011). These systems are generally assumed to be metastable, in that adaptive cycles often lead to changes that do not significantly alter the state of the system as defined by its objectives and functional relationships (Adger, 2006; Engle, 2011). However, it is possible that significant change, resulting in transformation, can redefine the *system objectives* or functional relationships of the system (Engle, 2011; Martin, 2012; Keck and Sakdapolrak, 2013).

The proposed framework uses a serial and cyclical process, allowing users to assess baseline conditions, predict hazard-related impacts, simulate potential costs and benefits associated with various adaptation and transformation strategies, and evaluate system-wide resilience with respect to trends in vulnerability and sustainability over time. This process is displayed at a macro-level in Figure 3.

Figure 3. Macro-level Diagram of the Sustainable Resilience Assessment Process

A more detailed representation of the process for assessing changes in sustainable resilience appears in Figure 4. It begins with a baseline system definition, followed by an assessment cycle. The assessment cycle begins with identification of risks and creation of hazard scenarios. Following these steps, a contextual vulnerability assessment (representing pre-existing/current conditions at the critical sub-component level) is conducted and used to estimate impacts in an assessment of the system's ability to resist systemic disruption. Following the evaluation of the system's ability to resist systemic disruption, a re-evaluation of macro-scale, long-term sustainability is conducted, taking into account the effects of the hazard on critical sustainability capital. Information resulting from this sustainability assessment is used to inform the development of adaptation or transformation strategies.

Adaptation strategies may include incremental, and in some cases temporary, changes that do not substantively alter the system (e.g., constructing a flood wall), while transformation strategies would result in large changes, culminating in a new system state (e.g., facility relocation). If systemic failure is expected to occur (multiple system objectives are severely disrupted or critical resources are depleted and cannot be sufficiently recovered without intervention), the development of transformation strategies may be prioritized over adaptation strategies. However, the decision to choose adaptation or transformation strategies is dependent in part on the willingness of system stakeholders to accept a certain degree of system failure or resource depletion, also known as *risk appetite* or *risk tolerance.* After adaptation or transformation strategies have been proposed, the cycle repeats for a subsequent time period. If adaptation or transformation occurs, it is assumed that the system definition is updated to reflect changes due to implementation of developed adaptation and/or transformation strategies (shown as "Define System" in Figure 3).

In order to estimate changes in sustainable resilience over time, the assessment cycle should be repeated several times, where the time interval between repetitions may be based on the type of hazard scenario, estimated *recovery* time, estimated strategy implementation time, and/or strategic planning updates. In each cycle, sustainability should be reassessed regardless of whether or not a systemic disruption has occurred, as sustainability capital can be altered by even minor hazard events that may not exceed system disruption thresholds. If used for planning purposes, it is recommended that a comprehensive update of an assessment be conducted on a decadal basis to coincide with long-term, strategic, system-wide planning and goals. During comprehensive updates, consideration should be given to instances where changing conditions (e.g., climate variability and cross-scalar impacts) create a need to reassess expected return periods and/or severity of natural hazards, related consequences, or the need to evaluate the potential for new hazards that have not been previously considered.

The framework can be used to assist in making decisions regarding the prioritization and selection of adaptation or transformation strategies (if used for planning purposes), or to evaluate the effectiveness of an implemented strategy or set of strategies (if used for post-hoc analytical assessment). Rather than providing merely a snapshot of system conditions at any specific time, the framework is intended to allow comparison of the system's expected performance over time, providing a way to estimate possible resilience trajectories given different hazard-response scenarios. The use of a serial assessment process aids operationalization of the framework by dividing assessment tasks into manageable units, and provides a model for dependency between vulnerability, resilience, and sustainability concepts. [Note added after publication: The framework also allows for cascading effects whereby a system may transition from adaptation to transformation in two primary paths: i) a sudden, catastrophic event moves the system from incremental adaptation to sudden transformation via irreparable destruction or lack of desire to return to a prior state (e.g., a community such as Mexico Beach, Florida decides to rebuild further from the shoreline after massive destruction following Hurricane Michael in 2018); and/or ii) a slower, chronic event or set of events creates a situation where adaptation is no longer feasible and transformation must be pursued (e.g., incremental loss of beachfront material due to multiple events that result in a need to relocate development and zoning boundaries over time)].

Navigating the Framework

Figure 4 provides a detailed illustration of the sustainable resilience framework. Below, we discuss each step in the framework in detail.

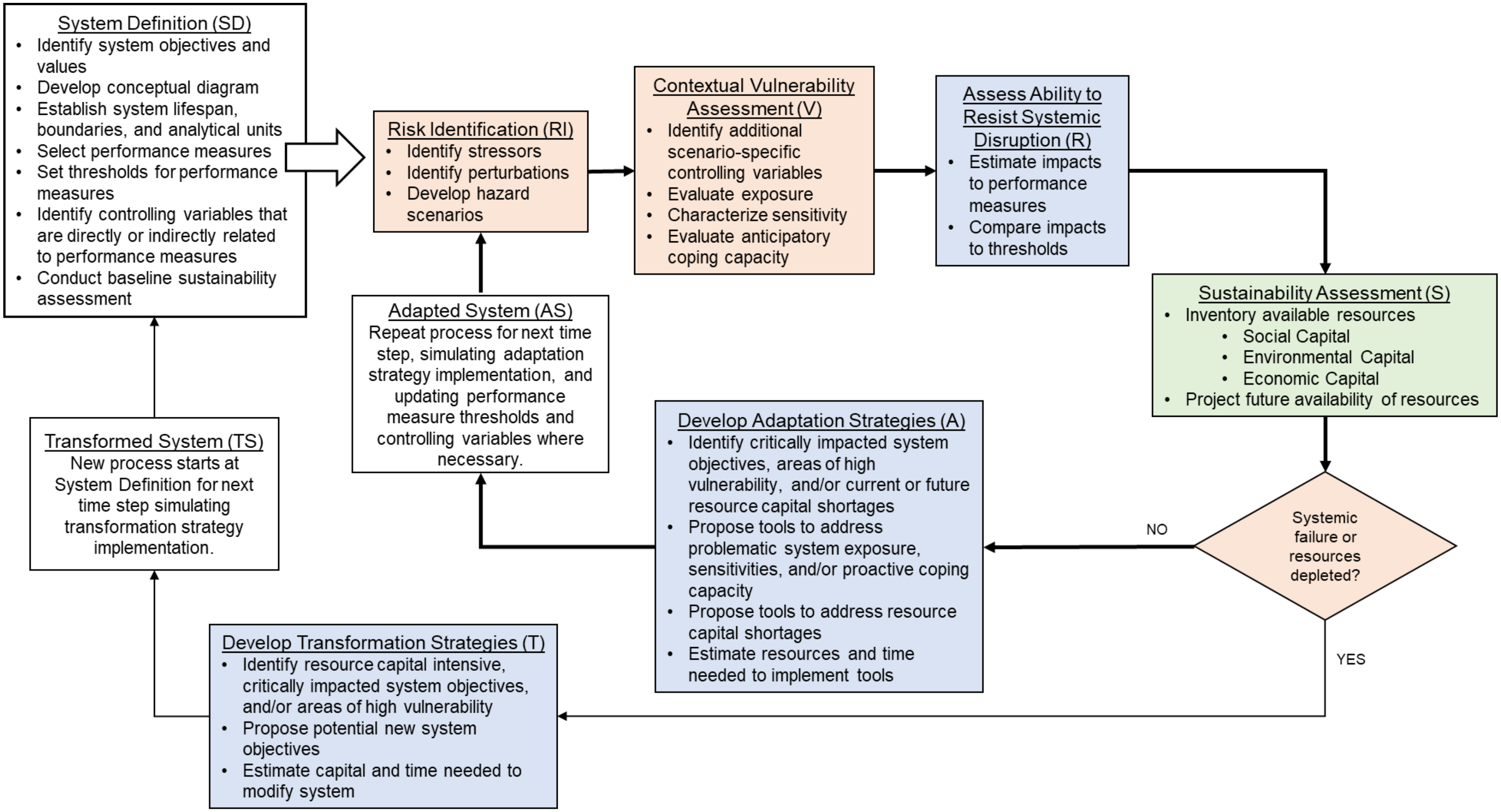

Figure 4. Sustainable Resilience Assessment Framework for Complex Adaptive Systems. [Operations associated with sustainability are shown in green, operations associated with risk and vulnerability are shown in orange, and operations associated with resilience are shown in blue. White indicates operations associated with all three concepts.]

System Definition (SD):

In order to account for the many possible system dynamics, it is necessary to accurately define the system and its critical relationships. Broadly speaking, system definition should include: i) identification of system objectives and values; ii) development of a conceptual diagram or network model of the interacting nested system(s); and iii) identification of controlling variables and thresholds. For the framework to fully function according to its intended purpose, the identification of the objective(s) and values of the system, as well as identification of thresholds, should ideally include multiple stakeholder participation and perspectives to reflect the diversity of values connected to the system (Bossel, 2001; Cumming et al., 2005; O'Connell et al., 2015). Recommended steps that can be included in the system definition phase are provided below.

System definition should begin with participatory identification of the system objectives and values, followed by development of a conceptual diagram of the system. When developing this diagram, it is necessary to include consideration of not only the primary system of interest (subject system), but also other related systems where dependency exists (e.g., critical and/or shared resources that may be impacted by growing or competing demands over time). This includes the nature of linkages and interactions (critical versus non-critical; acute versus chronic or cumulative effects) (Bossel, 2001). Whereas the failure of a single sub-system (e.g., a protective infrastructure asset such as a dam or a levee) may immediately jeopardize the subject system, long-term depletion or degradation of one or more sub-systems (e.g., surface or groundwater resources) can also result in potential for systemic disruption or systemic failure over time. Understanding of system interactions (dependencies and interdependencies) should extend beyond basic economic and physical relationships of the subject system to include linkages with environmental and social aspects across critical sustainability capital.

Once a conceptual diagram of the system has been developed, its spatial and temporal bounds and its interaction with related systems should be established in order to determine the extent to which interactions should be monitored. Performance measures or indicators that can be used to quantify system performance objectives should be selected (Bossel, 2001). Thresholds for acceptable performance levels, including allowable duration for disruption at varying scales (e.g., power outages, loss of transport), should be established using input from multiple stakeholders in order to reflect variations in risk perception and risk appetite, as well as expectations for recovery. Key controlling variables (direct and indirect) that relate to performance measures should also be identified. Finally, the system definition should include an accounting of the pre-hazard availability of critical sustainability capital and definition of critical resource levels by conducting a baseline sustainability assessment.

Risk Identification (RI):

Upon defining the system, identification of risks in the form of hazard scenarios is conducted. We adopt the definition of hazard from Turner et al., (2003), where a hazard represents any threat to a system, either a perturbation or a stressor. The likelihood of their occurrence should be used to develop a suite of hazard scenarios against which the system will be evaluated. Ideally, these scenarios should consider both high *exposure*, low frequency and low exposure, high frequency perturbations and stressors. The framework is intended for cyclical evaluation over time, allowing users to deliberately assess projections and possible outcomes related to climate variation, future development, and associated resource demands. When the framework is used for post-ante assessment, the risk identification step may simply involve description of a known and recorded hazard. This activity serves as the basis for establishing exposures used in the next step, contextual vulnerability assessment.

Contextual Vulnerability Assessment (V):

Following risk identification, the contextual vulnerability of critical system components to a hazard scenario is assessed. Contextual vulnerability is a static interpretation of vulnerability at a specific moment in time and operationalizes the concept of vulnerability by focusing on pre-hazard characteristics of sub-systems/components that describe the extent to which they may be expected to experience negative impacts of a hazard (Cutter et al., 2008; Gallopin, 2006). Assessment of contextual vulnerability should include evaluation of the exposure, sensitivity, and anticipatory coping capacity for each sub-system/component of the system (e.g., city block, road segment, social group, business sector, etc.). This static scale of vulnerability assessment makes use of the ability of vulnerability analyses to identify intra-system disparities and areas of critical concern.

Evaluation of exposure should include consideration of the magnitude (severity) and extent (spatial extent and temporal duration) of a hazard. Sensitivity evaluation should include consideration of the innate characteristics that influence the degree to which impacts will be suffered given a certain level of exposure. In order to distinguish sensitivity from *coping capacity*, we suggest that sensitivity include variables related to structure, such as societal factors that influence and limit a system's or component's set of possible actions (e.g., social class, cultural acceptance, aesthetic norms), as well as intrinsic physical characteristics (e.g., physical design, structural integrity, code/legal requirements). Evaluation of *anticipatory coping capacity* should include consideration of existing plans or capabilities that improve the effectiveness and range of actions available in response to a hazard. Variables used to represent anticipatory coping capacity should reflect the ability of the system to survive and adjust during a hazardous event via individual actions/choices or systematic policies and programs in place at the time of the disturbance (e.g., flood insurance, emergency notification system, evacuation or shelter-in-place plan, property protection plan) (Adger et al., 2004; Gallopin, 2006; Turner et al., 2003).

We suggest that expected impacts and the severity of consequences to the system are dependent on the vulnerability of individual system units (sub-system/components), and that an assessment of vulnerability at any discrete point in time (contextual vulnerability) can be used in a subsequent step to provide an approximation of the expected impacts to system performance measures.

Assess Ability to Resist Systemic Disruption (R):

Following contextual vulnerability assessment, an evaluation of the degree to which hazard-induced impacts to the system do not result in disruptions in system service (e.g., the ability to resist systemic disruption) is conducted. Ability to resist systemic disruption can be operationalized as the difference between estimated impacts of a hazard scenario on a performance measure (based on contextual vulnerability assessment) to the established threshold for that performance measure (Luers et al., 2003; Luers 2005; Cutter et al., 2008). The thresholds, as identified in the system definition stage, define the point at which a performance measure no longer provides an acceptable level of service and may be considered to be "disrupted." Assessment of ability to resist systemic disruption can indicate potential for disruption through critical lifeline impacts, or through cumulative/cascading impacts.

The impacts of a hazard scenario on a system may be estimated using a variety of quantitative and qualitative assessment methods. In quantitative methods, physics-based, data-driven, or simulation models can be used to evaluate the impact of hazard scenarios on the performance of system. While physics-based models can present limitations in accounting for uncertainty (Balica et al., 2013), data-driven methods such as regression models (Gidaris et al., 2017), tree-based methods (Mukherjee & Nateghi, 2017), and Bayesian analysis (Baroud and Barker, 2018) provide flexibility in modelling, interpretation, and prediction. Quantitative methods require that observational data be available for the system of interest. However, these methods readily allow for consideration of direct relationships between controlling variables used in vulnerability assessment and system performance measures. In order to account for indirect relationships such as cascading effects of hazards to other interdependent systems, inoperability economic modelling can be used to assess, for instance, how a disruption to an infrastructure cascades to different sectors in the economy (Baroud et al., 2015). For systems lacking observational data, simulation methods based on behavioral rules, such as agent-based modelling (Dawson, Peppe, & Wang, 2011; Hou, et al., 2017), or physical dynamics models (Huang & Hatterman, 2018; Lu, et al., 2018; Masoomi & van de Lindt, 2017) may be more applicable. Alternative approaches for cases with limited local data may employ use of well-documented national or state-level thresholds for impact severity, or use of participatory expert solicitation methods to generate qualitative estimates of severity based on vulnerability scores (Abkowitz et al., 2017). In the case where an actual hazard event has occurred, the impacts of the hazard on performance measures, as moderated by vulnerability, could be analytically estimated post-event assuming the availability of adequate event data. While these post-event, historic relationships between hazard, vulnerability, and impacts may not necessarily hold constant throughout the lifetime of a system, they can serve as a baseline for projected impact estimates.

Sustainability Assessment (S):

The primary purpose of sustainability assessment within this framework is to provide planners and decision makers with a measure of the availability and quality of critical sustainability capital needed in order for a system to function and survive. Sustainable development should maintain the desired level of system service without compromising trans-generational equity in the availability of three key resources: i) *social* - people, skills, health, and broad governance (provision of services, political capacity, law, and justice, among others); ii) *economic* - employment, income levels, market diversity, tax base, business growth, and internal/external funds, among others.; and iii) *environmental* – (natural and built) air, land, water, food, energy, ecosystem health, facilities, and infrastructure systems, sub-systems, and supporting networks. By this, we refer to a need for informed and balanced assessment across long-term social, economic, and environmental resources in order to avoid short-term gains in one resource at the expense of another (Westerink et al, 2013; Schewenius et al., 2014; Haaland & van den Bosch, 2015). As an example, short-term economic gains associated with rapid growth may fail to account for long-term impacts such as water demand, gentrification, transportation, and impacts to flooding due densification and loss of permeable area (each of which can contribute to future sources of vulnerability and risk).

Within the construct of the sustainable resilience assessment framework, a sustainability assessment involves a macro-scale inventory of currently available capital, evaluation of the relative health of resources, and an estimate of projected future resources given a continuation of the current system trajectories and resource use (including depletion/and or replenishment rates). Methods and tools for sustainability assessment can be scaled based on the intent of application, ranging from data intense lifecycle analysis to indicator-based approaches for communities (Singh et al., 2009; Sala et al., 2013). For the purposes of this framework, mixed method approaches that allow for use of qualitative and quantitative data such as multi-criteria decision analysis (Cinelli et al., 2014), urban frameworks (Adinyira et al., 2007), and packaged tools (Ness et al., 2007) are available. The sustainability assessment should not only provide an estimate of the funds and environmental resources available for implementing adaptation strategies, but also an estimate of the expected effectiveness of implementation via social capital constraints (e.g., governance) that influence organizational efficiency and strategy acceptance, and should adjust the baseline sustainability assessment to account for impacts to resources that may occur as a result of the hazard.

The new/revised sustainability assessment provides an estimate of resources currently available and expected to be available in the future for implementation of system adaptation/transformation strategies. If the sustainability assessment indicates that resources have been depleted beyond critical resource levels defined during the baseline sustainability assessment, a transformation of the system is recommended. It should be noted that while the linear projection of resource consumption recommended above is a positive first step in considering long-term resource use, it does not account for non-stationarity and rapid changes in population shifts and market shifts that can have significant, unexpected and cascading impacts upon critical resources over relatively short periods of time. Therefore, it should be acknowledged that these linear projections may provide an overly optimistic view of future resource availability, and conservative definitions of critical resource levels should be used to offset some of this *uncertainty*.

Develop Adaptation or Transformation Strategies:

The sustainability assessment anchors the subsequent development of adaptation or transformation strategies, recognizing that these strategies are limited by the ability to effectively implement them, and are dependent on the available social, economic, and environmental capital. We view adaptation as a process that includes incremental, and in some cases temporary, changes that do not substantively alter the objectives, values, and functional relationships of the system. Transformation, on the other hand, implies large and sudden changes that may result in a new system state. In the case where the system is expected to experience mild to moderate systemic disruption, adaptation strategies are typically developed. However, if the system is expected to experience systemic failure or if critical resources are expected to be depleted/non-recoverable, transformation strategies should be developed. When transformation occurs, the system should be appropriately redefined, and the process re-initiated with a new set of objectives (Walker et al., 2004). The development of adaptation and transformation strategies to evaluate is an activity which should be carried out as a participatory process with significant, inclusive stakeholder input.

Adaptation (A → AS):

If the system experiences mild to moderate disruption, adaptation strategies that have the potential to improve future system quality should be developed. These adaptation strategies should aim to modify exposure, sensitivity, anticipatory coping capacity, and/or sustainability capital availability. Once a set of strategies has been proposed, the assessment cycle should be repeated for a future time-step, where the length of the time-step could be based on either scheduled planning updates, estimated recovery time, or the estimated time to implement the developed strategy.[1] In this cycle, implementation of one or more of the adaptation strategies developed should be assumed, and controlling variable values and performance measure thresholds should be updated based on both adaptation strategy-based and time-based changes to reflect conditions

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[1] In situations where the framework is used to evaluate strategies that have already been selected and/or implemented by the system of interest, the development of strategies may be skipped and the process should move directly to repeating the assessment cycle for an additional time step assuming strategy implementation.

of the adapted system. Note that if no feasible adaptation strategies are developed, the system still undergoes recovery, and the assessment cycle can still be repeated for subsequent time points.

Transformation (T →TS):

In the case where system transformation is deemed necessary, developed strategies should lead to a new system definition (i.e., the system may have different objectives and values that imply changes in hazard-based risk and variables that control performance measures). Potential new system objectives that reduce or eliminate sustainability capital intensive activities, high vulnerability areas, and/or critically impacted system objectives can be proposed. Finally, sustainability capital and time needed to modify the system for each new system arrangement proposed should be estimated. The assessment process should then return to the system definition stage and repeat the assessment cycle described above for the expected transformed system conditions for a future time step whose length is based on the estimated time to reorganize the system.

Assessing Trade-offs and Changes in System Quality:

If using the framework for planning purposes, once the cycle has been conducted through at least two assessments of R for each hazard scenario and identification/development of adaptation/transformation strategies for each scenario, the adaptation and/or transformation strategies that are expected to result in the best overall improvements in system performance should be selected for actual implementation or further evaluation. In order to determine the strategies with the optimum effect on system performance, the trajectories of V, R, and S over the time period for which assessment cycles were completed should be examined in parallel. As analyses of V, R, and S will each entail examination of multiple variables, the creation of composite indicators that reduce each of these multidimensional concepts to a single value will assist with evaluation and optimization of V, R, and S trajectories. In the case of composite indicators for V and S which may be evaluated using dimensional variables with varying units of measure, these variables should be transformed into dimensionless standardized or normalized variables, prior to employing a variable aggregation scheme. For example, Cutter et al. (2003) employed principal components analysis, which standardizes and groups variables into factors, then aggregated factors scores using a linear additive combination. Other composite indicators have employed normalization of variables to system totals, z-score standardization, and min-max normalization to nondimensionalize variables, and used weighted and unweighted linear combinations, averages, and Pareto ranking schemes to combine these dimensionless variables (Tate, 2012). For V assessments, which are variable across the system for each time point being considered, the spatial distribution of the composite V indicator must be further aggregated for comparison with S and R, which are represented at the system level. The type of aggregation that is most appropriate will vary across systems, but example aggregation schemes could include taking the sum of all V composite indicator scores across the system, the median score, or the lower tenth percentile. In the case of aggregation of indicators for R, when R is evaluated as the estimated impacts of a hazard event in reference to thresholds to system performance (i.e., as a ratio), the variables should be dimensionless and the aggregation schemes employed for V and S may be used to reduce R to a single value.

In order to achieve equitably distributed and long-term improvements in system performance, the optimum balance between increases in R and S and decreases in V is needed. For example, a multiobjective optimization algorithm can help identify the amount of resources that will improve R and S while decreasing V. Although lacking, various modelling approaches can be developed or extended to achieve such balance; a few studies have aimed at optimizing for at least two of the three. Examples of such models include multiobjective mixed-integer linear programming to assess trade-offs between resilience, reliability, and vulnerability of water supply reservoir operation where the maximum shortfall affects vulnerability while maximum lengths of deficit affect the resilience of the system (Moy et al., 1986). Other examples include a resource allocation model that maximizes recovery while minimizing losses of the Deepwater Horizon oil spill (Mackenzie et al., 2016). Accounting for stakeholders preferences in achieving such balance is critical, especially when multiple infrastructure systems are involved. Optimization algorithms can be extended by adding a societal layer to systems performance to account for the preference of the decision maker and the community in the recovery of infrastructure systems (Bedoya et al., 2018). Other options include the incorporation of a multicriteria decision model where attributes are weighted according the decision makers' preferences (Peters et al., 2018). By referring to Figure 2, it can also be inferred that changes to the system that lead to increases in S will build adaptive capacity that may be utilized to develop further adaptation strategies.

Illustrative Walkthrough of the Framework

In this section, we outline how the framework may be applied to a social-environmental system, an urban community subject to flooding. While the framework can be used for more complete and interconnected systems, in order to provide a brief and illustrative example, this walkthrough focuses on a subset of the social-environmental system and a single hazard type. We discuss how the framework can be utilized to guide a set of analyses of this system, describe a set of analytical methods employed in these analyses, and present a subset of preliminary results from the analyses. In addition, we provide suggestions for methods and resources that may be used to extend this work by accounting for the many facets of the sustainable resilience assessment framework or by enhancing the practical utility of analytical results generated using the framework. The approach and analytical methods described are meant to demonstrate the guiding capability of the framework as opposed to providing an exhaustive or complete analysis.

System Definition (SD):

In this example, we examine an urban community that is threatened by extreme precipitation events which result in riverine and flash flooding. The city has experienced a large number of repetitive losses in urban housing near rivers and streams, and currently seeks to minimize future loss. In order to develop an understanding of the critical components and goals of the system, we consulted municipal planning documents for the community. As the planning documents were developed by the municipal government and were guided by significant community input, in the form of stakeholder engagement workshops, the planning document was assumed to represent the overall goals of the system. In addition, as the focus of the preliminary analyses was on flood hazards, guidance from the municipal water services department was solicited. The information obtained from these sources was used to develop a conceptual diagram of the system. The bounds of the primary system are defined by the boundary of the county in which the city is located, and a starting time of 2007 and time horizon of 75 years were selected. System performance measures chosen for consideration included economic losses due to building damage and emergency rescue requirements. The value of each performance measure was assumed to be equal to the threshold for system disruption given a known historic flood event.[2] A baseline sustainability assessment for the community indicated that the community had a moderate amount of readily available capital and a minimal amount of natural flood attenuation (in the form of green space buffering rivers and streams).[3]

Risk Identification (RI):

Within the past 10 years, the community experienced an extreme event in excess of the 1,000-year flood (measured as magnitude of precipitation over a 3-day, consecutive period). Catastrophic flooding resulted in over a billion dollars in private property damage and disruption of the local economy. An examination of potential changes in flood risk for the community based on variation in the frequency and severity of hazards due to changing climate was conducted using downscaled climate model projections and historic precipitation and river stage information.

To determine the extent to which local riverine flooding is linked to local daily precipitation, a lagged regression model (using the optimal lag period returned from a cross-correlation analysis) was conducted. The model produced an adjusted R-squared value of 0.88, and a correlation coefficient of 0.49 is obtained when using de-lagged data at river action stage and above with associated daily precipitation values. This suggests that local precipitation is significant not only to flash flooding, but also to riverine flooding in the area.

To assess the possibility of experiencing future precipitation events of similar or greater magnitude to the 1,000-year flood, analysis using local precipitation and river stage data with downscaled CMIP5 climate outputs for the worst-case scenario under RCP 8.5 (Taylor et al., 2012; Reclamation, 2014) was employed.[4] Analysis of precipitation anomalies using CMIP5 modelled outputs for the region was conducted in a manner consistent with current literature (Gao et al., 2017; Ryu & Hahoe, 2017). Linear interpolation using locally observed precipitation data and anomalies generated for CMIP5 observed data over the same period was employed to extrapolate the magnitude of rainfall events associated with anomalies for future periods as described by

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[2] Ideally, stakeholder engagement would be used to inform threshold selection for measures related to social and economic performance measures, while thresholds related to physical, environmental, and biological performance measures would be based on empirical and theoretical relationships established in literature.

[3] Note that ideally the sustainability assessment should account for social resources (such as community outreach and assistance centers) and should provide a more complete accounting of economic (including consideration of tappable debt lines and insurance policies) and environmental resources (such as water management structures and infrastructure) relevant to urban flooding.

[4] Full acknowledgment for CMIP5 models and references is located at Appendix H.

Gillespie-Marthaler et al. (2019b). Analysis results suggest that events of similar or greater magnitude to the 1,000-year flood are increasingly likely over the time horizon of interest with maximum projected events exceeding observed events by as much as 8% (Figure 5).

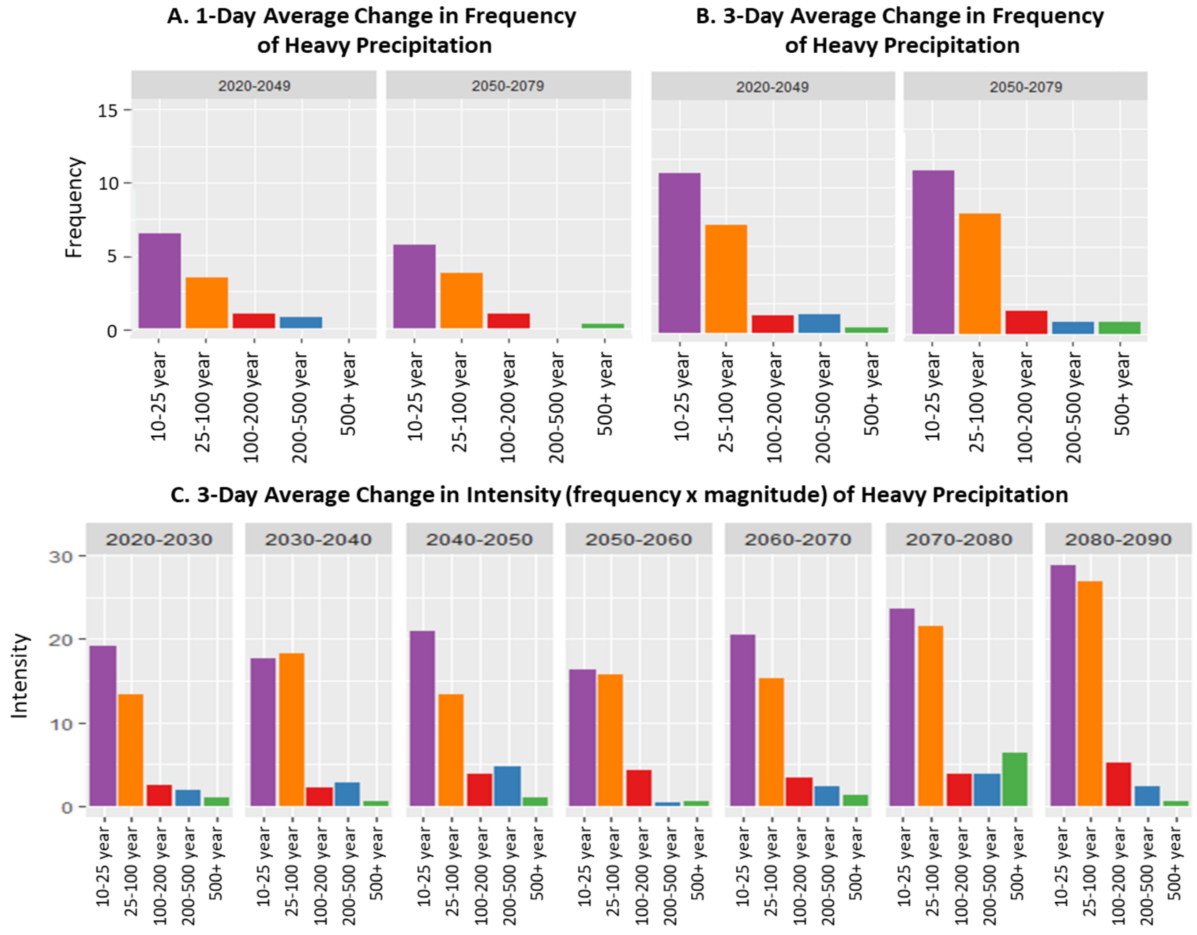

Figure 5. Analysis of Change in Frequency of Heavy Precipitation (modified from Gillespie-Marthaler et al., 2019)

This analysis suggests that more severe flooding is plausible within the community over the next few decades. The preliminary analyses described below uses the 1,000-year flood event as a base scenario with results suggesting that future climate conditions may exacerbate flooding conditions. [Note added after publication: The methods employed to develop worst-case scenarios for evaluating future sustainable resilience are not meant to predict or to represent the probability of extreme events, but to demonstrate the plausibility of such events in future planning horizons.]

Contextual Vulnerability Assessment (V):

System vulnerability was characterized using the primary physical assets (location of homes and other buildings) and neighborhoods as the units of analysis[5]. The exposure of physical assets was measured as flood depth and was determined by spatial intersection with inundation from the 1,000-year flood event. The sensitivity of assets was assumed to be a combination of the type of structure (e.g., mobile home, single family dwelling, apartment complex), resident population density, and neighborhood demographic characteristics. Anticipatory coping capacity was represented by the number of homeowners holding residential flood insurance. Spatial overlay of these factors suggested that localized areas of high vulnerability, where multiple negative characteristics, such as high inundation depth and high population density, overlap (Figure 6), were present throughout the system.

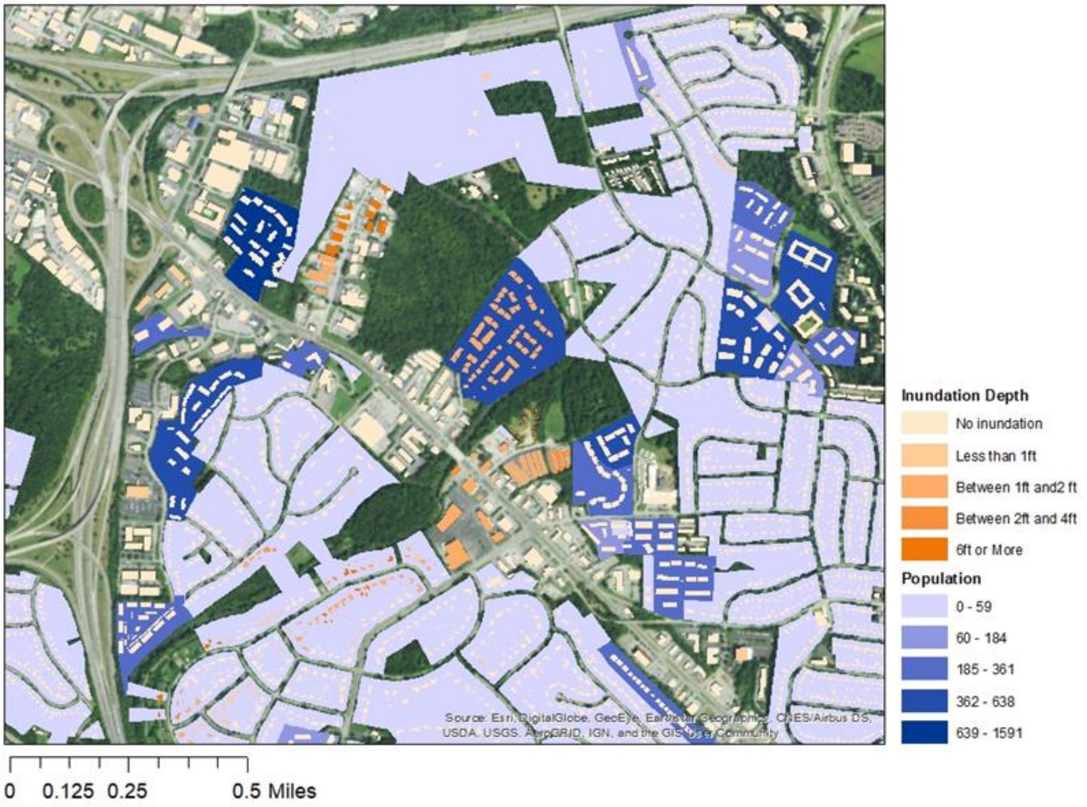

Figure 6. Spatial Distribution of Physical Exposure to Flooding and Resident Population (modified from Nelson, 2018)

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[5] Note that a complete sustainable resilience assessment should incorporate interdependent system assets such as energy and water infrastructure.

While not completed in the preliminary analyses, a composite indicator could be constructed using the vulnerability factors to represent the variation in overall vulnerability levels across the system. Common composite indicator construction methods include principal components analysis and linear additive combinations of normalized or standardized variables (Tate, 2012).

Assess Ability to Resist Systemic Disruption (R):

The impact to the system is estimated based on the relationship between the identified vulnerability factors and system performance measures. For example, in our preliminary analyses standard depth-damage algorithms employed in the hazard impact estimation software, HAZUS-MH, and data on building type, value, and inundation depth, are used to estimate economic building damages (FEMA, 2018). On the other hand, the emergency response requirements presented by a 1,000-year flood event are related to both the physical and social context of the system. In this case, existing information collected from the historic 1,000-year flood was used to conduct a regression analysis that relates both localized physical and social characteristics to emergency response. Results of a zero-inflated binomial logistic Bayesian spatial model indicated that emergency responses were more likely in areas with deeper flood inundation, higher renter populations, and with relatively high foreign-born populations. These model results provide information that can be applied to estimation of emergency responses requirements. For the starting year of 2007, the cumulative system-wide damage levels are expected to exceed the threshold for unacceptable system performance, implying that a system disruption would be considered to occur.[6]

Sustainability Assessment (S):

System impacts of the 1,000-year flood event scenario result in economic damages that require the use of available contingency funds, depleting the immediate economic capital of the system. Resources required for immediate recovery are significant, and consist of debris removal, repairs to roadways and structures, relocation of displaced individuals, and economic recovery for impacted businesses. In our preliminary analyses, the system-wide economic burden is estimated

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[6] Indirect impacts leading to cascading failures through other interdependent systems would ideally be considered to fully account for the cumulative impact of a systemic disruption.

as the difference between municipal government revenue and estimated building damages. The measure of environmental capital, natural flood attenuation, is not directly impacted by the flood event itself and hence remains unchanged. While the system is disrupted, it does not fail, and adaptation strategies, rather than transformation strategies, were developed.

Develop Adaptation Strategies (A):

The community affected by the floods has proposed and begun to implement a home buyout program as a way of reducing flood impacts and protecting residents. However, the benefits offered by this program and by potential expansion of the program are unknown. As a means of identifying the relative benefits of the program as it has been implemented and of further expansion, a set of alternative adaptation scenarios were proposed. These included a scenario in which no buyout program was implemented and one in which the buyout program was rapidly expanded by about 25%. The base scenario, the enacted buyout program, cost approximately $38M. The scenario with no buyouts would have no cost, while the expanded buyout program was estimated to cost a total of $50M. In cases where adaptation strategies are unknown, it is recommended that stakeholder participation be used to identify a set of potential adaptation scenarios.

Adapted System (AS):

For all scenarios, the assessment cycle was repeated for V and R given the same starting year of 2007 and at annual intervals for a period of 6 years. As the likelihood and magnitude of a 1,000-year flood event during this timeframe does not significantly change, the same risk scenario was used for all time steps (i.e., RI remained constant). In order to build the contextual data for assessments of the adaptation scenarios, spatial analysis was used to simulate removal (or lack of removal) of residential buildings through the buyout program. Bayesian spatiotemporal modelling was employed to evaluate the potential impact of increasing natural flood attenuation, a side-effect of the home-buyout program scenarios, on flood inundation depth using data from the historic

1,000-year flood event. Depth to damage curves were used to estimate building damages given the 1,000-year flood event.[7]

Values of system performance measures, vulnerability factors, and sustainability capital were plotted for each time point and adaptation scenario in order to provide an understanding of the near-term trajectories of V, R, and S. Figure 7 displays trajectories for the number of physically vulnerable assets and community residents computed for the various adaptation scenarios, suggesting that total physical vulnerability of assets will be reduced under the home-buyout program scenarios as long as development restrictions are not loosened and no new homes are added to the at-risk areas.

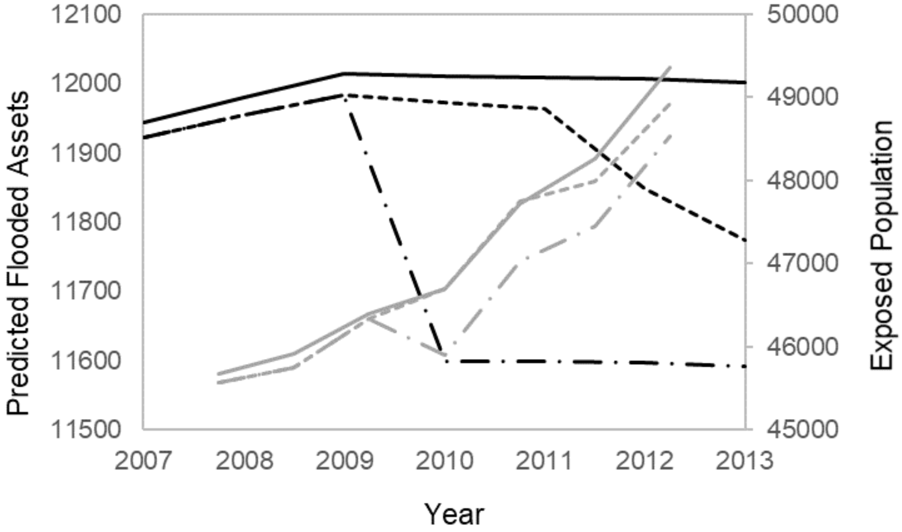

Figure 7. Trajectories for Damaged Property and Exposed Population (modified from Nelson, 2018) [Black lines correspond to flooded assets and grey lines to exposed population. Solid lines refer to a scenario with no home buyouts, dashed lines refer to a scenario with buyouts completed by the community, and dot-dash lines refer to a scenario with a rapidly expanded home buyout program.]

Figure 7 also indicates that the home-buyout program adaptations will reduce the relative physical vulnerability of community residents. However, it is clear that long as urbanization and densification continue to occur near riparian areas, the total vulnerable population will continue to

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[7] While not yet completed, we plan to utilize the previously established relationships between physical and social characteristics of the system and emergency responses using historic data to estimate emergency response requirements for the adaptation scenarios.

increase over time. The trajectories for property damage displayed in Figure 8 indicate that the economic building damages measure of system performance will be improved under the proposed home-buyout adaptation scenarios, yet also indicates that this particular system performance measure is strongly linked to local and national economic trends (Nelson, 2018).

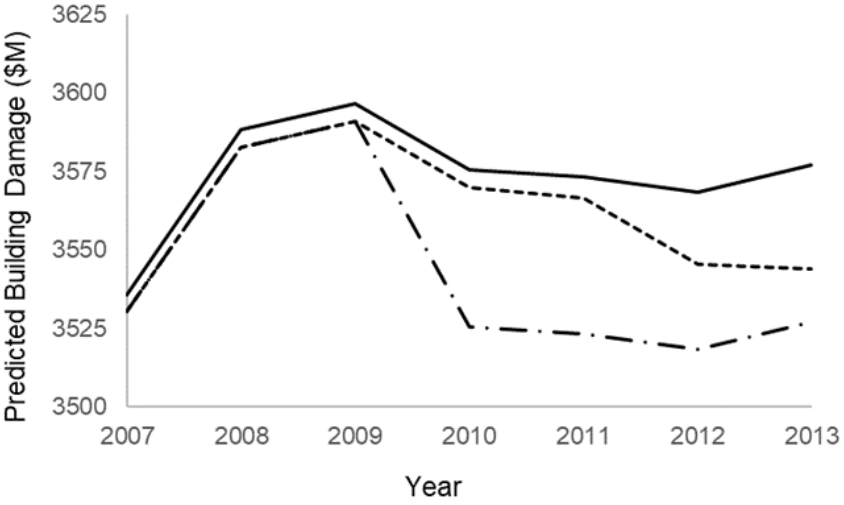


Figure 8. Trajectories for Building Damages (modified from Nelson, 2018) [The solid line refers to a scenario with no home buyouts, the dashed line refers to a scenario with buyouts completed by the community, and the dot-dash line refers to a scenario with a rapidly expanded home buyout program.]

The trajectory for natural flood attenuation as shown in Figure 9 suggests that the home-buyout program adaptation scenarios slightly increase the environmental capital of the system by expanding riparian buffer zones.

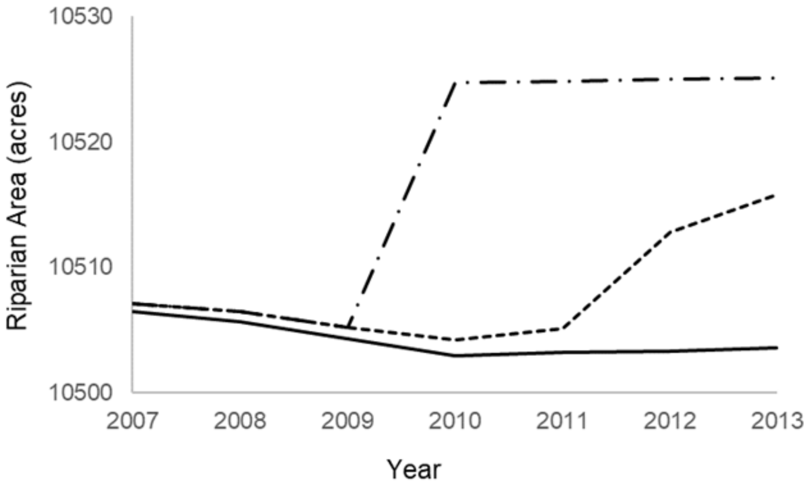


Figure 9. Trajectories for Riparian Area (modified from Nelson, 2018) [The solid line refers to a scenario with no home buyouts, the dashed line refers to a scenario with buyouts completed by the community, and the dot-dash line refers to a scenario with a rapidly expanded home buyout program.]

While the preliminary analyses described here were conducted for a short time period, more long-term outcomes could be estimated by conducting a suite of analyses integrating additional flood severity and urban development models with precipitation projections.

Assessing Trade-offs and Changes in System Quality:

Comparison of the trajectories for V, R, and S (Figures 7-9) illustrates the potential for the proposed adaptation scenarios to reduce economic losses, physical vulnerability to flooding, and increase natural flood attenuation capacity relative to a baseline, no action scenario. However, the trajectories also suggest that while the adaptations proposed may improve the relative system quality, they are not sufficient to address absolute system quality, which is strongly influenced by increasing population and development trends in the community. These population growth and associated increased development and increasing property value trends intersect with the flooding scenario in such a way that regardless of the proposed adaptation strategies, overall vulnerability will continue to increase and resilience decrease in the community. In addition, while local natural flood attenuation capacity is increased by the buyout program, the continued rapid conversion of green spaces to impervious cover in the urban core is expected to increase stormwater runoff, offsetting the produced benefits of increasing riparian buffer areas and reducing the overall sustainability of the system over time.

Discussion

Given the significant linkages and interactions between the concepts of vulnerability, resilience, sustainability, and adaptive capacity, we conclude that a unifying framework is needed to properly characterize complex adaptive social-environmental systems and assess their behavior in response to short-term disruptions and long-term challenges in the context of decision-making. We suggest that when these concepts are considered in an integrated framework, sustainable resilience becomes a universally positive system quality, as unit-of-analysis based inequities and long-term resource availability are both taken into account, and adaptation and transformation strategies are developed within the bounds of pre-defined desired system performance end-states. Within such a framework, a system that is persistent and strongly resists change is not necessarily considered to be resilient. In order to be resilient, the system must also meet stakeholder performance and value expectations, and maintain adequate resource pools to sustain the system for future generations.

The sustainable resilience assessment process proposed encourages consideration of multi-scalar and dynamic processes by strategically and iteratively considering micro-scale vulnerabilities, meso-scale risks, and macro-scale sustainability. The serial nature of the assessment framework enables both simplified operationalization, allowing both researchers and practitioners the flexibility to utilize relatively familiar assessment methodologies, and also provides a simplified path diagram to help explore relationships between concepts. The use of a cyclical and dynamic process ensures that decision makers understand how each concept may influence the other, therefore allowing for integration and balancing of priorities from different perspectives and a more effective allocation of resources. The cyclical process also allows for cumulative impacts over time to be assessed and brought to bear in adaptation/transformation decision-making processes in order to improve overall ability to:

- Identify/anticipate significant changes in availability of sustainability capital over time;
- More effectively use sustainability capital to reduce critical sub-system vulnerability and improve resilience outcomes through successive monitoring and evaluation of adaptation strategies; and

- Identify/anticipate system when and where transformation may be needed.

The proposed framework is not prescriptive in terms of how to conduct individual steps in the assessment process, allowing the flexibility to use existing or adapted methods and tools within the structure of the framework. It is also flexible with regard to level of complexity and scale, giving stakeholders and decision makers the ability to navigate through fundamental concepts of system behavior while developing concrete strategies to improve the ability of the system to resist, cope, adapt, and/or transform, with the end goal of improving overall system performance and achieving sustainable resilience. The development of the sustainable resilience assessment framework represents a step forward in terms of enabling integrative assessment for complex adaptive systems. However, further advances are needed before practical application of the framework can be made a reality. In order to further translate the sustainable resilience assessment framework into practice, an effort is underway to classify and map indicators and associated metrics (quantitative and qualitative) to the framework. Further work should also explore application of the framework for different purposes (post-hoc analysis, planning process), to different types of systems, at different levels of complexity, and using different methodologies.

CHAPTER IV

Selecting Indicators for Assessing Community Sustainable Resilience

Introduction

With a diverse and rapidly growing body of literature related to community resilience assessment, researchers and practitioners alike are seeking information on what should be measured in order to evaluate resilience, and how measurement (through use of indicators and metrics) can be achieved. This poses the following challenges: i) a vast and growing number of proposed indicators; ii) redundancy within and across indicators in terms of what to measure and how to measure it; and iii) inconsistency in the systems of interest (e.g., some focus largely on one aspect of community resilience such as social systems as opposed to other aspects such as economic or environmental systems). These challenges generate confusion regarding what should be included in a community assessment; how to ensure a balanced assessment across systems and sub-systems that make up a community; and which indicators and metrics are most appropriate for selection based on community characteristics and needs.

Recognizing the need for consolidation of indicators (and metrics) within a consistent structure that facilitates identification and selection for use in assessment processes, we have developed a classification scheme and organizational structure to support the budding concept of sustainable resilience (Gillespie-Marthaler et al., 2018; Nelson et al., 2019). Sustainable resilience is defined as the ability to maintain desired system performance while simultaneously considering intra-system and inter-generational distribution of impacts (resulting from vulnerability) and sustainability capital (availability of critical social, economic, and environmental resources). This paper reviews current indicator-based community resilience assessment literature from which a set of non-duplicative indicators and associated metrics are identified. To facilitate selection from among these indicators for community sustainable resilience assessments, a classification scheme and organizational structure is developed based on consideration of capital systems, sustainable resilience domains, and assessment phases.

The result is a set of indicators and metrics for community sustainable resilience assessment, and a classification system that aids in operationalization of indicator-based resilience assessment processes, including the new framework for sustainable resilience. These indicators and metrics are accessible through Appendix C (https://blindreview1.shinyapps.io/indicators/).

The remainder of the paper is organized as follows, the background is provided in Section 2 with a detailed literature review in Section 3, Section 4 describes the review and classification methods, and the proposed final set of sustainable resilience indicators is discussed in Section 5.

Background

Resilience – An Evolving Concept

Resilience is an evolving concept, continuing to grow in both theory and application since its original use in ecological sciences to describe a system's ability to, "absorb changes of state variables, driving variables, and parameters, and still persist," (Holling, 1973). The need to better understand and evaluate complex system performance in the presence of risk and the consequences of hazards or disruptive events (natural or manmade) has contributed to a diverse body of literature that includes the fields of engineering, social science, psychology, economics, disaster mitigation, and urban planning (Hosseini et al., 2016; Koliou et al., 2018). Resilience is often applied as an assessment framework in the presence of disturbance (typically identified through a form of risk assessment), where emphasis is placed on system response and recovery processes for infrastructure systems and communities (Tierney & Bruneau, 2007; Baroud et al., 2014; Lam et al., 2015; Linkov et al., 2018). Resilience in relation to systemic risk, where system adaptation and/or transformation are required to achieve acceptable performance, is an increasingly relevant body for both research and management (Florin & Nursimulu, 2018; Mochizuki et al, 2018). The concept of resilience is also applied as a process-based framework that includes planning, preparation, monitoring, and learning to respond to change in order to achieve desired long-term goals (Sharifi & Yamagata, 2014; Desouza & Flanery, 2013; Frazier et al., 2014; Cutter et al., 2014; Arup and The Rockefeller Foundation, 2014; UNISDR, 2017). The role of resilience in planning and preparing for the well-being of communities under emerging risks such as changes in extreme climate hazard is rapidly expanding as researchers and practitioners seek solutions to protect complex systems (Trump et al, 2017; Mochizuki et al, 2018).

Within resilience assessment research and practitioner communities, greater focus is currently placed on operationalizing resilience (Cutter, 2016a; Johansen et al., 2016; NAS, 2017). The term "operationalize" refers to the ability of communities to conduct resilience assessment in a practical, meaningful, and consistent manner. Authors are now beginning to take stock of the growing body of literature on community resilience assessment, and are identifying issues that present a challenge to building a body of common practice. Of note, lack of consistency in applied resilience assessment resulting from an overabundance of interpretations and methods for measurement appears to be inhibiting evaluation of the effectiveness of resilience as a guiding concept for communities (Cutter, 2016a; Sharifi, 2016; Meerow, 2016).

Key components needed to make resilience assessment more accessible and meaningful to communities lie in efforts focused on creating greater consistency in defining and identifying what to measure (Cutter et al., 2014; Sharifi, 2016; Cutter, 2016b; Johansen et al., 2016), as well as efforts to better integrate social and physical system impacts, and develop improved methods for measuring them within a community setting (Koliou et al., 2018; Chuang et al., 2018). While these issues are inherently linked to the context of the system for which a resilience assessment is being performed, there are similarities across systems with the same general structure that require a consistent approach to identification and facilitation of indicator selection. The work in this paper addresses these issues and offers an improved method for structuring and selecting indicators and metrics for sustainable resilience assessment within community systems.

Sustainable Resilience – A Recently Developed Concept

Sustainable resilience has recently emerged as a concept and assessment framework that allows for the evaluation of baseline and subsequent changes in both sustainability capital and vulnerability over time, as well as interactions resulting from implementation of (or failure to implement) management strategies intended to improve system resilience. It represents a system that seeks to reduce damage and loss over time by strategically monitoring and managing both vulnerability and sustainability to achieve desired performance outcomes. As such, a community strives to achieve desired levels of performance through strategic and balanced management of critical social, economic, and environmental resources and systems that support its capacity to overcome adverse impacts. Inherent to the achievement of sustainable resilience is the requisite need to measure, monitor, and manage the distribution of impacts across community system(s), as well as the distribution of resources over time in order to effectively anticipate, prepare for, respond to, and recover from future threats.

An illustration of the assessment framework is provided in Figure 10. In this framework, the baseline/pre-event assessment phase of the system is presumed to describe the current, contextual availability of critical resources and ability of a community to absorb shocks and stress that directly affect system outcomes (preparation, planning, mitigation, and adaptation already undertaken are accounted for here). The extent of harm experienced can affect the state of resources (access, quality, and quantity) available to the community that can be applied to future efforts such as recovery, planning, preparation, adaptation, and system maintenance by depleting economic resources, impairing physical infrastructure and ecosystems, and/or harming the populace of the system. The ability of a community to utilize remaining resources to implement recovery and desired change (e.g., adaptation when sufficient sustainability capital is available, or transformation when the system can no longer maintain desired performance given available capital) then affects future context and thus, future/post-event assessment phase(s) of the system.

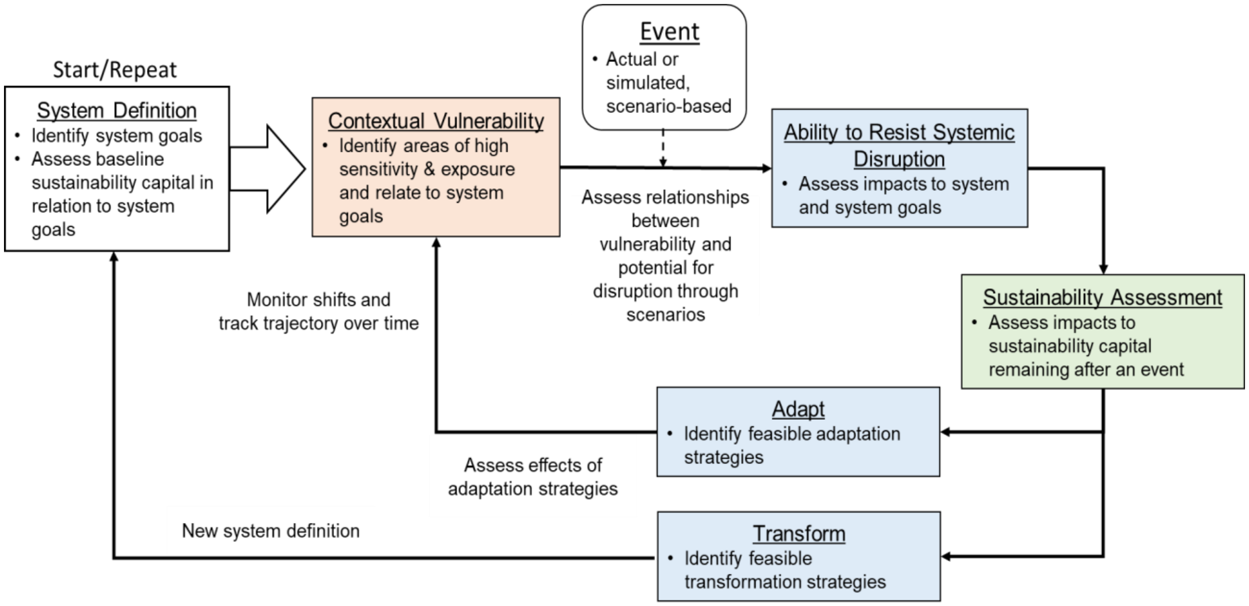


Figure 10: Illustration of the assessment framework for sustainable resilience (modified from Nelson et al., 2019)

While the framework for sustainable resilience does not attempt to directly measure adaptive capacity, the ability to adapt, prepare for and respond to disturbance (Berkes et al., 2003; Adger et al. 2004; Adger & Vincent, 2005; Adger, 2006; Engle, 2011), the concept is indirectly evaluated as the outcome of adaptation strategies and their impacts upon system contextual vulnerability, the ability to resist systemic disruption, and sustainability capital (Folke et al., 2002; Folke et al., 2003). The framework for sustainable resilience implies that understanding how resilience may be assessed at a point in time, and how it may change over time, depends on the ability to evaluate various states of vulnerability and sustainability capital as they relate to outcomes resulting from exposure to hazards. The ability of a system to implement change (via adaptive capacity, which may be seen to include any form of positive change intended to reduce vulnerability, including mitigation) is the mechanism by which sustainable resilience is achieved. Measurement or assessment of sustainable resilience requires the ability to link changes in system resources and drivers to possible outcomes affecting adaptive capacity (discussed in greater detail in subsequent sections).

Review of Indicators and Metrics in Community Sustainable Resilience Assessment

Communities & Use of Indicators for Assessment

Communities can be characterized as socio-environmental/technical systems composed of networks that are themselves both socio-environmental (people and natural/built environment) and socio-technical (people and technology) (Ernstson et al., 2010). In more general terms, a community consists of groups of individuals and necessary life-support systems (land, air, water, energy, critical services, infrastructure, commerce, among others) living within a place-based entity that is often defined by boundaries, and that share common interests, or common fates linked by collective actions (Wilkinson, 1991; Norris et al., 2008).

Communities must also be considered across varying spatial and temporal scales that can be difficult to distinguish due to multiple boundaries (physical and non-physical), system interactions (cross-scalar impacts, cascading effects, feedbacks), and consideration of potential tradeoffs over time across subsystems and networks (Alberti et al., 2003; Desouza & Flanery, 2013; Elmqvist et al., 2014). While there is similarity across the structural aspects of a community, its ability to achieve survival, well-being, and long-term viability is uniquely constrained by the available resources and the ability of the community to use them effectively to achieve desired outcomes (Norris et al., 2008, Turner, 2010). These disparities result in variations in vulnerability and distribution of harmful impacts across communities (Adger, 2006; Cutter 2003; Eakin & Luers, 2006; Cutter, 2016a). Different populations face different challenges in increasing adaptive capacity and achieving resilience within the same community, creating an uneven landscape and challenging format for assessment, planning, and successful outcomes.

Improving resilience and sustainability for communities is most meaningful when applied to populations within a community that are most vulnerable (e.g., the idea of increasing adaptive capacity and the ability to effect positive change for those who need it most). This is in keeping with the view that the poorest and most vulnerable populations within communities are the weakest links in achieving disaster preparedness and resilience (Godschalk, 2003; Godschalk et al. 2009; Berardi et al. 2011). Regardless of how a community may be defined, they all share a common attribute of their exposure to a variety of hazards, which can result in significant disruption to critical functions, threatening survival, well-being and sustainable resilience. It is therefore critical to understand how community resilience may be measured in order to track trends, monitor progress, and identify problem areas well in advance of potential disruption.

Indicators for measuring aspects of vulnerability, sustainability, and resilience within communities are abundant. Indicators are often used to refer to a measurable variable that is related to a theoretical (unobservable) variable, and are necessary to reduce the amount of data needed to describe a process and communicate effectively to diverse audiences (Kierstead & Leach, 2008). We define an "indicator" as a characteristic that is expected to have a simple and direct effect on resilience, while reserving the term "metric" for observable and measurable variables that are related to resilience indicators. For instance, community health may be identified as an indicator of resilience as it is expected to directly influence the ability of the community to withstand and recover from hazards. As community health is not directly measurable, it may be assessed based on a collection of metrics that can be directly evaluated and combined to characterize aspects of a community's health (e.g., reported infectious and chronic health issues, average life expectancy, among others). Metrics used to assess other types of system resilience, such as water infrastructure systems, can also be used to characterize aspects of community health and well-being.

Metrics can be assessed using qualitative (rating scales, categorical, among others) or quantitative methods (direct measurement, spatial analysis, modeling, among others), to provide information on the state of an indicator. While indicator-based assessments are crucial to establishing baselines and future scenarios for communities to enable decision-making, planning, and management, their effective use is dependent upon identification, selection, and application of useful and meaningful indicators and metrics (Parris and Kates, 2003). Some argue that the inability to achieve desired outcomes is directly related to poor selection of indicators, and that confusion regarding the multitude of indicators from various sets of indicators poses an obstacle to effective assessment and use of results to achieve goals (Briassoulis, 2001; Shen et al., 2011).
Review of community-based resilience assessment indicators and metrics reveals an abundance of indicators, rendering identification and selection of appropriate measures a difficult and likely

confusing task for researchers and practitioners (Sharifi, 2016; Cutter, 2016c; Koliou et al., 2018). This work builds upon current literature (Johansen et al., 2016) to offer a non-duplicative set of community resilience indicators with associated quantitative and qualitative metrics that can be used by any community type. As vulnerability and sustainability have an interdependent relationship with resilience (Gillespie-Marthaler et al., 2018), discussion on indicators representing all three concepts and their intersection with community assessment is provided below.

Community Vulnerability Indicators

Community vulnerability indicators reflect relationships between people and resources such as wealth, availability and access to key infrastructure, and services needed to protect populations from harm (Cutter, 1996; Cutter, et al., 2003; Chakraborty, 2005; Rygel, et al., 2006; Wilhelmi & Morss, 2013; DHS, 2016). Issues of equity, agency, and justice are also included in these indicators, but can be challenging to capture and consistently employ (Doorn, 2017). Age, gender, income, race/ethnicity, and skill level are often used in social vulnerability indicators, which typically rely on census data for consistency and standardization (Azar & Rain, 2007; Cutter, et al., 2003; Rygel, et al., 2006; Cutter, 2016a). Within census data, there are a large number of measured items from which to choose when constructing an indicator. Consistently available and standardized data are generally easier to obtain at larger scales (national, state, etc.) and more difficult to obtain as scale decreases to local communities (Mayer, 2008). The number and type of selected metrics can vary widely based on the type of assessment conducted and perspective on what can or should be measured, with concern cited by researchers regarding the need for more explicit relation between indicator selection and the impacts of vulnerability upon society (Chakraborty, 2005; Cutter, et al., 2003; Fekete, 2012; Krishnamurthy & Krishnamurthy, 2011; Rygel, et al., 2006; Eriksen & Kelly, 2007; Shepard et al., 2012). In some studies, the same indicator is used more than once to measure different aspects associated with vulnerability and its components (exposure, sensitivity, adaptive capacity) (Frazier et al., 2014), in part due to the difficulty in obtaining appropriate independent measures (Hinkel, 2011; Engle, 2011; Fekete, 2009; Dominey-Howes, 2007).

Community Sustainability Indicators

Sustainability indicators are used to evaluate impacts and intersections between human society and the natural and physical systems that society depends upon, and as such tend to follow the concept of sustainable development established by the Brundtland Report (WCED, 1987; Beatley & Newman, 2013). In particular, sustainability seeks to understand the long-term impacts caused by use, overuse, and degradation of critical resources and the resulting impacts to human society (Berkes & Folke, 1998; Kates et al., 2001; Marcotullio, 2001; Fiksel, 2006; Dietz & Neumayer, 2007). These are often complex relationships between nested systems (humans and watersheds, habitats, ecosystems, etc.) that can span multiple boundaries and generations (Bithas & Christofakis, 2006), and can be challenging to define and measure.

Recent compilations of community sustainability indicators exist within literature (Shen et al., 2011; Lynch et al., 2011; Wang et al., 2013; Hiremath et al., 2013). Reviews note several challenges in the focus, construction, and validation of indicator sets. Mori & Yamashita (2015) claim that many appear as though authors are simply making lists of social, economic, and environmental factors to cover as many aspects as possible, rather than focusing on means of assessment and basis for absolute or relative comparison of sustainability within and across communities. Challenges associated with subjectivity in selection, complexity in measuring interactions between systems, lack of empirical data, and difficulty with real and implied system boundaries are consistently cited in reviews (Shen et al., 2011; Mori & Christodoulou, 2012; Hiremath et al., 2013; Mori & Yamashita, 2015). Indicators often characterize capital sources (e.g., air, water, energy, land, ecosystems, etc.), the impacts of human development on sources (e.g., levels of quality or degradation via pollution or overuse), and resulting impacts to society (human health, prosperity, and equity), thereby indicating an overall capacity to adequately support current and future growth (Romero-Lankao et al., 2016). Community sustainability indicators are particularly challenged by the difficulty in establishing meaningful ranges of performance and thresholds for constrained processes (e.g., physical limits on natural and built systems, and limits on social and economic equity) without which basis for assessment or comparison is made less meaningful (Berkes & Folke, 1998; Mori & Christodoulou, 2012; Hiremath et al., 2013; Mori & Yamashita, 2015). It can be difficult to set thresholds, especially in light of different levels of acceptable scale for social norms that differ from one place to another, and across temporal scales (Graymore et al., 2009).

Community Resilience Indicators

Reviews of indicators for community resilience have been conducted in recent literature (Lu & Stead, 2013; Larkin et al., 2015; Hosseini et al., 2016; Sharifi, 2016; Cutter, 2016c; Johansen et al., 2016; Asadzadeh et al., 2017; Koliou et al., 2018), revealing an abundance of proposed indicators (Sharifi, 2016; Cutter, 2016c). Resilience indicators are focused on enabling communities to assess how well they are able to prepare for, respond to, and recover from disaster (natural or manmade), and as such, should include the concepts of risk, vulnerability, sustainability, and adaptive capacity (Gillespie-Marthaler et al., 2018, Nelson et al., 2018). However, many indicator sets are poorly balanced in terms of representing critical facets and distribution of social, economic, and environmental capital needed to maintain a community. Reviews are consistent in noting lack of representation of indicators related to natural systems with greater emphasis being placed on built systems or social systems (Sharifi, 2016), as well as weak integration of physical, social, and economic indicators and metrics (Koliou et al., 2018). Community resilience assessments use similar approaches for identification and selection of indicators to those described above for vulnerability and sustainability (Mayunga, 2007; Sherrieb et al., 2010; Sherrieb et al., 2012; Burton, 2012; Keck & Sakdapolrak, 2013). Hence, they are subject to many of the same issues with regards to potential for mischaracterization as well as lack of verification and benchmarking.

Current Challenges

Aside from challenges mentioned above regarding lack of data at multiple scales and a shortage of validation, verification, and benchmarking processes, challenges are posed by the lack of balanced representation across social, economic, and environmental systems within communities (Sharifi, 2016; Cai et al., 2018). Lack of representation and balance may indicate limited system understanding and the potential for poor or incomplete assessment results, depending upon the context and intent of assessment. In order to create a balanced set of indicators representing social, economic, and environmental (built and natural systems), it is necessary to consolidate indicators and metrics from various bodies of literature and sources. Many community resilience indicator sets appear sparse regarding inclusion of the natural environment, focusing on tree density and impervious surface, and neglecting more complex aspects of community health. In a recent review of disaster resilience measures by Cai et al. (2018), environmental and ecological indicators other than land use were found to be applied in six out of 174 reviewed articles. Despite growing awareness of long-term resilience and its linkages to the quality and maintenance of natural resources (ecosystem services that provide essential lifeline support and protection mechanisms such as water quality, flood control, green spaces, biodiversity, etc.), more effort is needed to include indicators that help decision-makers relate natural resources to corollary social, economic, and built infrastructure in order to achieve multiple benefits across systems (Milman & Short, 2008; Srinivasan et al., 2012; Ahern, 2013; Collier et al., 2013; Upadhyaya et al., 2014; Koliou et al., 2018).

Climate change, a component of the environment, is a significant factor that is often lacking in current community resilience indicator sets. It can affect both acute and chronic community stress (flood, drought, storm, among others), and disturbances related to climate are typically accompanied by other types of stress within and across social, economic, and environmental sub-systems (Coaffee, 2008; Leichenko, 2011; Collier et al., 2013; Hallegatte et al., 2013). However, it is necessary to go to sector or site-specific publications (e.g., UK indicators, coastal community indicators, and U.N. indicators) to find a robust selection of science-based climate change measures (for e.g., changes in salinity, pH, temperature, sea level, subsidence, and greenhouse gas emissions) to apply to community resilience assessment (Shaw, 2009; Sempier et al., 2010; Ranger & Surminski, 2013; Orencio & Fujii, 2013; UNISDR, 2017).

Greater attention is also needed in considering indicators within the economic capital system that represent capacity associated with use of immediate resources (local) and potentially available resources (regional) to respond and recover from hazards (Rose, 2011). Business recovery is an essential part of community resilience, which is often overlooked in existing indicator sets (Rose & Krausmann, 2013). Like climate change, it is necessary to utilize sector-specific publications to identify adequate indicators and metrics for use in assessing community resilience (Briguglio et al., 2009; Kern, 2010; U.N., 2015; UNISDR, 2017; Ranger & Surminski, 2013). Rose & Krausmann (2013) find many of the components of existing resilience indicator sets to be unimportant to the resilience of community businesses and economies due to a lack of focus on businesses especially during recovery. Integration of meaningful indicators and metrics requires incorporation of microeconomic (individual businesses), mesoeconomic (markets & industries), and macroeconomic (all economic entities and networks) perspectives, and the facets of preparation & response (business continuity planning), and recovery (financial mechanisms, assistance, and flexible supply chains) to speed return to normal operation (Briguglio & Galea, 2003; Rose & Krausmann, 2013).

Communities face a daunting task in terms of prioritizing allocation of sustainability capital to meet both current and future challenges. There are no universally accepted sets of indicators used by any single assessment concept (vulnerability, sustainability, or resilience), much less an integrated assessment concept for communities to reference (Parris & Kates, 2003; Romero & Lankao et al., 2016). Rationale for development of a universal set of indicators from a sustainability perspective that are easily translated to vulnerability and resilience includes i) ambiguity in concepts, ii) plurality of purpose in application of concepts, and iii) confusion regarding key terms, relationships, data, and means of measurement (Parris & Kates, 2003).

This rationale is echoed by recent work from the National Academy of Sciences, which finds that despite continued development of assessment approaches and indicators for resilience, many communities have not engaged in assessment as a common planning tool, largely due to difficulty in understanding how to apply existing approaches (i.e., where to start, what to measure, and how to measure it) (NAS, 2017). Implications for assessment of possible future scenarios and different courses of action to achieve desired outcomes for communities must therefore be informed by: i) greater understanding of conceptual linkages between vulnerability, resilience, and sustainability, ii) improved assessment methods that reflect those linkages, and iii) greater ability to select and appropriately apply indicators and metrics for assessment. To address the third point, we compiled indicators from a review of the literature on indicator-based community resilience assessment, including economic, disaster, and climate resilience assessment. Each type of assessment includes many indicators that can fall into vulnerability, sustainability, and resilience categories. We consolidate the identified indicators from each source and provide a classification structure to aid in selection of indicators for community sustainable resilience assessment (per Section 2.2). The remainder of this manuscript describes the review, consolidation, and classification process, and discusses the findings and their implications for operationalizing indicator-based community resilience assessment, with focus on sustainable resilience assessment.

Indicator Review and Classification Methods

Review Method

This study focused on peer-reviewed publications and practitioner reports on indicator-based assessment of community resilience based on the concept of sustainable resilience (*Sustainable Resilience – A Recently Developed Concept*) as applied to communities (*Communities & Use of Indicators for Assessment*). A literature search was conducted in December, 2017 (with an additional search conducted in July, 2018 to include new publications). The initial search results were generated by using the search terms in Table 4 (as a single search string, where commas are equivalent to the operator AND) within the Vanderbilt University Library Catalog search engine. The search was limited to documents within the subject areas listed in Table 4 and drew from multiple databases (Table 5). No restrictions were placed on publication year, but only English language publications with available full-text were included. The database search initially provided 712 results (including duplication). Search terms and subject areas are displayed in Table 4.

Search Terms	Subjects Areas
Indicators, Metrics, Community Resilience, Economic Resilience, Climate Change Resilience, Disaster Resilience, Assess, Measure, Define, Identify	Social Sciences, Earth Sciences, Climate Change, Health and Environmental Sciences, Resilience, Geography, Sustainability, Applied Sciences, Vulnerability, Environmental Management, Urban Planning, Vulnerability, Civil Engineering, Adaptation, Management, Biological Sciences, Public Policy, Public Health, Adaptation, Education, Economics, Environmental Studies, Engineering, Sustainable Development

Table 4. Search Terms & Subject Areas

Titles and authors of the identified documents were reviewed to remove duplicates. Abstracts were then reviewed to provide initial screening for applicability associated with the following criteria: i) the term “community” is consistent with section 3.1, rather than focusing on an individual subsystem; ii) the term “resilience” addresses multiple risks across community systems rather than focusing on a single risk or single subsystem; iii) the term “assessment” is used to measure resilience rather than focus on conceptual evaluation or analysis; and iv) individual indicators are identified and defined. Removal of duplicates and abstract review yielded 205 distinct documents for further review. Journal titles for the 205 documents are provided at

Appendix C. Google Scholar was then used to conduct a directed search for additional material not appearing in research databases including articles and reports referenced in the sources found in the database search and known foundation (e.g. Rockefeller Foundation) and government agency (e.g. Department of Homeland Security) reports. The directed search using Google Scholar provided an additional 66 documents for a total of 271 documents selected for full text review. Results are shown in Table 5.

Search Results (Sources)	No.
ABI/INFORM Complete	129
Annual Reviews	4
Directory of Open Access Journals (DOAJ)	10
JSTOR Archival	3
MEDLINE/PubMED (NLM)	21
OECD iLibrary	3
OneFile (GALE)	105
Palgrave Connect	9
PMC (PubMed Central)	12
SAGE Knowledge	7
Science Citation Index Expanded (WoS)	87
ScienceDirect Journals (Elsevier)	55
Social Science Premium Collection	95
Springer CrossRef	35
SpringerLink	41
SpringerLink (CrossRef)	35
SpringerLink Book Series	24
SpringerLink Open Access	10
SpringerLink Open Access	10
Taylor & Francis - Online Journals	11
World Bank eLibrary	6
Initial Total (with duplication)	712
Total (after title & abstract review)	205
Google Scholar Directed Search Results	66
Total (full text review)	271

Table 5. Search Results

The full text of each of the 271 remaining documents was examined and scanned for tables, lists, and explicit definition/identification of specific indicators. Remaining documents that identified indicators, yet provided no explanation (rationale for use) of the indicators within a community setting, were also dropped from further consideration to ensure that only theoretically and conceptually justified indicators were included. As a result, an additional 89 documents were dropped from further consideration. Of the remaining 182 documents (breakdown provided at Appendix D, https://blindreview1.shinyapps.io/search/) meeting specified criteria, a total of 91 unique references are used in the determination of indicators for community sustainable resilience (Appendix C, https://blindreview1.shinyapps.io/indicators/).

Each explicitly identified indicator within the final set of documents was added to a review table that included the following information: indicator name, indicator description, associated metrics (where available), and source/publication of the indicator. The subset of documents produced over 1,089 identified indicators (including duplication where an individual indicator may appear in more than one document) for community resilience, many of which included an explanation for both indicators and metrics (quantitative or qualitative measures). A complete list of the sources for retained indicators and metrics is provided in Appendices C and E.

While the methods employed to identify and collect literature for the review are similar to those used by Parsons et al. (2016), Cutter (2016), Sharifi (2016), and Asadzadeh et al. (2017), they go beyond the concepts of disaster resilience to encompass a broader set of resources that include a more robust selection of indicators for natural systems, climate change, and economic resilience that is consistent with the concept of sustainable resilience. Recognizing that the number of indicators identified is too extensive to be very helpful, the results were organized into a classification structure which is related to the sustainable resilience assessment framework (Nelson et al., 2019), and consolidated to help users understand how indicators may be applied within the aforementioned framework.

Classification by Primary and Secondary Capital Systems

The first step in classification of the indicator set was to organize the indicators by capital systems. Communities include social and bio-physical sub-systems which are generally considered as separate, but related, components of the community for methodological reasons (Hinkel, 2011). The literature universally recognizes these two sub-systems and often uses a more detailed categorization. Examples of variation in organization can be seen across the literature, depending on the nature and focus of assessment. For example, some are focused on social or social and built infrastructure factors (Cutter et al., 2008; Cutter et al., 2014; Parsons & Morley, 2017), while others are focused on distinction of rural needs and attributes (Cabell & Oelofse, 2012; McManus et al., 2012). Some are directed toward developed communities (Sharifi & Yamagata, 2014; DHS, 2016, NAS, 2017), while others are directed toward developing communities (UNISDR, 2017).

Using the construct of sustainable resilience as the basis for organization of indicators, the set of basic systems and sub-systems that make up a community can be readily classified according to forms of sustainability capital (social, economic, and environmental systems). Social systems comprise human-centric attributes (e.g., demographic) and social order (e.g., governance, services, policy, and planning) necessary to create and sustain the social fabric of a community. Economic systems represent the state, efficiency, stability, and capacity of financial and material transactions that make up businesses, industries, and markets necessary to provide employment and generate public and private finance to fuel community maintenance and growth. Environmental systems are composed of the physical systems that communities depend upon, including built (i.e., buildings and lifelines), natural (i.e., water, air, energy, land, food, ecosystems, and biota), and general (i.e., combinations of built and natural systems – sanitation, waste, climate, mapping, cultural/archaeological sites).

Columns for primary and secondary capital systems were added to the indicator review table and indicators were first assigned to the three primary capital systems (social, economic, and environmental) based on intent (e.g., what the indicator is attempting to represent or measure based on the indicator description in the review table) as depicted in Table 6. Indicators were then grouped by primary capital system and within the group were further organized by indicator intent and the type of associated metric (where available). The most common feature of these sub-groups was identified and listed as the secondary capital system.

Primary Capital System	Total Number Indicators
Social	671
Economic	159
Environmental	259
Total	1089

Table 6. Assignment of Candidate Indicators to Primary Capital Systems

Each secondary capital system defined is one that functionally supports and contributes to the parent primary capital system with reasonable consideration for parsimony (each secondary capital system is composed of five or more indicators). Table 7 provides a summary of the corresponding classification structure, with examples of indicators related to primary and secondary sub-systems displayed in 8. While this is by no means a definitive classification, it is consistent with system organizational structures in the literature and provides a starting point for assessment practitioners to identify indicators that relate to a variety of aspects of community systems.

Primary/Secondary Capital System	**Indicator Intent**
Social	
Community Composition	Populations and their relative abilities to cope with stress within the community
Governance	Leadership, management, accountability, and capacity for response
Policy & Planning	Promulgation and implementation of policies and plans to aid communities in anticipating, preparing for, responding to, and recovering from hazards
Services	Critical community services needed to sustain healthy, educated, and safe communities
Economic	
Micro / Mesoeconomic Efficiency	Health, preparedness, flexibility, diversity, and capacity of individual businesses, markets, and industries within the community
Macroeconomic Stability	Economic stability, capacity, and growth potential of the internal community and its external economic partners (state, regional, national, international)
Environmental	
Built	Operation, and maintenance of critical infrastructure and supporting networks, housing, shelter, and other facilities needed to support and sustain communities
Natural	Availability, quality, and quantity of natural systems and resources necessary to support and sustain communities
General	Systems that are combinations of built and natural systems needed to support and sustain communities

Table 7. Primary and Secondary Capital System Classification According to Indicator Intent

Primary/Secondary Capital System	**Indicator Examples**
Social	
Community	Relative health of community-led organizations; levels of trust, inclusion, awareness, and cohesion; demographic characteristics (population stability, race, household make-up, etc.); spatial distribution of populations (access to key services, mobility, etc.)
Governance	Institutional character/leadership; accountability & management (fiscal, manpower, etc.); participation (integration of efforts and coordination across offices and functions); representation (legal, justice, etc.); regional connectivity (collaboration/ partnerships); risk-focused (information, communication, etc.); capacity for response (ability to respond to crisis or disaster)

Policy & Planning	Timeliness and effectiveness of legislation, policy, plans (age, enforcement, etc.); existence of hazard mitigation, evacuation, recovery plans & policies (age, access, comprehensiveness, etc.); capacity for risk monitoring and assessment (dedicated staff, partnerships, etc.); engagement of public in planning & policy processes
Services	Availability, quality, quantity of critical services (healthcare, mental healthcare, education, training, law enforcement, first responders, etc.); adequacy of funding and training for services (salary, staff, equipment, training, etc.); availability of services outside immediate community; desirability (relative levels of health, services, and security compared to county, state, region, etc.)
Economic	
Micro / Mesoeconomic Efficiency	Wage profiles; workforce profiles; stability of property values, taxes, prices, etc.; stability of businesses; diversity in skills; desirability (opportunity for growth and development); diversity in livelihoods; availability of local jobs; business continuity planning
Macroeconomic Stability	Balance in supply/demand; ratio of revenues to debt; economic development planning; access to resources and support from partners and suppliers; flexibility and capacity for change given worst case economic scenarios for disaster
Environmental	
Built	Quality of and access to critical infrastructure and networks (communication, transportation, power, etc.); physical safety and security (protective structures; housing; building codes; emergency shelter; land use planning and zoning; community blight/renewal, etc.) [Information from resilience assessment for individual infrastructure systems can be used to help characterize aspects of overall community resilience]
Natural	Availability of water, food, energy, land, etc.; changes in land cover; biodiversity; ecosystem services; natural buffers; agriculture; resource conservation & protection; etc.
General	Access to resource distribution and sanitation/waste management systems (drinking water, wastewater, solid waste, etc.); historical and cultural assets; climate change monitoring and analysis; mapping and data capabilities

Table 8. Examples of Indicators by Capital System Category

Consolidation

Of the original 1,089 indicators compiled from the literature, many were designed to measure similar effects. To pare this down to a more manageable set of indicators and metrics for community resilience assessment purposes, an iterative process of synthesis and refinement based on indicator intent, topic, and associated metric was conducted. Within each capital system designation, pairwise comparisons of indicator descriptions were first made. Indicators with different names, but with functionally identical descriptions, were given closer examination. If associated metrics were available and were essentially the same, the two indicators were combined under a single indicator name and any associated unique metrics were added to the metrics list. (The source articles for the indicators were also retained and consolidated.) In the case that the descriptions were the same yet the metrics were noticeably different, the description of the listed indicator was reconsidered. Secondly, within each capital system pairwise comparisons of any metrics associated with an indicator were made. In the case that the indicator name and description were different yet the metrics used were the same, the indicators were combined under a single new indicator name with an expanded description. The final set of indicators in each capital system was then examined for consistency and compared against the original indicator set for comprehensiveness. Through this process, the original set of 1,089 indicators was condensed to a final set of 98 non-duplicative indicators with corresponding metrics. In order to further aid in operationalization of these indicators, the metrics associated with the indicators were segmented into two groups: qualitative and quantitative. This breakdown may assist assessment practitioners identify commonly employed metrics that are most relevant to their community data situation (i.e., data-rich or data-poor).

We recognize that there are limitations to the approach used in consolidating and refining indicators, as there may be additional opportunity to further consolidate based on focus and intent, and a need to continuously update the set over time as new insights within literature are gained. However, the current set allows for reasonable consolidation and a much less cumbersome way to access and apply indicators and metrics that represent multiple disciplines and considerations across the literature. Additionally, the classification of indicators and metrics by capital systems offers new insight into the assessment process by allowing researchers and users to better identify and understand impacts and linkages across systems given an event or scenario, as well as improved ability to track impacts and trajectories across capital systems over time.

Classification by Sustainable Resilience Domains

Initial classification of community sustainable resilience indicators by primary and secondary capital system helps define the basic building blocks of what a community needs in order to meet its sustainable resilience objectives. However, there is a progressive, often temporal, process of building and maintaining levels of sustainable resilience within a community setting. We refer to these levels as domains of sustainable resilience. These domains represent a hierarchical set of capabilities that communities generally seek to achieve and maintain, and which are necessary in order to ultimately realize sustainable resilience. Sustainable resilience requires attainment of survivability and desired levels of well-being that can be maintained over the life of the community through systematic and proactive actions (preparedness) to positively address distributions of harmful impacts, and access to necessary resources that drive capabilities for successful preparation, response, and recovery over time. The time horizon and level of priority associated with these sustainable resilience domains ideally flows from survival (short-term, highest priority) to well-being to sustainable resilience (long-term, lowest priority). The basic structure of the hierarchy is depicted in Figure 11, which provides examples of both needs and temporal horizon for each sustainable resilience domain.

In order to aid in assessment of community sustainable resilience across different temporal time-scales, and in order to aid in identification of high priority areas following an assessment, the indicators were classified by sustainable resilience domains i) survival, ii) well-being, or iii) preparedness.

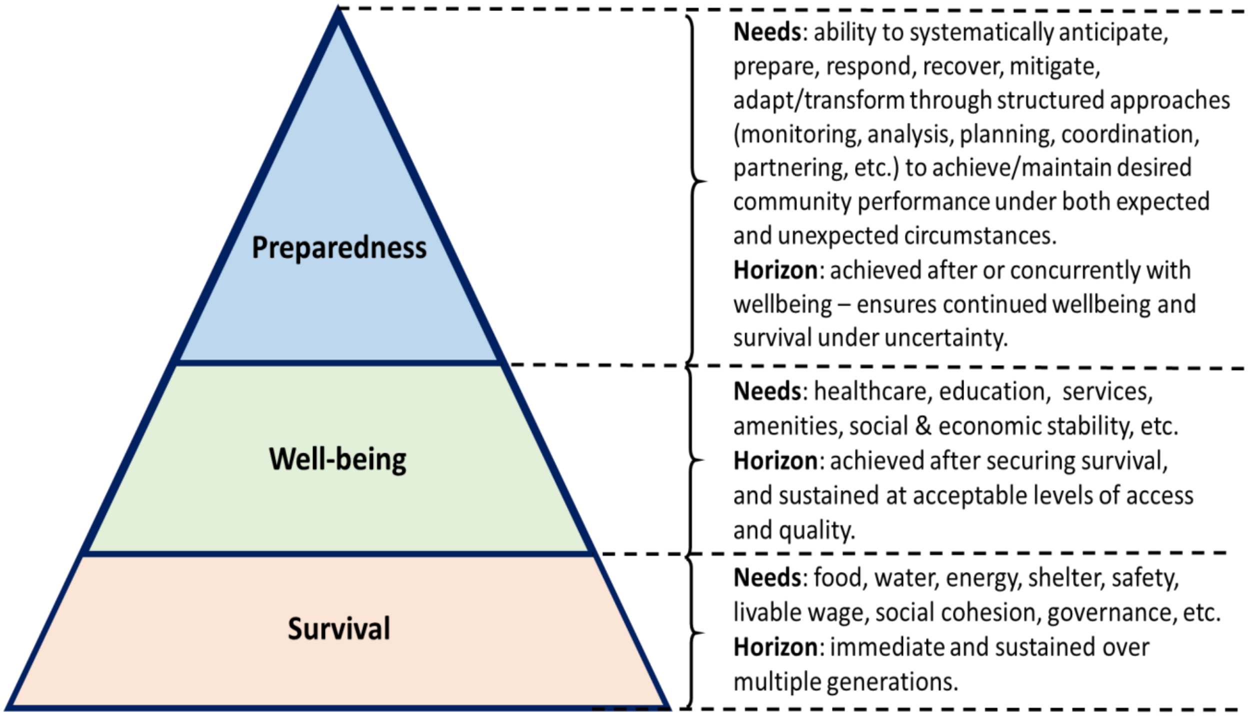


Figure 11. Sustainable Resilience Domains - Hierarchical Priorities Needed to Achieve Community Sustainable Resilience

In general, communities strive toward survival, increasing levels of well-being (quality of life), and preparedness through progression in development across social, economic, and environmental systems over time. Survival is an immediate priority, akin to meeting the most basic needs of a community (water, food, shelter, energy, safety, etc.). Once conditions ensuring survival are met, communities are able to progress to achieve adequate levels of well-being (also referred to as quality of life). Indicators within the consolidated indicator set that address availability (access, quality, and quantity) of sustainability capital (critical resources) in relation to threshold levels necessary to support and sustain life (e.g., does the community have access to reliable energy sources; is there adequate water supply for the next 30 years?) were classified as belonging to the survival domain. Metrics associated with these indicators are often evaluated at the aggregate community (macro) scale at basic threshold levels to determine sufficiency.

Well-being is related to a community's ability to provide physical, emotional, social, material, and developmental support that enables them to better cope, adapt, and/or transform under stress and uncertainty; contribute to collective goals; and ultimately thrive (Felce & Perry, 1995; Keyes, 1998; Diener & Suh, 1997; WHOQoL Group, 1995; WHOQoL Group, 1998; Magis, 2010; Andrews & Withey, 2012; Berkes & Ross, 2013; Birkmann et al., 2013; UN, 2015; NAS, 2017). Community well-being can be characterized by availability, quality, and equal access to services and amenities such as law enforcement, healthcare, education, jobs, and recreation. Availability and access are concerned not only with resource availability (e.g., are there enough schools, etc.), but also access to resources for all within the community (e.g., do all have access to the same quality of school, etc.). Varying levels of well-being are related to community desirability, stability, ability to cope, and potential for future growth across all demographics (e.g., quality of education and health care service with respect to state or national standards). As well-being increases, the collective ability to influence future conditions through enhanced coping and systematic planning, preparation, and structured approaches can also be expected to increase. Indicators related to sub-community (meso or micro) proximity, access, quality, and availability of resources to specific groups of residents (e.g., sufficient number of high quality K-12 schools available within a specific school zone or neighborhood) were classified as belonging to the well-being domain.

Preparedness requires survivability and desired levels of well-being that can be maintained under conditions of both expected and unexpected change. Preparedness requires consideration at both the aggregate community (macro) and sub-community (meso or micro) scales to determine a community's ability to maintain acceptable levels of performance under plausible scenarios of acute or chronic stress (e.g., hurricane, tornado, flood, drought) now and in the future. Indicators that are forward-looking and seek to protect and maintain/enhance desired levels of performance under current and future hazard scenarios through systematic processes for anticipation, preparation, mitigation, adaptation, planning, and learning were classified as belonging to the preparedness domain. This includes indicators related to the adequacy of processes in place to monitor changes in hazard frequency and severity over time, and the need for development of partnerships with institutions to share data and develop new methods for mitigation and adaptation.

While the hierarchical structure provided in Figure 11 may seem to imply that preparedness should not be a priority for communities struggling with maintaining well-being, our intention is not to suggest that no resources should be expended on preparedness while well-being falls short. In many cases, improvements in well-being and survival are not possible without advancing preparedness. Instead we suggest that resource allocation across the domains should generally be balanced, but with the understanding that benefits from increasing preparedness may take longer to accrue than the benefits produced from improving survival, and with recognition that in times of extreme stress it may be necessary to prioritize survival over preparedness or well-being.

Classification by Sustainable Resilience Assessment Framework Phases

The prior two forms of classification allow for identification of sustainability capital needed to support communities (primary and secondary capital systems), and how capital may be employed over time to achieve varying levels of resilience (resilience domains). However, neither of these classifications allow a user to identify the phase of a community's disaster/stress event and response process associated with the indicator. It has been acknowledged within the literature that omitting this consideration is problematic as it ignores distinctions between cause and effect, potentially biasing results, and providing little information about what variables and processes may be driving a system to experience harm (Dietz et al., 2009; Hinkel, 2011). Since there is no universally accepted theory that explains causal relationships involving social-environmental systems within a resilience framework, we suggest a final classification of indicators based on the aforementioned sustainable resilience framework that distinguishes between phases within the assessment process. This categorization includes two additional indicator classes (resources and drivers), which enable users to distinguish between indicators that represent the state of available resources (sustainability capital) and those that represent likelihood of loss (vulnerability).

Indicators that characterize the state (quality, quantity) and availability of critical social (people, services, and governance), economic (income, insurance, trade) and environmental (built and natural, infrastructure, land, water, energy) forms of capital are classified as resources (R). In general, resource indicators are seen to be positively correlated with adaptive capacity and sustainable resilience (e.g., an increase in critical resources can allow for greater flexibility and opportunity for change, whereas degradation or loss of resources can have the opposite effect). Indicators associated with potential for loss due to contextual exposure, sensitivity, or ability to cope/resist (related to levels of access, preparedness, and awareness) are classified as drivers (D). Indicators associated with drivers tend to be negatively correlated with adaptive capacity and sustainable resilience (e.g., an increase in vulnerability can lead to decreased flexibility and opportunity for change, whereas a decrease in vulnerability can have the opposite effect).

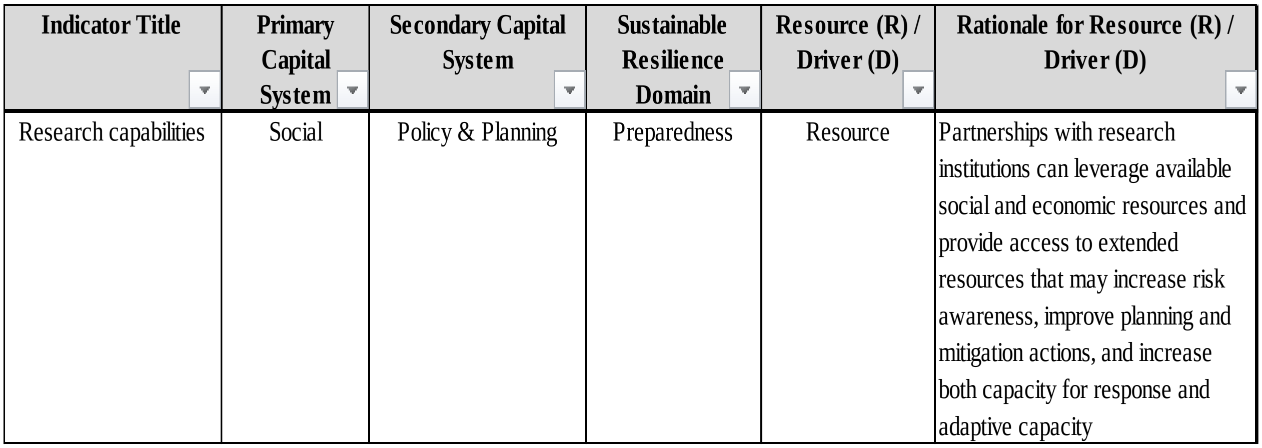
Whether an indicator is classified as a resource or a driver, or both, depends on the nature of operational assessment. For example, measures within the indicator “education and skill level” can be used to evaluate both resources and drivers, since varying skill levels and situational awareness may impact ability to cope with a hazard (driver), while high education and skill levels build social capital and increase adaptive capacity (resource). Outcomes (O) are not associated with independent indicators, but may instead be evaluated as impacts to resources and/or drivers resulting from the occurrence of change (positive or negative). Differentiation between drivers and resources can depend on the nature of the resilience assessment to which the indicators are to be applied. The rationale for differentiation between indicators as resources and drivers, and their relationship to adaptive capacity and sustainable resilience, is included in the table of indicators for community sustainable resilience in Appendix C.

Final Set of Indicators for Community Sustainable Resilience

Collectively, the classification and organizational structure developed allows users to more readily access a consolidated set of options for identification and selection of indicators and metrics that can be used in assessing community sustainable resilience. A summary of the classification scheme and organizational structure is displayed in Table 9, and an example of how classification and organization are applied to a single indicator is provided at Table 10.

Primary Capital Systems	**Social**	**Economic**	**Environmental**	**Sustainable Resilience Domain**	**Resource (R) / Driver (D)**	**Rationale for R / D**
Secondary Capital Systems	Community Composition Governance Policy & Planning Services	Micro / Mesoeconomic Efficiency Macroeconomic Stability	Built Natural General	*Survival* – required to meet basic needs *Well-being* – levels of services (healthcare, education, safety, etc.) *Preparedness* – systematically maintain/ enhance desired levels of performance under current and future scenarios	*Resource* – characterizes the state of sustainability capital as (quality , quantity & availability) of primary and secondary capital systems	*Higher levels* of (R) contribute to greater flexibility, adaptive capacity & enhance resilience; *Lower levels* of (R) indicate constraint, lower levels of adaptive capacity & detract from resilience
					Driver – characterizes vulnerability as potential for loss (levels of exposure, sensitivity, ability to cope)	*Higher levels* of (D) contribute to greater vulnerability and detract from resilience; *Lower levels* of (D) reduce vulnerability and enhance resilience

Table 9. Classification Scheme & Organizational Structure for Sustainable Resilience Community Assessment Indicators



Indicator Title	Primary Capital System	Secondary Capital System	Sustainable Resilience Domain	Resource (R) / Driver (D)	Rationale for Resource (R) / Driver (D)
Research capabilities	Social	Policy & Planning	Preparedness	Resource	Partnerships with research institutions can leverage available social and economic resources and provide access to extended resources that may increase risk awareness, improve planning and mitigation actions, and increase both capacity for response and adaptive capacity

Table 10. Classification Scheme and Organizational Structure Applied to a Single Indicator

The proposed set of 98 community sustainable resilience indicators and corresponding metrics are classified by primary and secondary capital systems, sustainable resilience domains, and sustainable resilience assessment phases. In addition, each indicator includes a rationale as to its potential impact on vulnerability (changes in exposure, sensitivity, and coping) and adaptive capacity (changes in sustainability capital). A breakdown of indicator counts for the proposed set of indicators for assessing community sustainable resilience is provided in Table 11.

Proposed Set of Community Sustainable Resilience Indicators							
Primary/ Secondary Capital System	**Sustainable Resilience Domain**			**Resource (R) / Driver (D)**			**Total**
	Survival	**Wellbeing**	**Preparedness**	**Resource (R)**	**Driver (D)**	**(R) & (D)**	
Social	15	18	11	9	14	21	44
Community Composition	7	5	0	2	4	6	12
Governance	3	7	1	6	3	2	11
Policy & Planning	0	2	9	1	5	5	11
Services	5	4	1	0	2	8	10
Economic	5	16	2	2	5	16	23
Micro / Mesoeconomic Efficiency	2	8	1	0	5	6	11
Macroeconomic Stability	3	8	1	2	0	10	12
Environmental	9	19	3	9	8	14	31
Built	6	10	1	3	7	7	17
Natural	1	8	0	4	0	5	9
General	2	1	2	2	1	2	5
Total	29	53	16	20	27	51	98

Table 11. Final Organization of Indicators for Assessing Community Sustainable Resilience

While there may be additional opportunity to further improve the resulting set of indicators, we believe that it is representative of a reasonably balanced perspective across critical concepts that is sufficiently non-duplicative to provide a meaningful starting point for use in evaluating community sustainable resilience. The full indicator table is provided at Appendix C, and can also be found here (https://blindreview1.shinyapps.io/indicators/). The link takes the reader to a web-enabled tool that allows for searching within the indicator set. The tool can be adapted over time as new indicators and metrics are developed. Care should be taken when using indicators to ensure appropriateness, balance, and constructive application in any assessment process.

Conclusions

There is considerable lack of specificity and consistency within indicator-based community resilience assessment literature that complicates the ability of practitioners and researchers to conduct community resilience assessments. By providing a review of indicators utilized within community resilience assessment literature, organizing the results into a classification structure, consolidating duplicative indicators, and relating the structure to the assessment process, this work addresses "indicator fatigue" (Engle et al., 2014 p. 1302) and enhances the ability to operationalize the assessment process. The concurrent development of a web-enabled, online appendix further facilitates the indicator identification and selection process.

The intended audience for tools and methods provided is one that has sufficient information and understanding regarding how to employ and constructively use information and processes, or an audience that can be educated sufficiently to employ them. Ideally, it is hoped that any audience desiring to understand the concepts provided can have access to both the tools and the training needed to operationalize resilience assessment.

While we have focused on how the indicator set can be used within the framework for sustainable resilience, it is ultimately intended to assist users with indicator selection for any form of community resilience assessment. Future work includes community-based case studies to test the efficacy of these indicators and metrics applied to the sustainable resilience framework. This is intended to provide a proof of concept, while also helping to delineate those indicators that are more likely to be measurable and meaningful in formulating assessment results. Future work also entails data driven approaches to further test the efficacy of this framework. Statistical dimension reduction and clustering techniques can be applied to the data implicated by the proposed set of indicators for the purpose of identifying potential redundancies from an empirical standpoint and provide a mapping for translating indicators to metrics and vice-versa. These efforts will help further delineate which indicators are measurable and meaningful in formulating community sustainable resilience assessments and/or reveal potential gaps in data availability.

CHAPTER V

Sustainable Resilience of Flood Protection Infrastructure in the U.S.: Failure Mode and Implications Analysis

Introduction

Dams and levees are used for a variety of purposes within the U.S., arguably the most important of which is protection from flooding through physical safeguarding of human lives, property, and commerce. Dams and levees are complex systems, comprised of physical and natural components that are themselves linked to other systems (energy production, water supply, recreation, transportation, environmental health, and human safety) (Alexander et al., 2012; FEMA, 2016; USACE, 2018a). With thousands of these structures in place and subject to increasing hazard, new methods are needed to assess flood protection system performance and corresponding impact to communities over time (Colten et al., 2008; Colten & Sumpter, 2009; NRC, 2012; Walker & Salt, 2012; Joyce et al., 2018). This is especially true under changing conditions that can create a set of circumstances capable of producing catastrophic impacts (e.g., population shifts, aging-failing infrastructure, and extreme climate events) (DHS, 2013; USACE, 2014; USACE, 2015a; NOAA, 2018a; NOAA, 2018b; GAO, 2018).

The concept of resilience has been applied to complex systems in assessing performance and the consequences of disruption or failure under uncertainty (Sills et al., 2008; Park et al., 2011; Park et al., 2013; Chang, 2014; Baroud et al., 2014; Joyce et al., 2018; Ongkowijoyo & Doloi, 2018). In this paper, the concept of "sustainable resilience" is used in the assessment of flood protection infrastructure, referring to a system's ability to maintain desired performance by changing in response to challenges over time, while simultaneously considering impacts to vulnerable populations and critical resources (Gillespie-Marthaler et al., 2018; Nelson et al., 2018). In this case, desired performance refers to the system's ability to prevent flooding caused by a release of water considered harmful to social, economic, and environmental (built and natural) resources. To illustrate how this concept is applied to flood protection infrastructure, a root-cause analysis is performed (identifying both primary and secondary failure modes) for 779 dam failures and 1,160 levee failures, in order to develop risk scenarios based on the most significant failure modes. Additionally, potential impact associated with extreme precipitation events is evaluated, and the assessment is illustrated in a case study involving flood protection infrastructure in

Nashville, Tennessee.

Background

Current Conditions

A large percentage of the nation's flood protection infrastructure is suspected to be in deteriorating condition. Approximately 90,580 dams exist in the U.S., and like levees, many were originally constructed over 50 years ago (ASCE, 2017). By 2030, more than half of the nation's dams will exceed 50 years in age, beyond the originally intended design basis (NRCS, 2003; Lane, 2008; ASCE, 2017). Many dams were originally constructed in rural areas for agricultural irrigation, and since their construction, populations living near dams have increased significantly (NRCS, 2003; NRC, 2012). Currently, 17% of existing dams are considered high-hazard potential; this percentage is increasing along with an estimated repair and maintenance cost of almost $65 billion across all dams (ASDSO, 2017; ASCE, 2017).

Approximately two-thirds of the nation's population lives in a county with at least one levee (ASCE, 2017). Of an estimated 100,000 miles of levee network in the U.S., just under 30,000 miles are documented; and of the total, only a fraction have been subjected to recent inspection and risk-based assessment, leaving the condition of many levees relatively unknown (NCLS, 2009; NRC, 2012; ASCE, 2017). The American Society for Civil Engineers (ASCE) estimates that $80 billion is needed to repair and maintain the nation's levee portfolio over the next 10 years, while USACE expects that $21 billion is needed to maintain its portion of the portfolio, which protects 11 million people and over $1.3 trillion in property (ASCE, 2017; USACE, 2018a; USACE, 2015b). Of the levees included in the USACE portfolio, 13% are considered moderate, high, or very high risk, with increasing numbers of people and property located behind their walls (USACE, 2018a).

Challenges

In 2012, the National Research Council (NRC) published a study on dam and levee safety and community resilience, finding that resilience is obstructed not only by system condition, but also by limited awareness and public availability of resilience and risk-related information (NRC, 2012). A balanced approach to improving resilience should include both structural enhancement and improvements in the integration of information, technology, planning, and education to prepare for and communicate both current and future risk across communities (NRC, 2012).

Lack of funding for maintenance and improvements to both dams and levees poses a long-term challenge to future flood protection resilience (ASCE, 2017). The U.S. currently operates under a policy where the greatest investments are generally made after systems have failed (having already resulted in loss of life and property), rendering it difficult to make significant strides in preparation, mitigation, and adaptation for future hazards (USACE, 2015b; GAO, 2016; GAO, 2017). Between 2005 and 2012, the government issued almost $22 billion in post-event supplemental appropriations (not part of planned funding) to address levee failures in the aftermath of Hurricane Katrina, Midwest flooding, and Hurricane Sandy (USACE, 2015b). Total post-event supplemental appropriations for Hurricanes Harvey, Irma, and Maria are still being tallied, but reported by the Government Accountability Office at an estimated $113 billion (GAO, 2018).[8]

Continued reliance on federal disaster relief has been a high priority concern for GAO since 2013 due to increasing frequency of climate-related disasters and escalating magnitude of related costs (GAO, 2013; GAO, 2015a; GAO, 2015b; GAO, 2017). While disaster relief may be unavoidable in extreme circumstances, future public harm and fiscal exposure can be reduced through consistent investments before disasters occur to identify risk, assess community and infrastructure resilience, educate vulnerable populations, implement mitigation and adaptation strategies, and improve overall resilience of infrastructure and communities (USACE, 2015b; ASCE, 2017; USACE, 2018a; GAO, 2015a; GAO, 2015b; GAO, 2018).

Dam and Levee Failure Analysis

Analysis began with a comprehensive literature review using multiple key words and phrases, and a variety of databases and search engines, including Thompson Reuters Web of Science (WoS), ASCE Library, JSTOR, SpringerLink, WorldCat, Google Scholar, and Google. The search focused on documentation of dam and levee failures that identified root causes and included discussion of impacts. Over ninety documents were identified based on these criteria.

While failure mode and effects analysis (FMEA), can be a useful tool in assessing potential failures and mitigating future occurrence in design and/or production processes (Sankar & Prabhu,

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[8] A portion of this amount may be attributed to wildfire activity as well as flooding. Wildfire-specific appropriations were subtracted from GAO totals provided.

2001), we do not attempt to employ the FMEA process or the failure mode, effects and criticality analysis (FMECA) process. While we recognize that the objectives of FMEA are to identify potential failure modes, evaluate the causes and effects of different component failure modes, and determine what could eliminate or reduce the likelihood of potential failure (Liu et al., 2013), the results of FMEA and FMECA are typically intended to mitigate more specific effects and improve performance during design and production in a variety of processes (Liu et al., 2013; Chang & Cheng, 2011), which is not the intent here. Lack of specific and more robust data to develop conventional risk priority numbers (RPN) based on occurrence (O), severity (S) and detection (D) render FMEA a less than optimal approach for this effort, but perhaps a candidate for future efforts given increased data for specific (meso- and/or micro-scale) modes and processes. Our approach begins at the macro-scale, using existing data (both qualitative and quantitative), as well as modeled data using established techniques and authoritative sources. This information is used to examine the overall state of flood protection infrastructure from the macro-scale, as well as trends in meso-scale contributing mechanisms (e.g., lack of maintenance, changes in hydrological patterns, changes in population, etc.) that effect the systems' overall ability to perform intended functions, and to better understand possible implications for sustainable resilience over time.

Multiple data sources for dams were concurrently investigated, which included the U.S. Army Corps of Engineers (USACE) National Dam Inventory (USACE, 2018b) and the Stanford University National Performance of Dams Program (NPDP) database (NPDP, 2018) among other lesser contributing sources. The USACE database contains information identifying and characterizing over 50,000 dams, is searchable by state, and is updated every two-years; however, it does not include information regarding historical failures. The NPDP database includes information on over 1,300 historic dam failure events. Data sources for levees include the National Levee Database, administered by USACE, which contains almost 30,000 miles of levee without information on historical failures (USACE, 2018c) as well as other minor sources. As noted by the National Research Council (NRC), data on historic levee failure and impacts is largely limited to individual reports and is difficult to consolidate on a national level (NRC, 2012).

Dam Failure

Analysis of root causes for dam failure involved extracting and validating events from databases and publications, with the largest contribution of individual events collected from the

NPDP[9] and the Association of State Dam Safety Officials (ASDSO). A total of 779 failure events, spanning the years 1852-2018, was collected. For the purpose of analysis, failure was defined as an uncontrolled release of water from the system (release of the dam reservoir over, through, or under a dam structure). Criteria for inclusion in the analysis included identification of i) year of incident, ii) location, iii) dam type, and iv) primary cause of failure. Where available, additional information included i) contributing cause(s) of failure, ii) number of fatalities, iii) damages and associated costs, and iv) description of impacts to social, economic, and environmental resources for communities. Limitations associated with this analysis involved the inability to accurately account for all historical and contemporary failures due to lack of available information and inaccuracies inherent through use and interpretation of best available information. In many cases, anecdotal information (e.g., media coverage) was used to better understand the extent of damages and impacts to communities. Information, including references, used in the analysis is located in a web-enabled appendix (Appendix F) with search and filter capability at: https://blindreview1.shinyapps.io/dams/.

A summary of fatalities and costs (adjusted for inflation and brought forward to 2018) resulting from dam failure analysis is provided in Table 12, with distinction drawn between events that occurred before and after enactment of the National Dam Inspection Act (1972) and the Dam Safety Act (1979) (S.2735, 2006).

Dam Failures in U.S. (1852-2017)	**Grand Total**	**Total Since 1972**	**Total Since 1979**
Total events	779	539	467
Cost (2018)	$14,009,576,127	$11,805,556,845	$1,175,200,834
Events with fatalities	69	27	15
Total fatalities	3936	707	42
Events with > 10 fatalities	23	8	1

Table 12. Summary of Fatalities & Costs Associated with Dam Failure Events (1852-2018)

A summary of the types of dams represented in the analysis is provided in Figure 12 (percentages are relative to 779 U.S. dam failure events included in the analysis). Of the dams included in the

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[9] For events collected from the NPDP database, failure cause was derived from the individual incident "event" tab, rather than the main output page for queries. Where the two outputs did not match, deference was given to the incident description provided in the "event" tab.

analysis, 66% are classified as earthen structures (e.g., homogeneous-earth, earth-fill, earth-zoned, earth-gravity, etc.).

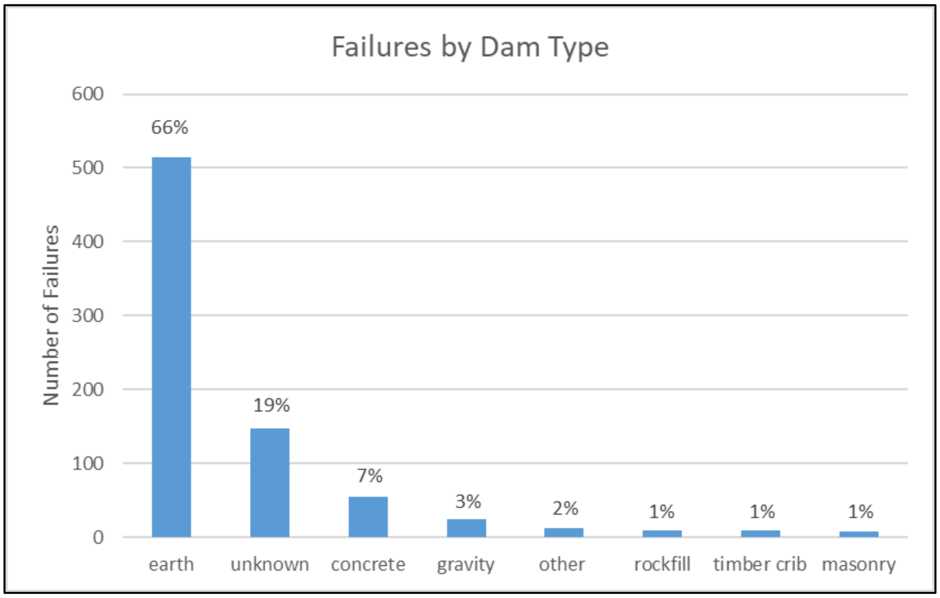

Figure 12. Distribution of Failures According to Dam Types

Primary, or root causes of failure (failure modes) were determined through examination of information (incident reports, explanations, narrative) documented for each dam, and where available, this information was validated against multiple sources. General descriptions for common dam failure modes identified in the analysis are provided in Table 13.

Failure Mode	General Description
Breach	Opening or break in structure (intentional or unintentional)
Cracking	Structural cracking due to movement
Foundation	Defects due to settlement of structure and/or slope instability
Overtopping	Water flowing over top (crest) of structure
Piping	Sinkholes due to poor filtration of seepage and movement of soils at the foundation
Poor Construction	Inadequate design/construction
Poor Maintenance	Inadequate maintenance and repair
Seepage	Wells or boreholes form due to poor drainage at foundation and abutments
Spillway	Inadequacy or deficiency that prevents controlled release of water (reservoir drawdown) through spillway structure

Table 13. General Descriptions for Dam Failure Modes

A summary of primary failure modes for dams is provided in Figure 13. The primary cause of dam failures is attributed to overtopping (42%). This finding is proportionally similar to ASDSO information regarding recent failures from 2010-2015 (ASDSO, 2018). Failure mode is unknown for 32% of events, while breach is cited in 12% of the records, with foundation, piping, and poor maintenance accounting for the remaining failures.

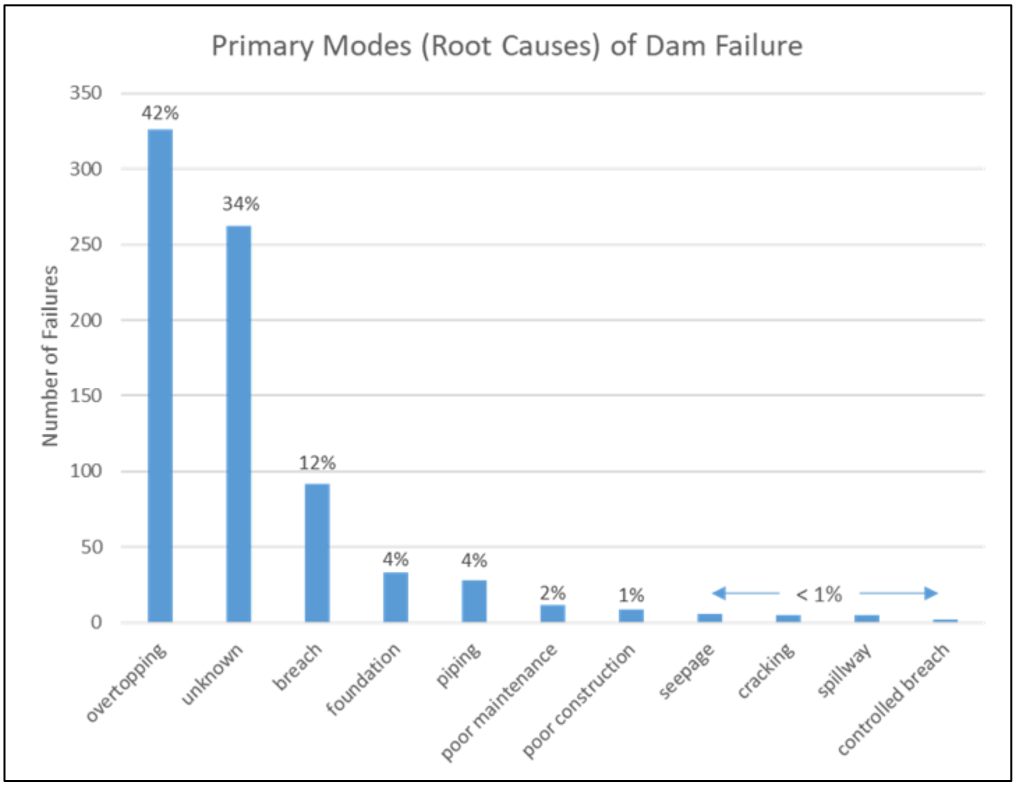

Figure 13: Primary Modes (Root Causes) of Dam Failure in the U.S.

Where available, secondary failure modes were also identified. Secondary modes are defined herein as significant contributing factors, without which failure may not have occurred or consequences may have been less severe. The majority (52%) of dam failures exhibited extreme weather as a secondary mode, primarily due to a hydrologic event (extreme/prolonged precipitation or storm with or without impacts associated with snowmelt). Thirty-eight percent of failures did not account for secondary modes, indicating that there was no secondary mode or none was recorded in the historical account. Figure 14 is an overall summary of secondary modes for dam failure based on events assessed.

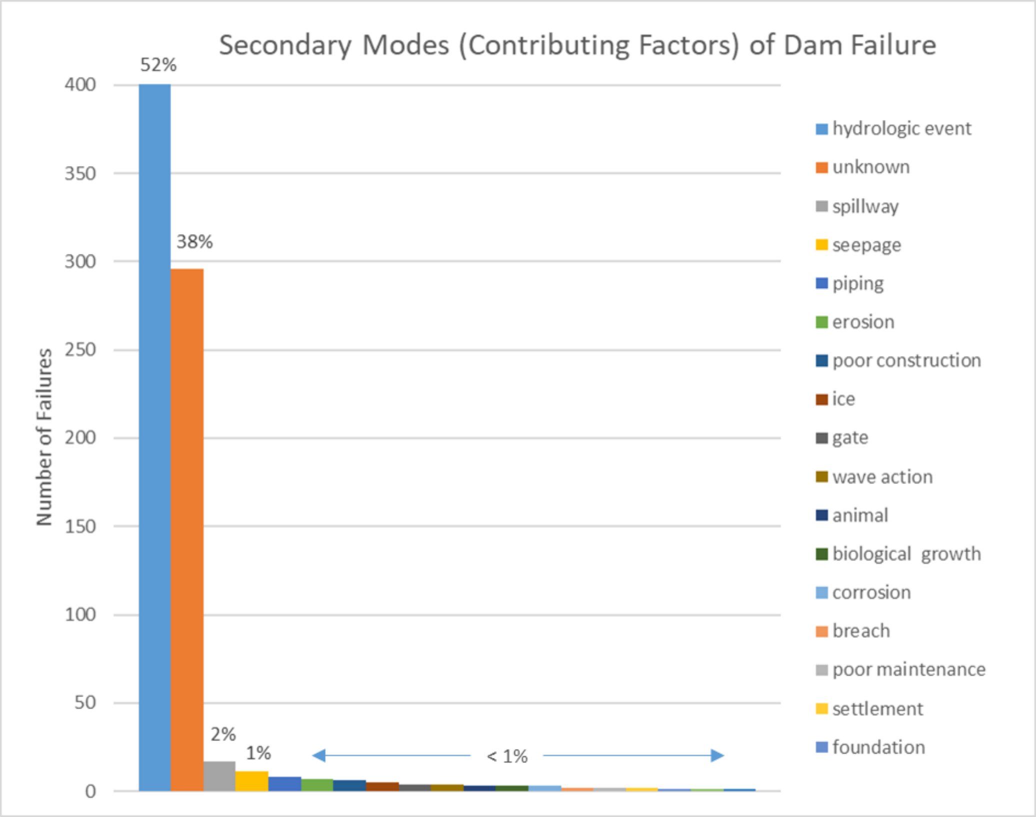

Figure14. Secondary Modes (Contributing Factors) of Dam Failure in the U.S.

The analysis results make clear that dam failure due to overtopping associated with a hydrologic event represents a significant risk scenario for downstream communities, with breach, foundation and piping failure also of concern. In particular, earthen dams (the majority of dam types associated with failure events in the analysis) appear highly susceptible to the effects of hydrologic events. Table 14 provides a summary of risk scenarios derived from failure mode analysis and developed for this paper that present a challenge to the sustainable resilience of dam infrastructure and downstream communities based on these observations.

Table 14. Scenarios Presenting Risk to Dam Failure and Community Resilience

Failure Scenario	Scenario Description	Primary Failure Mode	Secondary Failure Modes (most significant)	% Primary Mode Failures	% All Failures
1	Heavy and/or persistent rainfall (with or without snowmelt impacts) results in exceedance of reservoir capacity, allowing water to flow over the crest; spillway deficiencies preventing safe drawdown contribute	Overtopping	Hydrologic event, spillway	94	42
2	Heavy and/or persistent rainfall (with or without snowmelt impacts) results in load exceedance, causing a break in the structure that allows water to flow through; spillway deficiencies and/or piping which erodes foundation material contribute	Breach	Hydrologic event, Spillway, Piping	92	12
3	Heavy and/or persistent rainfall (with or without snowmelt impacts) leads to settlement or slope instability , resulting in partial or total collapse and release of water; erosion and/or poor construction contribute	Foundation	Hydrologic event, Erosion, Poor construction	66	4
4	Poor filtration beneath the structure and/or at abutments results in loss of foundation material and release of water; hydrologic events and/or animal burrowing contribute	Piping	Seepage, Hydrologic event, Animal	61	4
While all dam types display vulnerbaility to scenarios based on analysis, earthen dams comprise the majority of failure events.				Total	62

Levee Failure

Root cause analysis for levee failure relied heavily on individual reports, documenting events associated with large-scale disruption of levee systems in a specific region. The analysis includes 1,160 individual failure events, resulting from five flood episodes, Midwest (1993), California Central Valley (1997), New Orleans (2005), Midwest (2008 & 2011). While dams are considered to be individual structures, levees operate as systems of systems, rendering a different process for the analysis. Consequences are generally attributed to the collective impacts of a large-scale event, as opposed to an individual failure within a levee system.

Similarly to a dam failure event, levee failure event is defined as an uncontrolled release of water from the system (over, through, or under a levee structure). Criteria for inclusion in the analysis requires knowledge of i) year of incident, ii) location, and iii) primary cause of failure. All levees were earth embankment and a portion of levees also included flood walls atop the embankment structure. Where available, additional information includes i) contributing cause(s) of failure, ii) number of fatalities, iii) damages and associated costs, iv) description of impacts to social, economic, and environmental resources for impacted communities, and v) lessons learned.

Analysis limitations were similar to those encountered in analyzing dam failures. Information used in the analysis, including references, is located in a web-enabled appendix (Appendix G) with search and filter capability at: https://blindreview1.shinyapps.io/levees/. A summary of fatalities and costs (in $2018) resulting from levee failure analysis is provided in Table 15.

Table 15. Summary of Fatalities & Costs Associated with Levee Failure Events (1993-2011)

Levee Failures in U.S. (1993-2011)	Total
Total failure events	1160
Cost (2018)	$189,393,577,710
Fatalities	1576
Population displaced	153,000
Population evacuated	923,500

The greatest number of fatalities and cost ($2018) occurred in 2005 following Hurricane Katrina in New Orleans (estimated to be at least 1,500 fatalities and over $138 billion in total cost), resulting from multiple levee failures, record storm surge, and complications in evacuation and emergency response (Reible et al., 2006; Wolshon et al., 2006; Mlakar, 2006; Van Heerden, 2007; Sills et al., 2008; USACE, 2009). While legislation related to levee safety was enacted in 2016, it has yet to be appropriated (S.612, 2016). General descriptions for common levee failure modes identified in the analysis are provided in Table 16.

Failure Mode	General Description
Breach	Opening or break in structure (intentional or unintentional)
Cracking	Structural cracking due to movement
Overtopping	Water flowing over top (crown) of structure
Piping	Sinkholes due to poor filtration of seepage and movement of soils at the foundation and abutments
Seepage	Wells or boreholes form due to poor drainage at foundation and abutments
Sliding	Sheer failure where saturated sections of levee slide down the face of the levee due to high water events
Sloughing	Erosion of landside levee slope due to seepage or piping
Subsidence	Loss of levee elevation due to removal of subsurface support via piping, sinkholes, seismic activity, etc.

Table 16. General Descriptions for Levee Failure Modes

The vast majority of levee failures in the analysis are attributed to overtopping (97%). While slightly over ninety percent of levee failures included are non-federal, this finding is proportionally similar to results from assessments performed by USACE on over 70% of its existing portfolio, where overtopping is the major driver for failure (USACE, 2018a). A summary of primary failure modes for levees is provided in Figure 15.

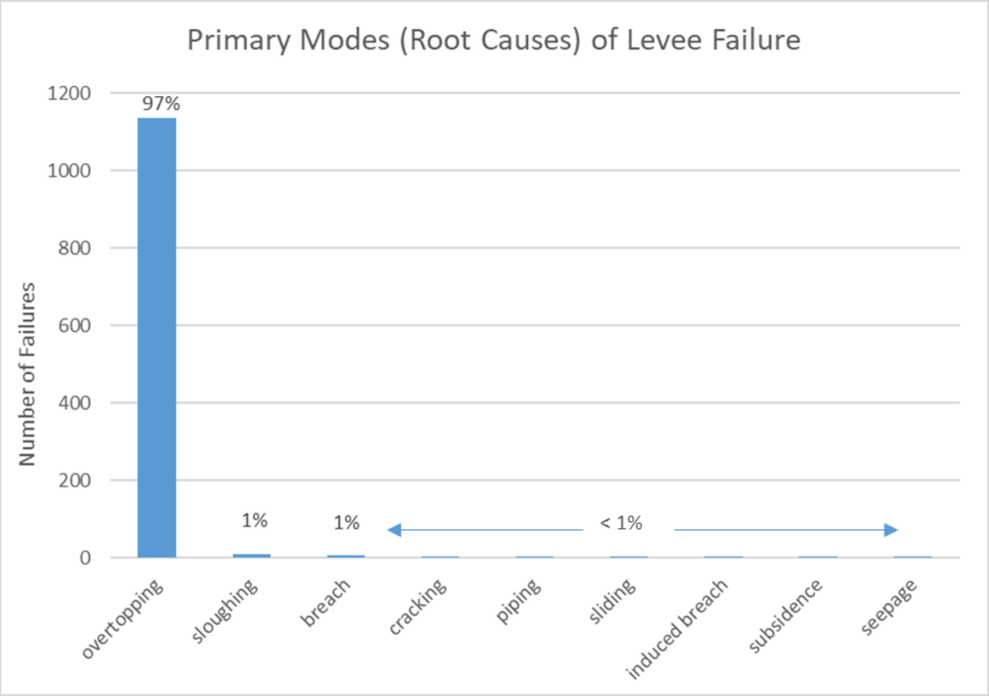

Figure 15. Primary Modes (Root Causes) of Levee Failure in the U.S.

Every levee failure in the analysis is, by definition, related to extreme weather, represented as a hydrologic event characterized by extreme/prolonged precipitation (with or without impacts from snowmelt), and/or storm (including hurricanes, coastal and inland flooding, and storm surge). Secondary modes for levee failure are therefore considered as contributing factors other than hydrologic event. Figure 16 depicts the overall distribution of secondary modes for levee failure due to overtopping and hydrologic event.

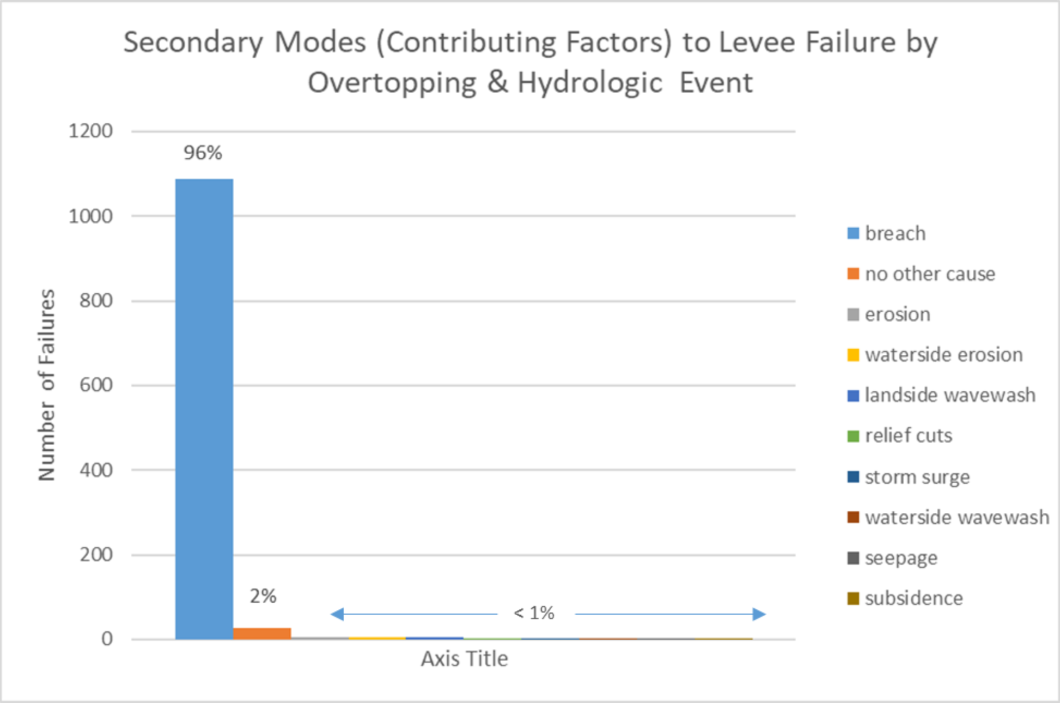

Figure 16. Secondary Modes (Contributing Factors) of Levee Failure in the U.S.

Breach contributed to 96% of levee failures due to overtopping and hydrologic event. Table 17 provides a summary of high risk scenarios derived from failure mode analysis and developed for this paper that present a current challenge to the sustainable resilience of levee infrastructure and nearby communities.

Failure Scenario	Scenario Description	Levee Type*	Primary Failure Mode	Secondary Failure Modes (most significant)	% Primary Mode Failures	% All Failures
1	Storm surge and/or heavy and/or persistent rainfall (with or without snowmelt impacts, and excessive soil satutation) exceeds levee capacity, allowing water to flow over the crown; load exceedance and breaching contribute	all	Overtopping	Hydrologic event, (with or without breach)	98	97
2	Storm surge and/or heavy and/or persistent rainfall (with or without snowmelt impacts, and excessive soil saturation) results in landside slope instability and loss of embankment material, allowing release of water; seepage or piping may also contribute	all	Sloughing	Hydrologic event	1	1
3	Storm surge and/or heavy and/or persistent rainfall (with or without snowmelt impacts, and excessive soil saturation) results in load exceedance, causing a break in the embankment, allowing release of water; erosion may also contribute	all	Breach	Hydrologic event	1	1
* Earthen embankments (with and without floodwall) comprise all failure events.					Total	99

Table 17. Scenarios Presenting Highest Risk to Levee Failure and Community Resilience

Lessons learned from each of the five flood events assessed (Midwest (1993), California Central Valley (1997), New Orleans (2005), Midwest (2008 & 2011)) display a need for real-time monitoring of precipitation, river stage, streamflow/discharge, and soil moisture data, in addition to the ability to share this information across networks to aid in coordination and communication during events. Table 18 provides a summary of key issues identified for events.

Event	Levee Failure - Lessons Learned/Needs Identified	References*
Midwest, 1993	- Need reliable real-time data on stream flow, stage, and soil moisture conditions (improved monitoring networks) - Need improved models for future flooding and levee failure - Need comprehensive floodplain management & improved understanding of how changes in land use effect flooding within/across river basins	Galloway, 1994; Interagency Floodplain Management Task Force, 1994
CA Central Valley, 1997	- Need improved coordination of flood releases across delta - Need a comprehensive approach to managing runoff - Need increase in telemetered gaging stations for streamflow and precipitation - Lack of maintenance contributed to failure (obstructed culverts, vegetation, etc.) - Need improved monitoring of seismic effects - Need improved coordination/communication for evacuation processes	FEAT, 1997; Burton & Cutter, 2008
New Orleans, 2005	- Need improved/increased risk assessment for levees susceptible to storm surge (foundation and floodwall inadequacy contributed to breaching) - Overtopping alone would have resulted in far less flooding - Need to understand how climate impacts storm intensity - Need improved warning, coordination, communication & evacuation processes	Sills et al., 2008; Wolshon, 2006; ASCE, 2007; USACE, 2007; Cutter & Gall, 2007; USACE, 2009
Midwest, 2008	- Limited river gaging information constrained the National Weather Service and others in developing timely and accurate river stage forecasts - Need to review accuracy of the stage-discharge, discharge-frequency, and stage-frequency relationships essential to flood control planning (determine how changes in land use patterns and climate alter relationships) - Need greater enforcement of building restrictions, land use planning in floodplains	Bernhardt et al., 2011; Holmes et al., 2010; Gleason, 2008; Carter, 2009
Midwest, 2011	- Smart phone application/real-time GPS location of conditions in the field provided flood fighters ability to upload images, describe damage, and share critical data	USACE, 2012

* Greater detail and a complete set of references can be found at Appendix B (https://blindreview1.shinyapps.io/levees/).

Table 18. Lessons Learned from Past Levee Failures

Many of the items in Table 18 can be applied to dam failures where similar failure modes exist. Early warning systems and enhancements in evacuation and emergency response processes are critical to reducing human injury, and require continuous improvement. The need for improved models and greater understanding of how changes in land use and climate may impact riverine, flash, and coastal flooding scenarios persists in the wake of events like Hurricane Sandy (Grinsted et al., 2013; Garner et al., 2017; Dietrich, 2018); Hurricane Harvey (Shah et al., 2017; Trenberth et al., 2018; GAO, 2018), flooding in Louisiana (Wiel et al., 2017), Hurricanes Irma and Maria (GAO, 2018), and most recently, Hurricanes Florence and Michael.

Implications for Future Sustainable Resilience of Flood Protection Infrastructure

Factors Affecting Sustainable Resilience of Flood Protection Infrastructure

Past and current events illustrate that changes in land use and development can impact local and regional hydrology affecting flood patterns and intensity (Interagency Floodplain Management Task Force, 1994; Villarini et al., 2011). Likewise, changes in coastal conditions brought about by subsidence and rising sea level can alter storm surge intensity and magnitude of flooding (Burkett et al., 2001; Van Heerden, 2007; Sills et al., 2008; Garner et al., 2017; Trenberth et al., 2018). Continued exposure of aging/failing infrastructure to extreme events and dynamic processes can create new and potentially unforeseen challenges for communities and the infrastructure they depend upon (Hallegatte, 2009; Neumann et al., 2015; Melvin et al., 2016; GAO, 2016 and 2018). Conditions such as those produced by long-term drought, followed by heavy precipitation can push infrastructure beyond design standards and initiate or accelerate failure as evidenced by Oroville Dam (Vahedifard, 2017). These conditions, coupled with increasing concentrations of people and property downstream of dams and behind levee walls create greater risk of injury and damage (NRCS, 2003; NRC, 2012; ASCE, 2017; USACE, 2018a; USACE, 2018f), potentially jeopardizing future sustainable resilience.

NOAA recently updated its analysis of extreme climate disasters exceeding a billion dollars in cost.[10] Since Hurricane Katrina in 2005[11], NOAA has recorded 128 events exceeding the billion dollar threshold in cost (NOAA, 2018b).[12] Notably, extreme precipitation and storm accounts for 83% of billion dollar events documented by NOAA (106 of 128), representing 86% of total cost and 90% of total deaths (NOAA, 2018b).[13,14]

The aforementioned scenarios presenting highest risk to flood protection infrastructure failure and community sustainable resilience are also primarily attributed to occurrence of extreme hydrologic events. Figure 17 provides a summary of extreme hydrologic events (similar to those documented in dam and levee failures) present in the 106 precipitation/storm-related NOAA

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[10] Reflecting cost after 2018 Consumer Price Index adjustment.

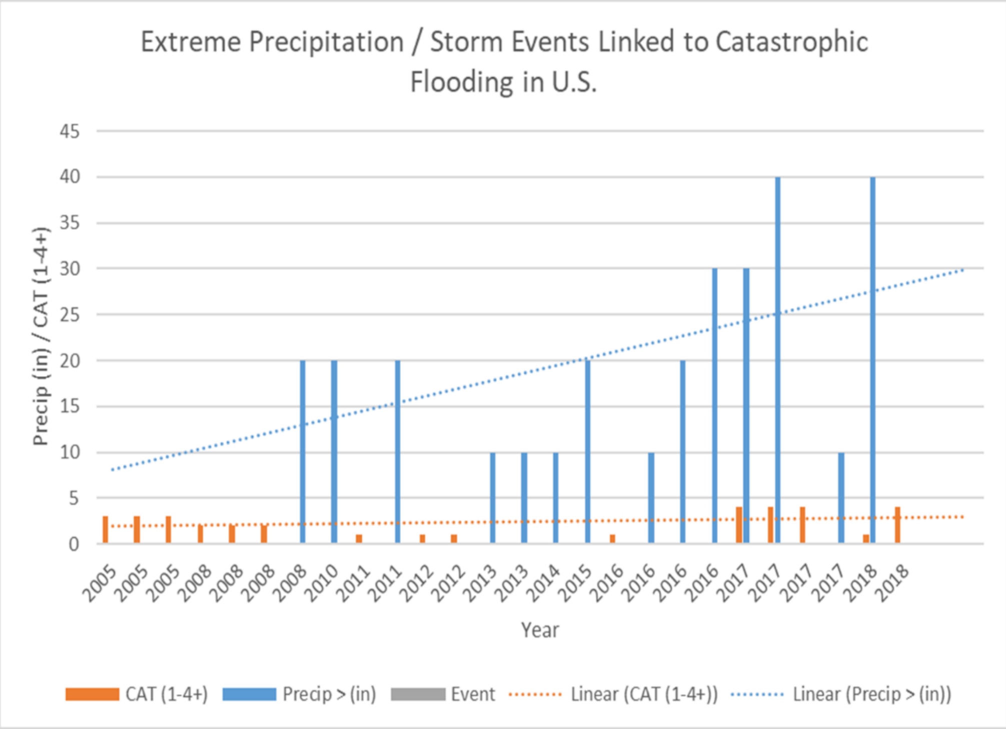
[11] Largely considered a watershed event in terms of media coverage and magnitude of consequences.

[12] Totaling just under one trillion at $995.1 billion, and 4,472 lives lost (NOAA, 2018b). If new estimates for loss of life associated with Hurricane Maria are included, the total increases to 7,447 (Santos-Burgoa et al., 2018).

[13] Does not include Hurricane Florence (estimated at $1.2 billion and 42 deaths as of Sep 24, 2018 by CBS, 2018).

[14] Estimated at $853.3 billion in cost and 4,015 deaths. Estimates associated with Hurricane Maria increase total deaths to 6,990, while the proportion remains unchanged at 90% (Santos-Burgoa et al., 2018).

events since 2005. Events in italics are associated with documented dam and levee failures (Katrina 2005, Midwest 2008, Midwest 2011, South Carolina 2015; Midwest 2017). The hurricane category (CAT) represents magnitude at landfall (levels 1-4+). Precipitation is the total recorded for the event. Storm categories and precipitation totals are derived from the following: NOAA, 2018b; Holmes et al., 2010; USACE, 2012; NASA, 2017; Belles, 2018; NOAA, 2018e. Figure 17 also depicts increasing linear trends in catastrophic events associated with flooding where both extreme precipitation and hurricane-related events appear to be increasing.



Event	Year
Hurricane Wilma	2005
Hurricane Rita	2005
Hurricane Katrina	2005
Hurricane Ike	2008
Hurricane Gustav	2008
Hurricane Dolly	2008
Midwest Flood	2008
Southeast Flood	2010
Hurricane Irene	2011
Midwest Flood	2011
Super Storm Sandy	2012
Hurricane Isaac	2012
Colorado Flood	2013
Illinois Flood	2013
Michigan Flood	2014
South Carolina Flood	2015
Hurricane Matthew	2016
Houston Flood	2016
Texas Flood	2016
Louisiana Flood	2016
Hurricane Maria	2017
Hurricane Harvey	2017
Hurricane Irma	2017
Midwest Flood	2017
Hurricane Florence	2018
Hurricane Michael	2018

Figure 17. Extreme Hydrologic Events Linked to Catastrophic Flooding (2005-2018) (NOAA, 2018b; Holmes et al., 2010; USACE, 2012; NASA, 2017; Belles, 2018; NOAA, 2018e)

Precipitation associated with events in Figure 17 is considered the total rainfall within a specified duration (hours or days), and can be compared to local recurrence intervals or intensity-duration-frequency (IDF) tables to gage relative magnitude (NOAA, 2018d).[15]

Extreme hydrologic events are often characterized in terms of a 100-year, 500-year, 1,000-

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[15] Intensity-duration-frequency (IDF) tables provide a measure of rainfall intensity over specified durations necessary to produce a storm event (1, 4, 10, 25, 50, 100, 200, 500, 1000-year storm). The NOAA Atlas 14 Point Precipitation Frequency Estimates are provided by state and NOAA gage here: https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html (NOAA, 2018d).

year (and so on), which refers to the likelihood of observing an event of specified magnitude in any given year, based on calculation of a return, or recurrence interval from observed data for a specific location (USGS, 2018). A 100-year event has a 1 in 100 (1%) probability of occurring in a given year, and risk associated with such an event is determined based on its probability and expected damage. Events in excess of the 100-year standard have been recorded multiple times since 2005. Hurricane Harvey produced record floods in excess of 500 and 1,000-year events (Harris County, 2018), and Hurricanes Irma, Maria, and Florence have set records in terms of flooding and destruction in 2017 (GAO, 2018; Santos-Burgoa et al., 2018; Belles, 2018). Damages from Hurricane Michael were also catastrophic where the category 4 storm and heavy surge made landfall on the Gulf Coast in Florida (NOAA, 2018e).

Recurrence intervals and associated risks are often used in planning and design of infrastructure. For example, the 100-year standard for storm surge is the basis for current structural specifications associated with the Hurricane and Storm Damage Risk Reduction System in the greater New Orleans area (USACE, 2018e). Risk and resilience are impacted by the correct determination and application of recurrence intervals, which are used to define both the public perception of, and the physical consequences potentially associated with, a hazard event (e.g., a community may assume a levee built to a 100-year standard should protect them from a 100-year storm, and may not question whether or not the standard is correct). Since recurrence intervals are largely based on historical data (what has been observed in the past), they are subject to uncertainty in future projections and, hence, need to be updated over time (NOAA, 2018d). Examination of observed precipitation data for the U.S. Gulf Coastal region from 1900 to 2016 displays an increasing recurrence, and associated likelihood, of extreme flooding events, like those experienced in 2017 (Weil et al., 2017). Future sustainable resilience requires consideration of how recurrence intervals and associated risks may change based on possible changes in the frequency and magnitude of extreme hydrologic events over the next several decades (within the life of both new and existing flood protection infrastructure).

Use of General Circulation Models (GCMs) and Future Scenario Development

Current literature displays convergence regarding both observed and predicted impacts of warming temperatures on increasing frequency and magnitude of extreme precipitation events (Allan & Soden, 2008; O’Gorman & Schneider, 2009; Kharin et al., 2013; Kendon et al., 2014;

Ban et al., 2015; Fischer & Kutti, 2016). Regional variation has been found to depend on relative changes in convective moisture, where increasing temperature generally produces greater precipitation in humid climates than dry climates due to the Clausius–Clapeyron equation (Prein et al., 2017a; Bao et al., 2017)[16]. Analysis of observed and modeled data indicates that the most significant increases in frequency and magnitude of precipitation appear to occur in the highest percentile events (rarest, or most extreme events), often at the expense of lower magnitude (more moderate) precipitation events, leading to longer dry periods that are followed by heavy rain and excessive runoff (Allan & Soden, 2008; Karl et al., 2009; Wang et al., 2017; Gao et al., 2017; Arritt et al., 2018). Uncertainty remains regarding the rate, or scale associated with increased frequency and magnitude over time (Bao et al., 2017; Wang et al., 2017). Some studies suggest that scaling associated with Clausius–Clapeyron is likely to be more severe than models predict, where observed scaling exceeds modeled results (Allan & Soden, 2008). Such patterns can impact both drought and flood risk, and the need to review and possibly update recurrence intervals, risk assessments, and associated infrastructure standards (Wang et al., 2017; Kharin et al., 2018).

Similar convergence in literature is displayed for increasing magnitude of tropical cyclone impact in the North Atlantic, where the most extreme events appear most sensitive to warming temperatures (Grinsted, 2013). The 2017 U.S. hurricane season, which produced hurricanes Harvey, Irma, and Maria, was fueled by high sea surface temperatures and oceanic heat content (Lim et al., 2018). Midwest flooding may also be correlated with warming episodes in the North Atlantic water cycle via ocean-to-land-moisture-transport as determined by significance of salinity signatures identified during Spring precipitation prior to the 1993, 2008, and 2015 floods (Li et al., 2018).

In the case of both precipitation and tropical cyclones, increases in predicted magnitude of extreme events (as well as magnitude of resulting damage) appear more pronounced as temperature rises. General circulation models (GCMs) operate under the assumption of four possible future scenarios termed ‘representative concentration pathways’ (RCPs) that range from limiting average global temperature increase to 2 degrees Celsius (RCP 2.6), to a worst-case scenario (RCP 8.5),

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[16] This relationship is generally explained by the Clausius–Clapeyron equation (saturation vapor pressure of water increases with increasing in temperature, leading to increases in precipitation).

which results in greater temperature increase in the absence of mitigation strategies, and resulting radiative forcing (van Vuuren et al., 2011). Current studies indicate that RCP 2.6 may now be out of reach, and likely scenarios more realistically include those resulting in global temperature increase in excess of 2 degrees Celsius (Raftery et al., 2017; Mauritsen & Pincus, 2017; Peters et al., 2017; McGushin et al., 2018).

For every degree Celsius increase in temperature, models predict a two- to seven-fold increase in events similar to the magnitude of Hurricane Katrina (Grinsted, 2013). The global trajectory is now approaching a 1.5 degree Celsius increase as early as 2030 (McGushin et al., 2018). At an increase of 2 degrees Celsius, sea level rise may contribute to storm surge magnitudes that cost an additional $1.4 trillion in global annual losses (Jevrejeva et al., 2018). A worst-case future (RCP 8.5) may result in a 15% to 40% increase in maximum precipitation rates produced by convective storms (Prein et al., 2017b); sea level rise contributing to storm surge magnitudes that cost an additional $14 to $27 trillion in global annual losses (Jevrejeva et al., 2018). Modeled projections for almost all scenarios currently result in increasing risk due to flood and storm, with greatest risks represented by RCP 8.5 (Grinsted et al., 2013; Kharin et al., 2018; Jevrejeva et al., 2018; Pant & Cha, 2018). This has prompted a general call to review risk assessments and standards for flood protection infrastructure (Prein et al., 2017b; Kharin et al., 2018) to ensure that future hazard scenarios are identified and sufficiently accounted for in design and planning efforts.

Case Study: Nashville's Flood Protection Infrastructure

A case study is presented in which a single highest risk scenario for flood protection infrastructure is applied as represented in Tables 14 and 17. The scenario is that of heavy and persistent rainfall which exceeds the design capacity of a levee, resulting in an uncontrolled release of water that causes harm to social, economic, and environmental (built and natural) resources, thereby disrupting nearby communities. History provides a recent example of this scenario in Nashville, TN in 2010. This flood event exceeded all known events in the local, recorded account, spanning over seventy years. To better understand development and application of possible future scenarios for extreme events of similar magnitude, application of GCM and local data analysis provides insight into potential future risk and resulting implications for local sustainable resilience.

Nashville 2010 Flood

Nashville, Tennessee experienced extreme precipitation in May 2010, resulting in catastrophic riverine and flash flooding which caused eleven deaths, over $2 billion in damages, and an estimated $3.6 billion in economic losses (Nashville-Davidson County, 2011; Nashville-Davidson County, 2015a; Nashville-Davidson County, 2015b). During this period, precipitation in the area exceeded known historic records for 24-hour (184 millimeters), 2-day (345 millimeters), and 3-day (over 431 millimeters) events, corresponding to 7.24, 13.58, and 17 inches, respectively (Nashville-Davidson County, 2015a; Keim et al., 2018). The 24-hour record corresponds to a 792-year event, while the 2-day and 3-day records exceed 1,000-year events, with the 2-day cumulative precipitation amount corresponding to a 13,833-year event (Keim et al., 2018). The Cumberland River crested near levees protecting the downtown area at over 15.43 meters, or 50.62 feet (just below the 500-year level) (USACE, 2018d; Davidson County, 2015c).

While local dams did not fail, one of two levees protecting the downtown area failed due to overtopping, resulting in economic losses (Davidson County, 2015c). Investment in flood protection occurred following 2010 to ensure protection up to a 500-year event for at least one of two levees protecting the downtown Nashville area along the Cumberland River (Nashville-Davidson County, 2015c). Studies conducted in the aftermath of the 2010 event indicate that heavy precipitation has increased within the area over the last 30 years, and that precipitation totals in excess of the 2010 event are possible (Higgins et al., 2011; Moore et al., 2012; Keim et al., 2018). Given current flood protection standards for local levees, it is possible that extreme precipitation in excess of the 2010 event could exceed design standards, resulting in levee failure and impacts to sustainable resilience for both infrastructure and the community.

Development of Worst-Case Scenario for Local Flood Protection Infrastructure

To better understand potential impacts to heavy precipitation (95th percentile and above) resulting from climate-based changes for the Nashville area, and how those changes may be related to sustainable resilience, analysis using both local data and downscaled CMIP5 climate projections is employed. In recognition of the limitations associated with the use of GCMs for local projection, the analysis is undertaken to provide better understanding of model processes, and how they may be related to future scenario development to aid in sustainable resilience planning.

First, the significance of precipitation on the Cumberland River is determined in order to validate risk posed to local flood protection infrastructure resulting from the scenario selected above. Daily stage (height)[17] and precipitation observations[18] from 2004 to 2018 are determined to be positively correlated where stage height is a lagging variable (cross-correlation is used to identify the optimal lag period of two days between variables) as shown at Figure 18.

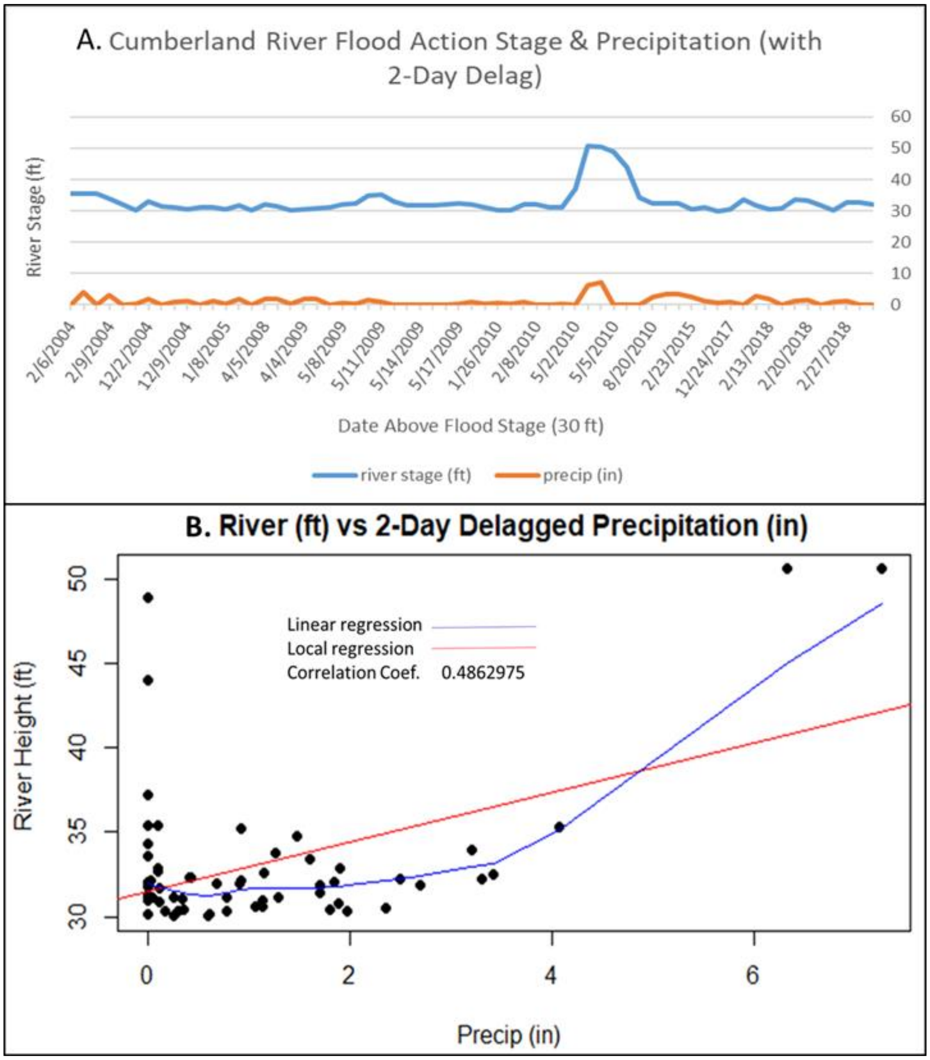

Figure 18. A. Plot of Time-Series De-Lagged Variables (River Stage Height and Precipitation) above Flood Stage for Cumberland River (>= 30 ft), B. Plot of De-Lagged Variables (River Stage Height and Precipitation) above Flood Action Stage for Cumberland River (>= 30 ft) with Linear and Local Regression Lines & Correlation Coefficient

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[17] Stage height data obtained from USACE river gage located at Davidson County, Shelby Street Bridge, Nashville TN (USACE, 2018d).

[18] Daily precipitation data obtained from the NOAA online data center for Nashville, TN (NOAA, 2018c).

A lagged regression model using the optimal lag period produces an Adjusted R-squared value of 0.88. A correlation coefficient of 0.49 is obtained using de-lagged data at river action stage and above with associated daily precipitation values.[19] This suggests that precipitation is significant to riverine flooding, and that extreme precipitation events pose a threat to local levees. As the Cumberland River is the receiving stream for the metropolitan area, this finding is consistent with current, local flood risk assessment (Nashville-Davidson County, 2015c). To assess the potential for experiencing extreme precipitation events in the future, analysis using local precipitation gage data (NOAA, 2018c) with downscaled Coupled Model Intercomparison Project (CMIP5) climate model outputs for a worst-case scenario (RCP 8.5) is employed (NOAA, 2018c; Maurer et al., 2007; Meehl et al., 2007; Hibbard et al., 2007; Meehl et al., 2009; Taylor et al., 2012; Reclamation, 2013; Reclamation, 2014).

Analysis of standardized precipitation anomalies using CMIP5 modeled outputs from twenty models for Nashville (covering four, 12 by 12 km grids) is conducted in a manner consistent with current climate literature (Hansen et al., 2012; Gao et al., 2017; Ryu & Hahoe, 2017). A list of CMIP5 models used is provided in Appendix H. Linear interpolation between locally observed daily precipitation (NOAA, 2018c) and anomalies calculated for CMIP5 observed daily precipitation (Maurer et al., 2002; Maurer et al., 2007) over the same period (1950-1999) is employed to determine thresholds (in the form of anomaly-equivalents) for the magnitude of both 24-hour and 3-day heavy events based on local intensity-duration-frequency (IDF) tables (NOAA, 2018d). Observed data derived from CMIP5 are scaled to account for multiple variables including variation in land cover and changes in terrain across North America (Maurer et al., 2002; Maurer et al., 2007). Due to scaling scling, a comparison of CMIP5 observed data and locally observed data from NOAA gage stations reveals a similarity in pattern of precipitation highs and lows for both 1-day and 3-day annual maxima, but a consistent difference in magnitude of maximum events likely corresponding to factors noted by Maurer et al. (2002).

We deem it necessary to compare local NOAA gage station data to CMIP5 observed data to relate CMIP5-derived anomalies to actual observed magnitudes if specific IDF-derived thresholds are desired for worst-case precipitation event analysis. Otherwise, percentile-based

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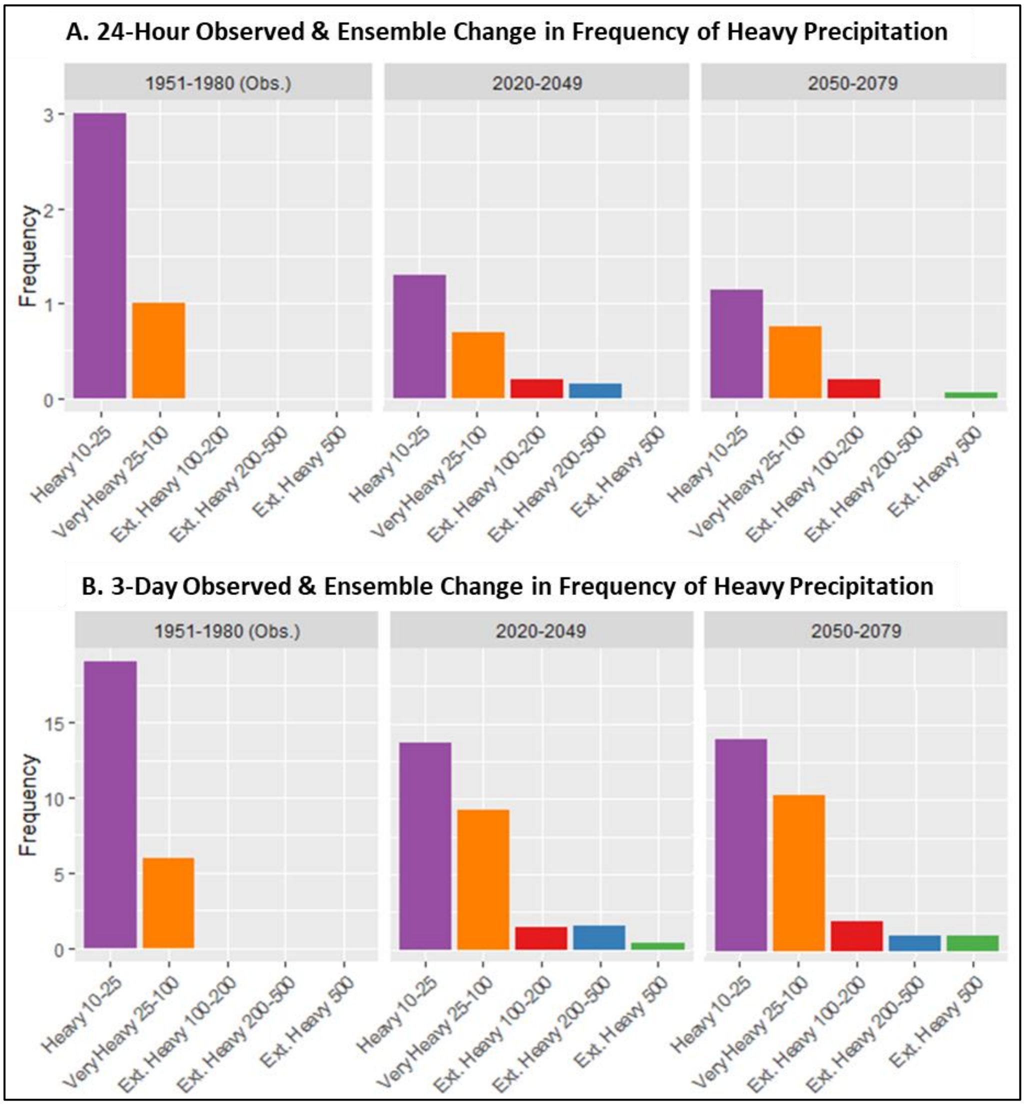
[19] Flood stage for the Cumberland River at the gage nearest local levees is 12.19 meters (40 feet). Action stage is at 9.14 meters (30 feet), a level determined by USACE as requiring close monitoring and preparation for action in the event of flood (USACE, 2018d).

thresholds can be established (z-score analysis) to determine exceedances consistent with (Hansen et al., 2012; Gao et al., 2017). Establishment of a linear relationship between locally observed precipitation gage data (NOAA, 2018c) and anomalies for CMIP5 observed data (Maurer et al., 2007) for 24-hour and 3-day events allows for calibration of historic threshold exceedance (as anomaly-equivalents) based on known events from local record, and the ability to estimate projected event magnitudes from modeled anomalies used in Nelson et al. (2019). A summary of the method used is at Appendix I.

The maximum 24-hour and 3-day event thresholds were selected (highest observed historical rainfall for the area) based on the Nashville 2010 flood, where precipitation amounts exceeded NOAA IDF thresholds for the 1000-year storm for both 2- and 3-day events (NOAA, 2018d). The maximum historic thresholds were used in addition to the IDF-based thresholds for the analysis. Anomaly-equivalents for IDF values were determined to establish thresholds for analysis, categorized as i) 10-25 year event, ii) 25-100 year event, iii) 100-200 year event, iv) 200-500 year event, and v) 500+ year event. These thresholds were used in analysis of projected (future) extreme precipitation scenarios by comparing the frequency (count) and intensity (count multiplied by magnitude) of threshold exceedances between the baseline period (1951-1980) and future periods though the remainder of the twenty-first century, determined by modeled outputs in a manner consistent with prior studies (Hansen et al., 2012; Gao et al., 2017; Ryu & Hahoe, 2017). The period (1951-1980) is selected as the baseline period for analysis of frequency and magnitude of threshold exceedance due to minimal signature associated with effects of climate change (Hansen et al., 2012).

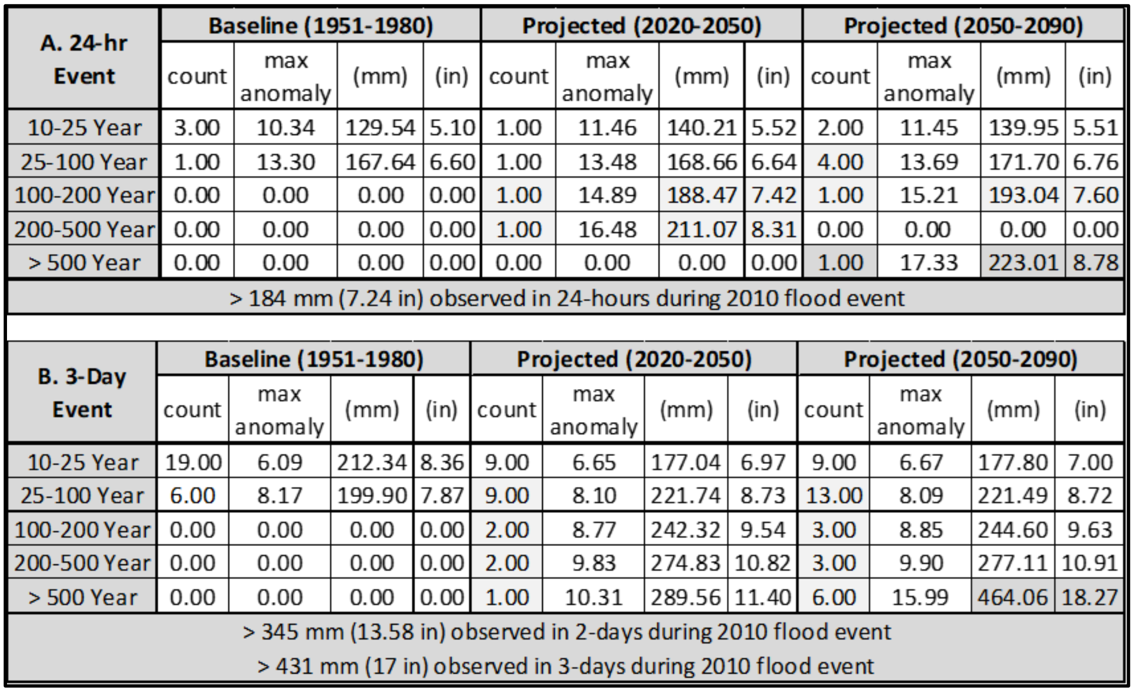
Analysis results suggest that precipitation events of similar or greater magnitude to those experienced in 2010 may be plausible given ensemble modeled outputs (average of results for all 20 models) as demonstrated in Nelson et al., 2019. Local observed data over the baseline period does not contain occurrences of 'extremely heavy 100-200 year events' and above for 24-hour and 3-day totals, including the second largest event on record for the area, set in 1979 at 167.74 mm (6.6 inches) (NOAA, 2018c). Projected, or future, periods (based on modeled outputs) contain occurrences of exceedances in thresholds at the 100-200, 200-500, and greater than 500-year event. The frequency of lower magnitude events at the 10-25 year threshold appears to decrease in future periods, a result consistent with similar analyses (Gao et al., 2017; Bao et al., 2017; Prein et al., 2017b). Changes in frequency (count) of threshold exceedance for observed and projected periods are displayed in Figure 19.


A. 24-Hour Observed & Ensemble Change in Frequency of Heavy Precipitation

B. 3-Day Observed & Ensemble Change in Frequency of Heavy Precipitation

Figure 19. Change in Frequency (Count) of Threshold Exceedance for Heavy Precipitation

When both frequency of exceedance and magnitude of maximum anomalies are considered and compared to the 2010 event, the potential for more frequent and larger magnitude is plausible within projected periods (as shown in Table 19). This suggests that Nashville should consider levee failure beyond its present protective design due to plausible future hydrologic events.



A. 24-hr Event	Baseline (1951-1980)				Projected (2020-2050)				Projected (2050-2090)			
	count	max anomaly	(mm)	(in)	count	max anomaly	(mm)	(in)	count	max anomaly	(mm)	(in)
10-25 Year	3.00	10.34	129.54	5.10	1.00	11.46	140.21	5.52	2.00	11.45	139.95	5.51
25-100 Year	1.00	13.30	167.64	6.60	1.00	13.48	168.66	6.64	4.00	13.69	171.70	6.76
100-200 Year	0.00	0.00	0.00	0.00	1.00	14.89	188.47	7.42	1.00	15.21	193.04	7.60
200-500 Year	0.00	0.00	0.00	0.00	1.00	16.48	211.07	8.31	0.00	0.00	0.00	0.00
> 500 Year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	17.33	223.01	8.78
> 184 mm (7.24 in) observed in 24-hours during 2010 flood event												

B. 3-Day Event	Baseline (1951-1980)				Projected (2020-2050)				Projected (2050-2090)			
	count	max anomaly	(mm)	(in)	count	max anomaly	(mm)	(in)	count	max anomaly	(mm)	(in)
10-25 Year	19.00	6.09	212.34	8.36	9.00	6.65	177.04	6.97	9.00	6.67	177.80	7.00
25-100 Year	6.00	8.17	199.90	7.87	9.00	8.10	221.74	8.73	13.00	8.09	221.49	8.72
100-200 Year	0.00	0.00	0.00	0.00	2.00	8.77	242.32	9.54	3.00	8.85	244.60	9.63
200-500 Year	0.00	0.00	0.00	0.00	2.00	9.83	274.83	10.82	3.00	9.90	277.11	10.91
> 500 Year	0.00	0.00	0.00	0.00	1.00	10.31	289.56	11.40	6.00	15.99	464.06	18.27
> 345 mm (13.58 in) observed in 2-days during 2010 flood event > 431 mm (17 in) observed in 3-days during 2010 flood event												

Table 19. Summary of Observed and Projected Frequency & Magnitude of Heavy Precipitation

Both exceedances in frequency and magnitude of maximum modeled anomalies are highlighted in Table 19. The frequency of both 24-hour and 3-day events exceeding the 200-year threshold increases in projected periods (with a slightly greater increase in frequency after mid-century for 200-500+ year storms, where greater significance is evident in 3-day precipitation events). The magnitude of the maximum modeled precipitation occurrence for a 24-hour event increases by over twenty-one percent above the magnitude observed in 2010, approximating a precipitation event somewhat above the 500-year threshold. The maximum modeled 3-day event increases by over seven percent above the magnitude observed in 2010. While the resulting increase in the 3-day event is smaller than that for a 24-event, it is well above the 1,000-year threshold and exceeds the record-setting rainfall observed in 2010 for a 3-day period (also exceeding the 1,000-year threshold). The decadal trajectory for projected precipitation intensity (threshold exceedance count multiplied by maximum anomaly magnitude) for 3-day events, which may be seen to produce the most severe conditions based on potential for levee impact due to increased river stage following at least 2 days of heavy rain, can be seen in Figure 20.

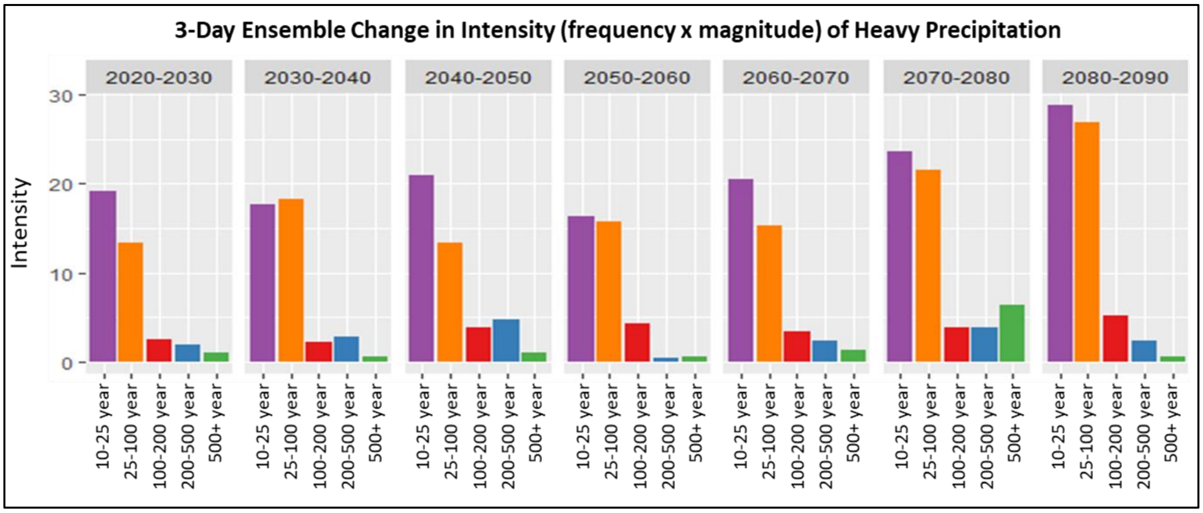


Figure 20. Decadal Trajectory for Ensemble Projected Heavy Precipitation for 3-Day Events

Due to relatively significant uncertainty in GCM prediction, especially when used at local scales, Figures 19 and 20 are not intended to represent a precise estimation for future extreme precipitation change, but rather to illustrate that extreme event occurrence may be plausible in any decade based on modeled outputs and is not necessarily more prevalent post mid-century. The methods employed here to develop a worst-case scenario for evaluating future sustainable resilience are not meant to predict or to represent the probability of extreme events, but to demonstrate the plausibility of such events in future planning horizons.

An increase in extreme precipitation events over the remainder of the century is largely consistent with results obtained in other recent studies including EPA (2016), stating likelihood of trends since mid-20th century, resulting in a 27% increase in heavy rainfall; and research conducted on counties in the state of Tennessee by Camp et al. (2016), which found an increase in both frequency and magnitude of extremely heavy precipitation with an average of over seven percent increase in magnitude for 3-day precipitation events above the 95th percentile. Differences in estimated heavy precipitation increase across studies highlight the need for additional research and improved ability to identify heavy rainfall trajectories more specifically by percentile (threshold) to better understand nuances in frequency and magnitude change both above and below the 95th percentile.

Conclusions

Based on a review of recorded dam and levee failures, it is apparent that overtopping and breach of earthen dams/levees due to hydrologic events is of foremost concern. This poses a significant threat to sustainable resilience for infrastructure and communities protected by these barriers. Given that extreme hydrologic events (in the form of precipitation at or greater than the 95th percentile) are projected to increase in both frequency and magnitude over the remainder of the century when compared to observed baselines and historic events, this concern is exacerbated.

Using the Nashville, TN area as an illustrative example, where a significant flood in 2010 caused an earthen levee to fail, it was shown that, despite post-event improvements made to the levee, overtopping and breach due to a future extreme hydrologic event poses a potentially significant threat. These results suggest that additional flood adaptation strategies (updating recurrence intervals, risk assessments, public education, and other actions to reduce risk) are likely needed to sustain desired performance of flood protection infrastructure and prevention of uncontrolled release of water leading to harmful social, economic, and environmental resources. While this analysis focuses on flood protection infrastructure, the methods used here can be generalized to other types of infrastructure susceptible to flood risk, and to other locations based on selection of local data and identification of geographic area via CMIP5.

CHAPTER VI

Conclusion

The body of work represented by this dissertation began with a need to understand how the concepts of risk, vulnerability, resilience, sustainability, and adaptive capacity are linked, and a desire to demonstrate how aligning these concepts to better fit within the spatial and temporal needs of complex systems may improve the understanding of how to assess complex adaptive system performance. The process produced a multi-step approach, resulting in four peer-reviewed papers, which provide the following accomplishments.

Chapter 2 provided a gap analysis of the concepts of vulnerability, resilience, and sustainability to identify strengths and weaknesses in their application to complex system assessment. Our investigation revealed that differences in perspective and scale across individual concepts produce strengths and weaknesses (gaps) when assessing a complex system. When used independently to assess complex system performance over time, a single concept can overlook varying aspects of system quality leading to deficient or incomplete assessment and maladaptive consequences. Further analysis of each concept in terms of focal lens, goals, spatial and temporal scale, defining terminology, and key measures and practice, revealed specific areas where gaps can be filled and value can be added through focused integration. This resulted in a new concept, termed sustainable resilience, that accounts for changes in sustainability capital and sub-system vulnerability and their ability to increase or decrease system-wide resilience over time through moderation of adaptive capacity.

Chapter 3 built upon work described in Chapter 2 to develop a unifying framework for sustainable resilience that can properly characterize complex adaptive social-environmental systems and assess their behavior in response to short-term disruptions and long-term challenges in the context of decision-making. The framework uses a serial process that enables operationalization at varying scales (depending on the needs of the user and system), allowing both researchers and practitioners the flexibility to utilize familiar assessment methodologies as well as the ability to employ more sophisticated and nascent approaches, while providing a path diagram to assist users in exploring relationships between concepts. Use of cyclical iterations and development of multiple scenarios (representing dynamic processes) ensures that decision makers understand how each concept may influence the other. This provides the ability to integrate and balance of priorities from different perspectives and achieve more effective allocation of resources for adaptation and/or transformation strategies. A detailed walk-through of the assessment framework for sustainable resilience is provided with illustration of use of methods and applications for each phase in the assessment process.

In the process of illustrating methods and applications for use of the framework developed in chapter 3, a need arose to collect and consolidate the vast array of indicators and associated metrics for use in community resilience assessment, which led to the development of Chapter 4. In addition to a rapidly growing number of indicators across literature, it was found that redundancy and inconsistency in their application generates confusion regarding what should be included in a community resilience assessment and how to balance the use of indicators to achieve meaningful results. This work resulted in the identification and consolidation of over 1,000 individual indicators across social, economic, and environmental indices. Through a process of iterative review and consolidation applied through a classification system developed for assessing sustainable resilience of communities, a final set of non-duplicative indicators and associated metrics is provided to assist in operationalizing the practice of community resilience assessment. The set of indicators is classified based on identification of: primary and secondary capital systems; sustainable resilience domains; and phases of the sustainable resilience assessment framework. While the primary intent was focused on how the indicator set may be used within the framework for sustainable resilience, it is ultimately intended to assist users with indicator selection for any form of community resilience assessment.

Chapter 5 built upon Chapters 3 and 4 to further illustrate how the assessment framework for sustainable resilience can be used to understand dynamic systems and their possible impacts upon communities. Failure mode analysis was conducted for over 700 dams and 1,100 levees in the U.S., with the results indicating that overtopping and breach due to hydrological events (extreme or prolonged precipitation and/or storm) are the leading causes of both dam and levee failure. The failure mode analysis results were used to develop high-risk scenarios for flood protection infrastructure, which were then applied to Nashville, TN using local and modeled data to assess possible impacts to the community resulting from extreme precipitation events in the future. Anomaly analysis of GCM data via CMIP5 and determination of precipitation thresholds using local, historically derived data in conjunction with worst-case data from the 2010 Nashville flood suggest that extreme precipitation is likely to increase above the 95th percentile for both 1 and 3-day rain events. Despite post-event improvements made to a levee that failed in 2010, results also suggest that overtopping and breach due to a future extreme hydrologic event poses a potentially significant threat. Additional flood adaptation strategies (updating recurrence intervals, risk assessments, public education, and other actions to reduce risk) are likely needed to sustain desired performance of flood protection infrastructure. Methods used in this analysis can be generalized to other types of infrastructure susceptible to flood risk, and to other locations based on selection of local data and identification of geographic area via CMIP5.

In summary, the body of work represented in this document provides the following advances in the study and application of resilience assessment:

1. Development and definition of a new approach to dynamic resilience assessment for complex adaptive systems (e.g., sustainable resilience);
2. Development and illustration of a dynamic assessment framework for sustainable resilience;
3. Consolidation of over 1,000 indicators and associated metrics from across multiple fields, using a novel classification scheme designed to aid in selection and application of indicators to the assessment framework for sustainable resilience;
4. A detailed demonstration of assessing impacts to community sustainable resilience through examination of high-risk scenarios for flood protection infrastructure in conjunction with analysis of projected extreme precipitation using local and modeled data from CMIP5, and synthesis of results to assess possible impacts to Nashville, TN based on worst historical events and the potential for exceeding events and established performance thresholds; and
5. An alternative approach to traditional FMEA, using existing data (both qualitative and quantitative) as well as modeled data from multiple, authoritative sources. This information is used to examine not only the state of flood protection infrastructure, but trends in large-scale mechanisms (lack of maintenance, changes in hydrological patterns, changes in population, etc.) that effect the systems' overall ability to perform intended functions, and to better understand possible implications for sustainable resilience.

While the items above are designed with the concept of sustainable resilience in mind, in each case, the results and tools provided can be generalized to apply to any resilience assessment framework, any type of infrastructure, and any community based on availability of data. The results of this research should help push the boundaries of operational resilience assessment and use of results to increase community goals toward survival, well-being, and long-term preparedness. These efforts offer a new interpretation that can potentially help communities in building adaptive capacity and applying resources in a more efficient manner that leads to greater effectiveness in achieving resilience goals.

The methods employed to develop worst-case scenarios for evaluating future sustainable resilience are not meant to predict or to represent the probability of extreme events, but to demonstrate the plausibility of such events in future planning horizons. While this research focused on a single community and a specific hazard (, the methods developed can be generalized and applied to any type of system, hazard, or risk-based environment to better understand performance over time (e.g., sudden or incremental shifts in economy, governance, or the possibility of intentional threat). In addition, the framework allows for consideration and scenario development to address emerging risk, hazards that we may not have encountered in the past, but may become more pressing in the future due to cumulative effects or exceedance of unprecedented threshlds. While there is no feasible way to address the unkown, the sustainable resilience framework suggests that adaptive capacity is critical to anticipation, preparation, response, recovery, and overall long-term viability for any system under risk, whether certain or uncertain. Investments made and strategies implemented to build adaptive capacity today will likely define the ability to act effectively in the future.

The tools and methods provided herein are a starting point intended to increase understanding and access to needed definitions, an assessment framework, a set of indicators and metrics, a new way of looking at data to elicit plausible risk scenarios, and illustration of how each of these items may be employed. The intended audience for tools and methods provided is one that has sufficient information and understanding regarding how to employ and constructively use information and processes, or an audience that can be educated sufficiently to employ them. Ideally, it is hoped that any audience desiring to understand the concepts provided can have access to both the tools and the training needed to operationalize resilience assessment.

Although there are many limitations associated with the work as described (scaled application, sub-setting of indicators, testing on a single community, etc.), this research sets the stage for development of new applications and improved methods (e.g., new policy concepts, new measurement techniques, new models, etc.). It is understood that this work cannot provide a universal solution to a very complex problem – making communities more resilient - but it is hoped that this contribution will improve understanding and common practice through demonstration.

Additional research is needed to further test and validate the established Sustainable Resilience Assessment Framework, including assessment of various types of complex adaptive systems. In addition, testing, validation, and benchmarking of the set of indicators and metrics for assessing the sustainable resilience of communities is needed to help in understanding how to prioritize indicators and which may matter most in assessment processes. Lastly, additional effort is needed to compare multiple applications and outcomes associated with the method developed to relate CMIP5 anomalies to locally derived precipitation data to better translate modeled data into meaningful information that can help communities understand plausible implications for worst-case climate based scenarios through use of familiar and non-familiar methods and sources. Again, the methods employed to develop worst-case scenarios for evaluating future sustainable resilience are not meant to predict or to represent the probability of extreme events, but to demonstrate the plausibility of such events in future planning horizons.

APPENDIX

Appendix A: Dictionary of Terms and Concepts (1)

Term	Definition
Ability to Resist Systemic Disruption	Degree to which hazard-induced impacts to the system do not result in disruptions in system service (a static state); the ratio of impacts to performance measure thresholds.
Adaptation	An incremental change undertaken either in anticipation of stress, or in response to stress, intended to improve survivability or quality.
Adaptation/Transformation Strategies	Actions (collective or independent) developed by decision makers as part of an assessment/planning process that are intended to reduce anticipated injury and loss to a system; transformation strategies can result in a new system definition.
Adaptive Capacity	Also called adaptability, the ability to cope with, recover from, and adapt/transform through effective use of available sustainability capital in response to a hazardous event at a point in time.
Anticipatory Coping Capacity	A subset of adaptive capacity that specifically refers to conditions existing prior to a hazardous event; the ability to reduce the impact of a hazardous event via preparation/readiness. Includes planned individual actions, community support systems, or system-wide policies and programs in-place at the time of a hazardous event that improve the effectiveness and range of actions available in response to the event.
Complex Adaptive Systems	Systems characterized by multi-scalar and cross-scalar dynamics, feedback loops, interactions, that exhibit changes in system function and/or objectives over time.
Coupled Systems	Systems that are linked such that a system(s) may depend on one or more systems whereby the quality or fate of any individual system is shared or impacted by others.
Contextual Vulnerability	Extent to which a system is likely to experience losses from some hazard based on conditions at a specific point in time immediately prior to the onset of the hazard (a static, pre-existing or current state); a function of exposure, sensitivity, and anticipatory coping capacity.

Coping Capacity	Also called capacity of response, adaptive capacity, and coping ability. Refers to the ability to absorb shock and respond to immediate threats.
Economic Capital	Money, property, credit, markets, other forms of financial capital that provide currency for economic activity and allow for transactions needed to ensure system viability and insure against risk.
Environmental Capital	Includes both built and natural resources (sometimes called natural capital), refers to renewable and non-renewable natural resources (air, water, land, vegetation, wildlife, energy) essential for human survival and economic activity. Most are non-substitutable (e.g., the atmosphere cannot be replaced). Non-renewables includes fossil fuels, mineral deposits, extinction of species, etc. Also includes engineered/built structures and supporting infrastructure systems.
Exposure	The magnitude (severity) and extent (in terms of spatial extent and temporal duration) of a hazard.
Hazard	A threat to a system, either a perturbation, disturbance, or stressor.
Preparedness	A state of readiness that requires anticipation, planning, and actions needed to support response and recovery from disturbance.
Rapidity	Speed of recovery from a state of disturbance to an acceptable level of performance that can be similar to the pre-disturbance or a new state.
Recovery	A time in which a system attempts to restore system function immediately following a hazard.
Redundancy	Existence and availability of duplicate or alternate components within a system, such that if one component fails, an alternate can perform its function to prevent systemic disruption or failure.
Reliability	Ability to operate without failure under specified conditions.
Resilience	Ability of a system to resist systemic disruption, recover, adapt, and transform given a hazardous event in order to maintain desired performance.
Resilience Assessment	Evaluates/measures system performance with respect to failure scenarios, resulting impacts, time to achieve recovery, and associated costs using quantitative and semi-quantitative methods; it can be applied at multiple scales.

Resilient systems	Systems that possess physical, social, and organizational characteristics (both natural and designed/built) that allow the system to minimize systemic performance disruption given a hazard scenario, recover rapidly and effectively following a hazard scenario, or transform in response to a hazard in order to provide an acceptable level of service to society over the life of the system.
Risk	Occurrence of an event with an associated probability that results in a set of consequences.
Risk Appetite/Risk Tolerance	The amount of risk of adverse impacts that a system is willing to accept, usually as part of a trade-off with some other expected gain (e.g. financial).
Robustness	Ability to operate without failure under changing or adverse conditions (tests bounds of reliability).
Sensitivity	Innate physical characteristics and/or social structures that influence the degree to which impacts will be suffered given a certain level of hazard exposure.
Social Capital	Also called human capital, refers to the networks and relationships among people that enable society to function (e.g., community groups, associations, education, welfare, communication, law, government, policy, among others).
Social-Environmental System	Complex adaptive systems that are subject to multi-scalar relationships between the system, sub-systems, and external systems and where interactions between physical and non-physical factors are common. Related terms include: Coupled Human-Environmental System, Social-Ecological System, and Coupled Human-Natural System.
Strategic	Designed or planned to serve a purpose or intent through identification and alignment of long-term goals and objectives, and the means of achieving them.
Sustainability	Ability to operate without failure by achieving balance across availability and performance of critical resources (social, environmental, and economic) such that negative impacts to the environment are reduced while positive impacts to society and economy are maintained at an acceptable level both now and into the future.
Sustainability Assessment	Evaluates/measures current and projected health (availability and performance) of critical social, environmental, and economic resources needed in order for a system to function and survive using quantitative and semi-quantitative methods; it can be applied at multiple scales.

Sustainability Capital	The set of social, economic, and environmental capital that supports the existence of a community.
Sustainable Development	Development that maintains a desired level of system performance without compromising trans-generational equity in the availability of three key resources: social, environmental, and economic capital.
Sustainable Resilience	Ability of a system to maintain desired system performance by changing in response to expected and unexpected challenges over time, while simultaneously considering intra-system and inter-generational distribution of impacts and sustainability capital.
System Objective	A primary goal of the system as defined by the purpose of the system.
Systemic Disruption	Situation in which a system performance measure no longer provides an acceptable level of service.
Systemic Failure	Situation in which multiple system objectives are severely disrupted or irreversibly compromised.
Threshold	Value delineating between acceptable and unacceptable performance of a system objective.
Transformation	Change from an existing state to a new state through gradual transition (incremental adaptation) or abrupt transition such that the original system objectives are significantly altered.
Uncertainty	The range of possible values (multiple possible outcomes) within which the true value of a measurement lies. Various methods can be used to incorporate uncertainty into decision making process.
Vulnerability	Extent to which a system is likely to experience losses due to a hazard; a function of exposure, sensitivity, and adaptive capacity.
Vulnerability Assessment	Evaluates/measures levels of exposure, sensitivity, and adaptive capacity of critical system parts, components, or sub-components to determine the potential for loss related to a hazardous event using quantitative or semi-quantitative methods.

Appendix B: Dictionary of Terms and Concepts (2)

Term	Definition
Ability to Resist Systemic Disruption	Degree to which hazard-induced impacts to the system do not result in disruptions in system service (a static state); the ratio of impacts to performance measure thresholds.
Adaptation	An incremental change undertaken either in anticipation of stress, or in response to stress, intended to improve survivability or quality.
Adaptation/Transformation Strategies	Actions (collective or independent) developed by decision makers as part of an assessment/planning process that are intended to reduce anticipated injury and loss to a system; transformation strategies can result in a new system definition.
Adaptive Capacity	Also called adaptability, the ability to cope with, recover from, and adapt/transform through effective use of available sustainability capital in response to a hazardous event at a point in time.
Anticipatory Coping Capacity	A subset of adaptive capacity that specifically refers to conditions existing prior to a hazardous event; the ability to reduce the impact of a hazardous event via preparation/readiness. Includes planned individual actions, community support systems, or system-wide policies and programs in-place at the time of a hazardous event that improve the effectiveness and range of actions available in response to the event.
Complex Adaptive Systems	Systems characterized by multi-scalar and cross-scalar dynamics, feedback loops, interactions, that exhibit changes in system function and/or objectives over time.
Contextual Vulnerability	Extent to which a system is likely to experience losses from some hazard based on conditions at a specific point in time immediately prior to the onset of the hazard (a static, pre-existing or current state); a function of exposure, sensitivity, and anticipatory coping capacity.
Coping Capacity	Also called capacity of response, adaptive capacity, and coping ability. Refers to the ability to absorb shock and respond to immediate threats.
Economic Capital	Money, property, credit, markets, other forms of financial capital that provide currency for economic activity and allow for transactions needed to ensure system viability and insure against risk.
Environmental Capital	Includes both built and natural resources (sometimes called natural capital), refers to renewable and non-renewable natural resources (air, water, land, vegetation, wildlife, energy) essential for human survival and economic activity. Most are non-substitutable (e.g., the

	atmosphere cannot be replaced). Non-renewables includes fossil fuels, mineral deposits, extinction of species, etc. Also includes engineered/built structures and supporting infrastructure systems.
Exposure	The magnitude (severity) and extent (in terms of spatial extent and temporal duration) of a hazard.
Hazard	A threat to a system, either a perturbation, disturbance, or stressor.
Recovery	A time in which a system attempts to restore system function immediately following a hazard.
Resilience	Ability of a system to resist systemic disruption, recover, adapt, and transform given a hazardous event in order to maintain desired performance.
Risk Appetite/Risk Tolerance	The amount of risk of adverse impacts that a system is willing to accept, usually as part of a trade-off with some other expected gain (e.g. financial).
Social Capital	Also called human capital, refers to the networks and relationships among people that enable society to function (e.g., community groups, associations, education, welfare, communication, law, government, policy, among others).
Social-Environmental System	Complex adaptive systems that are subject to multi-scalar relationships between the system, sub-systems, and external systems and where interactions between physical and non-physical factors are common. Related terms include: Coupled Human-Environmental System, Social-Ecological System, and Coupled Human-Natural System.
Strategic	Designed or planned to serve a purpose or intent through identification and alignment of long-term goals and objectives, and the means of achieving them.
Sustainability	Ability to operate without failure by achieving balance across availability and performance of critical resources (social, environmental, and economic) such that negative impacts to the environment are reduced while positive impacts to society and economy are maintained at an acceptable level both now and into the future.
Sustainability Assessment	Evaluates/measures current and projected health (availability and performance) of critical social, environmental, and economic resources needed in order for a system to function and survive using quantitative and semi-quantitative methods; it can be applied at multiple scales.
Sustainability Capital	The set of social, economic, and environmental capital that supports the existence of a community.
Sustainable Development	Development that maintains a desired level of system performance without compromising trans-generational equity in the availability of three key resources: social, environmental, and economic capital.

Sustainable Resilience	Ability of a system to maintain desired system performance by changing in response to expected and unexpected challenges over time, while simultaneously considering intra-system and inter-generational distribution of impacts and sustainability capital.
System Objective	A primary goal of the system as defined by the purpose of the system.
Systemic Disruption	Situation in which a system performance measure no longer provides an acceptable level of service.
Systemic Failure	Situation in which multiple system objectives are severely disrupted or irreversibly compromised.
Threshold	Value delineating between acceptable and unacceptable performance of a system objective.
Transformation	Change from an existing state to a new state through gradual transition (incremental adaptation) or abrupt transition such that the original system objectives are significantly altered.
Uncertainty	The range of possible values (multiple possible outcomes) within which the true value of a measurement lies. Various methods can be used to incorporate uncertainty into decision making process.
Vulnerability	Extent to which a system is likely to experience losses due to a hazard; a function of exposure, sensitivity, and adaptive capacity.
Vulnerability Assessment	Evaluates/measures levels of exposure, sensitivity, and adaptive capacity of critical system parts, components, or sub-components to determine the potential for loss related to a hazardous event using quantitative or semi-quantitative methods.

Appendix C: Indicators and Metrics for Assessing Community Sustainable Resilience

(see following pages)

Also available in filterable/searchable format at: https://blindreview1.shinyapps.io/indicators/

Indicator Title	Primary Capital System	Secondary Capital System	Sustainable Resilience Domain	Quantitative Metrics	Qualitative Metrics	Primary and (Secondary) References	Resource (R) / Driver (D)	Rationale for Resource (R) / Driver (D)
Socially organized	Social	Community Composition	Survival	# community-led groups that provide support to the community; # community advisory groups for business, industry, agriculture, etc.; # of trade unions or other formally recognized local chapters; # community gardens or other shared assets that contribute to the community; # of volunteer-based organizations (fire fighters, community watch, shelters, food pantries, Red Cross, Good Will, Kiwanis, Rotary, etc.); # community-wide events per year; % of population engaged in volunteering during the previous year	Relative health of community-led organizations in terms of recruiting and sustaining members and attracting volunteers; existence of informal leadership within the community that can rally and organize community members in time of crisis (church leaders, business leaders, etc.); relative health of volunteer-based social support organizations	Cabell and Oelofse, 2012'; 'Cox and Hamlen, 2015'; NAS, 2017; Sempier et al., 2010; Thoms, 2016; Yoon et al., 2016; DHS, 2016; UNISDR, 2017; (Levin, 1999; Holling, 2001; Milestad and Darnhofer, 2003; Atwell et al., 2010; McKey et al., 2010)	Resource and Driver	Low levels of cohesion indicate greater sensitivity and decreased coping ability (driver); high levels of cohesion increase social capital by improving collective action, which can increase adaptive capacity (resource)
Community identity, cohesion end engagement	Social	Community Composition	Well-being	% resident participation in community-wide events; % voting age population that participates in presidential elections; % participation in town hall meetings, public hearings, etc.	Relative level of trust (resident trust in government and leadership, and trust amongst residents and resident groups); sense of close community (across small communities, and between neighborhoods within large communities); level of community engagement and interest in addressing and solving community issues	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; NAS, 2017; 'Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; 'Parsons et al., 2016'; 'Cutter et al., 2014'; Cutter, 2016c; 'McManus et al., 2012'; Cabell and Oelofse, 2012'; Shen et al., 2011;	Resource	High levels of trust and engagement build social capital, which can increase adaptive capacity

						Hughes & Bushell, 2013; UNISDR, 2017; (Berkes et al., 2003; Darnhofer et al., 2010; Milestad et al., 2010; Shava et al., 2010; Peacock et al., 2010; Sherrieb et al., 2010)		
Family/household composition	Social	Community Composition	Survival	% single parent families; % families with children 13-17, 6-12; 3-5, 2 and under; % single person households; % multi-family households; # of children per household; # of households caring for an elderly parent/grandparent; % population in group housing; % seniors in group housing ; % children in group housing; % households with home care/need for assistance (medical, core activities, etc.)	Identification of areas with predominant demographic characteristics (clusters)	Parsons et al., 2016'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; Thoms, 2016; Kontakosta & Malik, 2018	Driver	Higher levels of individual/households with strong physical and mental capacity indicates lower sensitivity, and can increase coping ability
Population age	Social	Community Composition	Survival	Median age; % age makeup (adults over 65, adults between 50-64, adults 35-49, adults 25-34, adults 18-24, children 13-17, children 6-12, children 3-5, children 2 and under)	Identification of areas with predominant demographic characteristics (clusters)	Cutter et al., 2014; Cutter, 2016c; Sharifi, 2016; NAS, 2017; Thoms, 2016; Yoon et al., 2016; Kontakosta & Malik, 2018	Resource and Driver	Higher levels of individual/households with strong physical and mental capacity indicates lower sensitivity and greater coping ability (driver); balanced age structure also builds social capital by providing a stable workforce, which can increase adaptive capacity (resource)
Diversity	Social	Community Composition	Survival	% racial/ethnic makeup; ratio of male to female; % religious affiliation; % population with disability or special needs; % migrant population; % population	Identification of areas with predominant demographic characteristics (clusters)	Sharifi and Yamagata, 2014; ' 'Sharifi, 2016'; 'Cox and Hamlen,	Driver	Populations that may be marginalized or isolated in terms of identify and special needs have higher sensitivity and may

				without proficient English speaking skills		2015'; Thoms, 2016; Yoon et al., 2016; Kontakosta & Malik, 2018		have less coping ability
Equality, acceptance, and inclusion	Social	Community Composition	Well-being	% median income by gender, race, religion, etc.; # hate related crimes per year; # demonstrations actively protesting a specific culture, religion, etc. % absolute difference in male and female income; % absolute incomes difference by race/ethnicity; inverted Gini coefficient	General respect for different cultures and races; inclusion of residents of all backgrounds, abilities, genders, roles in community events; positive/healthy behavioral norms; open hostility, ostracism, or exclusion of people based on race, culture, religion, sexual orientation, etc. There is equality in income across gender, race/ethnicity. Fair and transparent policies for immigrants and children	Sharifi and Yamagata, 2014; "Sharifi, 2016'; 'Cutter et al., 2014'; Cutter, 2016c; Thoms, 2015; U.N., 2015; UNISDR, 2017; (Norris et al., 2008; Sherrieb et al., 2010; Enarson, 2012)	Resource and Driver	Lack of economic power and social acceptance of these populations can increase sensitivity and reduce coping ability (driver); openly prejudicial attitudes and segregation leads to lack of community cohesion and trust, reducing social capital and adaptive capacity (resource)
Education and skill level	Social	Community Composition	Well-being	% population with graduate degree or higher, % population with 4-year college degree, % population with 2-year degree, % population with technical degree or certification; % population with only high school degree or GED, % population with some high school, but no degree; ratio of population with high school education to post-high school education	Trends in education level especially high school degree completion and above	Parsons et al., 2016'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; Thoms, 2016; (Morrow, 2008; Sherrieb et al., 2010)	Resource and Driver	Low skill level and lack of situational awareness may increase sensitivity and coping ability (driver); high education and skill levels build social capital, workforce diversity, and can increase adaptive capacity (resource).

Availability and access to community organizations and activities	Social	Community Composition	Well-being	# of churches/places of worship per 1,000 residents (or appropriate alternative); # recreation centers or community activity centers per 1,000 residents (or appropriate alternative); # public libraries per 1,000 residents (or appropriate alternative); # public parks/playgrounds per 1,000 residents (or appropriate alternative)	Are the number of churches/places of worship proportional to religious makeup of residents; are places or worship, libraries, parks, playgrounds, etc., distributed equitably throughout the community	Cox and Hamlen, 2015'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'Cox and Hamlen, 2015'; Thoms, 2016; (Sherrieb et al., 2010; Walsh, 2007)	Resource and Driver	Lack of access to opportunities for social engagement and recreation may decrease mental and physical health, reducing ability to cope (driver); social and recreational opportunities can build social capital by increasing health, engendering trust, cooperation, and cohesion in the community, which can increase adaptive capacity (resource)
Availability and access to essential services	Social	Community Composition	Survival	# of schools within an area or distance to schools; # of day care centers within an area or distance to them; # of healthcare providers within an area, # of grocery stores within an area ; # of K-12 schools per 1,000 children (or other appropriate measure); average distance from schools to households with children; % and amount ($) of public resources spent on education, health, and social protection	General proximity and availability of key resources and services based on demographics (schools, day care, healthcare, groceries, etc..); School buses are available and accessible to all K-12 students; maximum distance from home to school does not exceed 10 miles for public education	Cutter et al., 2014; Cutter, 2016c; Sharifi, 2016; NAS, 2017; Lynch et al., 2011; U.N., 2015	Resource and Driver	Those without access to essential services are more likely to have higher sensitivity and low coping ability as they are less likely to have the physical, monetary, and time resources necessary to respond to hazards (driver); improved access to schools, daycares, healthcare providers, and grocery stores builds social capital by providing for basic needs, allowing greater flexibility in resources, and increasing desirability, which can increase adaptive capacity (resource)

Car ownership, mobility	Social	Community Composition	Well-being	% households without access to a vehicle; # of cars per household	Most of the community has access to a vehicle	Sharifi and Yamagata, 2014; Sharifi, 2016'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017	Driver	Lack of personal or household mobility may increase exposure and sensitivity, and decrease coping ability unless alternative means of transport and evacuation are maintained and ready
Sufficient affordable food supply	Social	Community Composition	Survival	% population without access to fresh produce on a regular basis; % households with children without access to fresh produce on a regular basis; % population requiring assistance with food; # foodbanks or other services to supply food when needed; # local food suppliers and farms; # of community supported agriculture (CSA); % population participating in SNAP or WIC; % of children and expecting mothers without adequate nutrition; % children eligible for free and reduced lunch programs; # cases malnutrition reported annually for children and adults (wasting and overweight); % population on food subsidy programs by age, gender, race	All residents have access to adequate food, including fresh produce on a regular basis; minimal population needs assistance with buying/obtaining an adequate supply of food; food assistance is available and accessible to those in need	Arup (Rockefeller) , 2014'; 'Cutter et al., 2014'; Cutter, 2016c; 'Cox and Hamlen, 2015'; Shen et al., 2011; Lynch et al., 2011; Venton 2014; U.N., 2015; UNISDR, 2017; (Berardi et al., 2011; Pingali et al., 2005; Tobin and Whiteford, 2013)	Driver	Lack of nutrition and access to healthy food weakens mental and physical capacity, especially in children, increasing sensitivity and decreasing coping ability
Population stability	Social	Community Composition	Survival	% residents who remain in the community for 5 years or less (excluding college or community college students); % annual births and deaths occurring within community; number of new residents moving into community annually; % change in working age population (under 25, 25-50, 50 and over); % population over 65	Relative stability in total population, relative stability in working age population, increase in aging population, decrease in population between 18-35; increase in young families; overall sense of predictability in population	Parsons et al., 2016'; 'Cutter et al., 2014'; Cutter, 2016c; 'McManus et al., 2012'; 'Cox and Hamlen, 2015'; NAS, 2017; (Norris et al., 2008; Sherrieb et	Resource	A stable and robust population builds social and economic capital and increases adaptive capacity

						al., 2010; NAS, 2012)		
Community emergency/disaster awareness	Social	Governance	Well-being	# warning sirens per 1,000 people (or other appropriate measure); % operational warning sirens; # and type of public warning signals; frequency of warning siren tests or other warning signal tests; # and type of public access to information on hazard, risk, preparation, response, emergency services, emergency contact information, evacuation procedures and routes (including websites, fliers, news letters, radio, TV, public meetings, etc.); # and location of designated emergency shelters; % population aware of most likely and most severe disaster scenarios and how to respond	Information is available to both permanent and seasonal residents, and is provided in a language other than English if necessary; emergency preparedness checklists and supply lists are made available to the public; evacuation routes are clearly marked and procedures are made publicly available through a variety of sources; signs are clearly posted on designated emergency shelters; information on location of designated emergency shelters is publicly available; all residents know how to contact emergency services and first responders; all residents are aware of most likely and most severe disaster scenarios and know how to respond	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; 'Cabell and Oelofse, 2012'; 'Matthews et al., 2014'; Thoms, 2016; DHS, 2016; U.N., 2015	Driver	Awareness of resources and available guidance can decrease sensitivity and exposure and improve coping

Regional Connectivity	Social	Governance	Survival	# of adjacent independent communities, counties, cities; # of special districts (military installations/facilities, federal lands/facilities, other significant non-community owned or operated lands/facilities) within 100 miles; # of tribal entities within 100 miles;# of inter-community/regional partnerships/organizations/planning committees	Relative isolation or connectivity of community with outside communities and entities	Arup (Rockefeller), 2014'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'Cox and Hamlen, 2015'; DHS, 2016; UNISDR, 2017; (Murphy, 2007; Ansell et al., 2010)	Resource and Driver	Physical isolation can increase exposure and sensitivity to hazards, reducing coping ability (driver); strong connection and coordination with regional governance and trade activities increases social and economic capital and adaptive capacity through extension and leveraging of resources (resource)
Effective external coordination (local and regional governments)	Social	Governance	Well-being	# of participants in regional planning groups; % participation/attendance in regional planning and coordination activities; frequency of regional planning group meetings/calls: # and type (purpose) of MOUs and agreements in place to provide assistance during disasters (shelter, food, equipment, hospitals, first responders, medical aid, etc.)	Active participation in planning, decision-making, and issues that impact governance across community boundaries; active coordination with special districts; active consultation/coordination with tribes; identification of significant intra-community partnerships; identification of significant shared community/regional/state plans and agreements	'Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; 'Cabell and Oelofse, 2012'; 'Matthews et al., 2014'; UNISDR, 2017	Resource	Coordination and partition with other governments can increase social and economic capital by improving capacity for response, growth, and extending resource availability and access, thus increasing adaptive capacity

Integration of risk reduction, resilience, sustainability, and adaptation across institutions and decisions	Social	Governance	Preparedness	# of integrated policies that address risk reduction, resilience, sustainability, and adaptation; # of cross-departmental working groups that actively participate in policy and planning for risk reduction, resilience, sustainability, and adaptation; # adaptation actions planned; $ allocated for adaptation; cost-benefit analysis for adaptation actions;	Risk identification, assessment, mitigation, adaptation, communication, and response are appropriately integrated into strategic plans, master plans, transportation plans, budgets, land use plans, economic plans, infrastructure plans, climate adaptation plans, sustainability plans, etc. to ensure consistency and coordination across government sectors and responsibilities; laws, directives, and policies reflect sustainable and resilient practices that protect critical resources, functions, and services	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; Hughes & Bushell, 2013; Thoms, 2016; DHS, 2016; U.N. 2015; UNISDR, 2017	Resource	Integrated planning can improve government efficiency, effectiveness, and capacity for response, which builds social capital, coordination within and across government functions can help to align resources for greater efficiency and effective use, increasing economic capital, which can increase adaptive capacity

Appropriate government processes and decision-making communication	Social	Governance	Well-being	# of public access areas (website, newsletter, etc.) where results of community decisions, announcements for upcoming events and public meetings/hearings, etc., are made available; # of public meetings and hearings held	Community/city website that clearly displays organizational hierarchy (organization chart) with key areas of responsibility, staff members, and contact information; site provides residents with access to plans, policies, partnerships, and other information necessary to maintain contact, coordination, and effective governance; site provides information regarding relationships with associated counties, cities, regions, state, etc.; site provides access to meeting minutes, records of public hearings, information regarding public decisions, actions, and upcoming events and activities for public participation; alternative notification is provided in the form of newsletters, public postings, newspaper articles, and availability of civic plans and documents in public facilities (courthouse, library, administrative building, etc.)	Arup (Rockefeller), 2014'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; DHS, 2016; UNISDR, 2017	Resource	Increased transparency and opportunity for awareness and engagement can improve government effectiveness, trust, and capacity for response, which builds social capital and increases adaptive capacity

Institutional character	Social	Governance	Well-being	# cases of corruption, fraud, waste, abuse on an annual basis; # elected officials suspended or removed from office; # of unresolved or unheard legal cases made against the local government by residents; # of official complaints lodged by residents against the local government or elected officials	Persons in elected positions fulfill full terms; decisions and actions are transparent and communicated through various means to residents; leaders and elected officials engage in community activities to support learning and innovation; there are official mechanisms for reporting and investigating fraud, abuse, and transgression of legal or ethical standards; hotlines and contact information for reporting such items to appropriate government staff are publicly posted and easily accessible; there are whistle-blower protections and anti-retributive protections in place for workers and members of the community; there are accessible and reliable means of conflict resolution between residents and government entities; local leadership and elected officials seek input from the community and opportunities for public comment, public hearings, etc. are advertised and publicized in a timely and effective manner	Parsons et al., 2016'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016; 'Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; Shen et al., 2011; UNISDR, 2017	Resource	Accountability, transparency, and trust build social capital and economic capital through greater efficiency and effectiveness of resources, which increases adaptive capacity

Efficient and effective management of resources	Social	Governance	Well-being	% annual change in community budget by major service/allocation (police, fire, education, health, public works, transportation, disaster response, etc.);# of externally awarded grants used for civic purposes on annual basis; # of internally or externally originated audits per year	Are responsibilities and resources decentralized and delegated, or centrally controlled; does the government actively pursue opportunities for grants or external funding to supplement existing funds; are results of audits and public investigations made accessible to the community; are fiscal plans and results made available to the community	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; 'Cabell and Oelofse, 2012'; McManus et al., 2012, (Buchmann, 2009; Shava et al., 2010)	Resource	Improved government efficiency and effectiveness can increase capacity for response and build social and economic capital, leading to increased adaptive capacity
Critical services/management staffing	Social	Governance	Survival	# and type of critical government positions vacant	Are critical government and service positions filled	'Sharifi, 2016'; 'Cox and Hamlen, 2015'; 'Cabell and Oelofse, 2012';	Driver	Lack of appropriate staffing may increase sensitivity and decrease ability to cope by diminishing capacity for response
Accessible criminal and civil justice	Social	Governance	Well-being	# lawyers per 1,000 residents (or other appropriate measure); # of public defenders per 1,000 residents (or other appropriate measure); # courthouses per 1,000 residents (or other appropriate measure); # unheard/backlogged cases per year	Are legal services sufficient to meet the needs of the community (skill level, affordability, accessibility, language considerations, impartiality, etc.); are legal actions (hearings, decisions, etc.) carried out in a timely, consistent, and impartial manner	Arup (Rockefeller), 2014'	Resource	Access to fair and impartial justice services can increase trust and engagement, which builds social capital and can increase adaptive capacity

Emergency/disaster funding	Social	Governance	Well-being	$ allocated for emergency/disaster response and recovery	There are sufficient fiscal and other critical resources immediately available to respond to disruption and/or disaster; additional resources are available within 24-48 hours (through partnerships with other communities, or external aid) to continue and complete response and recovery efforts to restore essential services and safety; emergency personnel are identified by skill and location in the event of notification; existence of an emergency response center	Arup (Rockefeller), 2014'; Orencio & Fujii, 2013; Yoon et al., 2016; UNISDR, 2017	Resource and Driver	Lack of allocation of resources to disaster relief efforts can increase sensitivity and reduce coping during hazards (driver); ready access to disaster relief resources and coordination of response efforts increases trust, capacity for response, and can increase efficient use of immediate resources and may reduce the need for outside help, increasing adaptive capacity (resource)
Emergency/disaster response & recovery time	Social	Governance	Survival	Amount of time required to respond to and recover essential services and/or total recovery time following disruption (power outage, water main break, road accessibility, etc.) or disaster (flood, tornado, etc.) per event per year; # deaths, injuries, missing due to immediate impact of emergency/ disaster per year; # deaths, injuries, missing related to aftermath and recovery following emergency/disaster per year; amount ($) direct and indirect economic loss due to emergency/disaster per year by sector; % population without essential services and duration of time without services (power, drinking water, sanitation, transportation, medical care, etc.)	Are recovery times following service disruption or disaster reasonable (prevent unnecessary or collateral loss, damage, injury)?	'Sharifi, 2016'; 'Cox and Hamlen, 2015'; 'Cabell and Oelofse, 2012'; U.N., 2015; Mitchell et al., 2013; UNISDR, 2017	Driver	Extended disaster response times can increase exposure and sensitivity of the community to hazards, by failing to mitigate damages before complete or unnecessary injury, loss, and or failure occurs

Adequate and effective community disaster mitigation & adaptation planning	Social	Policy & Planning	Preparedness	Age of current disaster mitigation plan (preferably within 5 years of current date); date of plan approval if required by FEMA/State; % community budget allocated to disaster mitigation planning; last review within 3 years and public is made aware of timelines and opportunities to engage; # priorities and actions for disaster mitigation and adaptation in most recent plans with timelines and targets for completion; % actions completed since last plan update; cost-benefit for adaptation and mitigation actions; $ allocated for planning and plan implementation (including actions and projects identified in plans); date of last post-disaster review of plans, actions, and lessons learned; date of last skills inventory to ensure all key skills and experience are available during disaster	A community disaster mitigation plan exists; is the plan incorporated into a state required mitigation plan (Stafford Act and 44 Code of Federal Regulations (CFR) Part 201); is the plan developed with State, Tribal, or local planning guidance developed by the Federal Emergency Management Agency (FEMA); Does the plan address the following: Plan is current and routinely updated; broadly available to public; coordinated with regional neighbors; addresses adequate disaster staffing and staff rotation requirements for emergency operation center; addresses all local hazards and risks; includes current maps for key assets and infrastructure; identifies special skills, training and knowledge that might help in a disaster; identifies emergency supplies (e.g., food, medical supplies, fuel, generators); identifies external support and resources; includes community stakeholder engagement and public comment; identifies emergency communication methods, equipment and procedures (amateur radio (HAMS) and/or satellite phone operators) to assist with	Cox and Hamlen, 2015'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Matthews et al., 2014'; 'Arup (Rockefeller), 2014'; Sempier et al., 2010; DHS, 2016; Mitchell et al., 2013; UNISDR, 2017; Parsons & Morley, 2017	Resource and Driver	Lack of comprehensive and coordinated disaster mitigation planning can increase sensitive and exposure, and reduce coping ability (driver); comprehensive and coordinated planning efforts can align response and resource allocation, increasing efficiency, effectiveness, and capacity for response, thus increasing social, economic, and environmental capital, as well as adaptive capacity through greater ability to anticipate, prepare for, respond to, and recover from hazards (resource)

					emergency communication; identifies evacuation plan; addresses communication and cooperation between fire-fighting, search and rescue, policing, and medical responders; includes measures for temporary human and animal shelter, food, water, power and fuel for permanent and seasonal residents; addresses accessibility (for those with disabilities, low income) and equity; includes coordination with schools, hospitals, support agencies, care facilities and businesses; maximizes regional cooperation for training, equipment, and services; includes establishing interagency and inter-governmental communication channels and cooperation agreements			

Schools/daycares are prepared for emergency/disaster	Social	Policy & Planning	Preparedness	# of schools and licensed daycare facilities that do not meet current building codes; # of schools and licensed daycare facilities that do not have adequate security measures; # schools without current (updated annually) emergency/disaster plans, evacuation procedures, and communication plans; # of schools and licensed daycare centers that have not conducted an emergency drill within the last 6 months; % schools that provide in-class training and education to parents on how to respond to emergency/disaster in school including post-event reunification; # days per year schools are closed due to disaster/emergency; # injuries and deaths (adults and children) occurring on school grounds due to emergency/disaster; # affected 5-12 year olds and # days without access to learning facilities and materials due to emergency/disaster annually	School/daycare emergency/disaster plans include the following: clear instruction on response to emergency/disasters; identification of emergency supplies; communication with critical services (law enforcement, emergency healthcare; etc.); evacuation and how to move/transport children and injured; communication plan for parents and caregivers; faculty, staff, students, and families are aware of the plan and understand what to do; the plan is made available and easily accessible to families; rapid scale-up and assistance is available to return students and teachers to school as quickly as possible following disaster	Cox and Hamlen, 2015'; Mitchell et al., 2013; UNISDR, 2017	Resource and Driver	Lack of comprehensive and coordinated disaster mitigation planning can increase sensitive and exposure, and reduce coping ability (driver); comprehensive and coordinated planning efforts can align response and resource allocation, increasing efficiency, effectiveness, and capacity for response, thus increasing social, economic, and environmental resources, increasing adaptive capacity through greater ability to anticipate, prepare for, respond to, and recover from hazards (resource)
Residents are prepared for emergency/disaster	Social	Policy & Planning	Preparedness	# of public access areas (website, newsletter, etc.) where emergency/disaster preparation guidelines or checklists are made available; % population exposed to high to moderate risk from disaster by type (flood, hurricane, etc.); # and identification of media channels (tv, radio, online, mobile alert, text alert, etc.) to notify & inform public;	Maps made available to community showing where high risk areas are located; Guidelines or checklists for household emergency/disaster are made available and accessible to the community; households at high risk (or remote locations) are prepared to survive at least 2 weeks without outside help (e.g., food stores, back up power and heat, alternate water supplies, access to fuel; communication; medication; etc.); most	Cox and Hamlen, 2015'; Thoms, 2016; DHS, 2016; Mitchell et al., 2013	Driver	Lack of access to timely and accurate information and resources increases sensitivity and exposure, decreasing coping ability

					residents minimize disaster risks (e.g., trimming trees around the home, insulating pipes); Residents know where to go and what to do in event of disaster			
Local healthcare facilities (e.g., nursing stations, residential care) are prepared for emergency/disaster	Social	Policy & Planning	Preparedness	# of healthcare facilities that do not meet current building codes; # of healthcare facilities that do not have adequate security measures; # facilities without current (updated annually) emergency/disaster plans, evacuation procedures, and communication plans	Healthcare facility emergency/disaster plans include the following: identification of emergency supplies; hazardous material storage; communication; evacuation and how to move/transport people who are bedridden or otherwise disabled; plans to meet the increase in demands for health/mental health services in a disaster; coordinated with regional healthcare facilities	Cox and Hamlen, 2015'	Resource and Driver	Lack of comprehensive and coordinated disaster mitigation planning can increase sensitive and exposure, and reduce coping ability (driver); comprehensive and coordinated planning efforts can align response and resource allocation, increasing efficiency, effectiveness, and capacity for response, thus increasing social, economic, and environmental capital, as well as adaptive capacity through greater ability to anticipate, prepare for, respond to, and recover from hazards (resource)

Community evacuation plan	Social	Policy & Planning	Preparedness	Age of evacuation plan; evacuation plan publicly accessible; # evacuation centers	Evacuation plans and publicly accessible information includes: broad access to evacuation information; evacuation procedures and hazard-specific alternatives (e.g. in case of chemical spill, nuclear accident); plan includes up-to-date inventories (what, where) of equipment & vehicles that could be used in evacuation (e.g., snowmobiles, quads, buses, trucks) and response (e.g., front end loaders, tractors); address communication and cooperation between fire-fighting, search and rescue, policing, and medical responders; addresses permanent and non-permanent residents, and animal (livestock and pets)	Cox and Hamlen, 2015'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Matthews et al., 2014'; Kontakosta & Malik, 2018	Resource and Driver	Lack of comprehensive and coordinated disaster mitigation planning can increase sensitive and exposure, and reduce coping ability (driver); comprehensive and coordinated planning efforts can align response and resource allocation, increasing efficiency, effectiveness, and capacity for response, thus increasing social, economic, and environmental capital, as well as adaptive capacity through greater ability to anticipate, prepare for, respond to, and recover from hazards (resource)
Effective policy, legislation, planning	Social	Policy & Planning	Well-being	# enforcement actions for failure to comply with applicable codes per year; number of key policies or plans older than 10 years; # of new policies or pieces of legislation passed; # policy impact and progress reports provided; # or extent of policy monitoring activities	Policy, plans, and legislation are passed; enforcement and monitoring of policies occur	Parsons et al., 2016'; 'Cox and Hamlen, 2015'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Matthews et al., 2014'	Driver	Inability ability to pass and enforce policies can increase sensitivity to hazards and reduce coping ability (driver)

Active hazard/disaster mitigation efforts	Social	Policy & Planning	Preparedness	Annual amount ($) spent on hazard mitigation efforts (projects, education, etc.); # and amount of disaster mitigation grants or other external funding for disaster planning, mitigation, or education received over last 10 years; # and type of incentives offered to residents and businesses to mitigate hazard (rebates, lower rates, tax credits, etc.); # public-private partnerships benefitting hazard mitigation; % total public infrastructure disaster relief funds spent on Section 406 Mitigation for disasters in preceding 5 years; % of Small Business Administration (SBA) home disaster loan funds spent on mitigation assistance	Active community engagement in hazard mitigation; local business engagement in hazard mitigation	Cutter et al., 2014'; Cutter, 2016c; 'Cox and Hamlen, 2015'; NAS, 2017; DHS, 2016; Mitchell et al., 2013; UNISDR, 2017; (Rose, 2007; Godschalk et al., 2009; Cutter et al., 2008; Tierney and Bruneau, 2007)	Driver	Lack of necessary mitigation funding and implementation of mitigation activities can increase sensitivity and exposure and reduce the coping ability of the community during hazards
Comprehensive hazard monitoring and risk assessment	Social	Policy & Planning	Preparedness	# dedicated data management staff; # of real-time, continuous monitoring stations (precipitation, temperature, wind, streamflow, stream height, air quality, noise, storm, sea level, water quality, seismic, drought, etc.); # and type of most probable and most severe hazards faced by the community; worst-case scenario estimates of damage and loss ($) with descriptions for each most probable and most severe hazard (% homes/businesses destroyed, % homes/businesses covered by insurance; # displaced; ($) wages lost; # work days lost; # casualties (injuries & deaths); etc.); % GDP lost in most probable and severe scenarios; % funding available to cope with most severe and most probably risk scenarios; % hazard areas mapped; Date of most recent maps depicting hazard areas	Current and up to date methods for gathering, storing, managing, analyzing, and sharing data and information related to hazard monitoring (databases, models, etc.); current vulnerability or risk assessments; documentation of historical hazards (Presidential and State declarations, impacts associated with historical events, etc.); means for identifying and assessing future hazard scenarios; partnerships with universities, research organizations, or other communities to share resources, information, and results; inclusion of climate change in vulnerability and risk analysis; publication of health and safety related data and changes in data	Arup (Rockefeller), 2014'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Matthews et al., 2014'; 'Parsons et al., 2016'; Hughes & Bushell, 2013; Hiremath et al., 2013; DHS, 2016; UNISDR, 2017; Parsons & Morely 2017	Resource and Driver	Lack of ability to both historical and future risk can negatively impact the ability to anticipate, plan, and prepare for hazards, which can increase sensitivity and exposure and reduce the coping ability of the community (driver); monitoring and management of accurate and consistent data and information related to hazards and risk is essential for planning, preparation, and response activities; dedicated workforce and resources to ensure proper risk analysis and integrated activities can increase social and economic capital through increased

					over time; understanding of climate change and how to incorporate risk into planning and decision making			response capacity thus increasing adaptive capacity
Research capabilities	Social	Policy & Planning	Preparedness	# of partnerships with universities, consultants, or research agencies; $ funding for research activities; % workforce in research, science, technology	Partnerships with universities, research organizations, or other communities to share resources, information, and results; inclusion of climate change in vulnerability and risk analysis	'Cox and Hamlen, 2015'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; Thoms, 2016; U.N., 2015; UNISDR, 2017	Resource	Partnerships with research institutions can leverage available social and economic resources and provide access to extended resources that may increase risk awareness, improve planning and mitigation actions, and increase both capacity for response and adaptive capacity

Community recovery & planning	Social	Policy & Planning	Preparedness	Age of current community disaster recovery plan (preferably within 5 years of current date); amount ($) annually on disaster preparedness and recovery; # days to reopen schools following emergency/disaster annually; # residents and # days without power, water, sanitary services per year due to emergency/disaster; amount (tons) debris removed and # days to remove debris following emergency/disaster; # roads, bridges, access points closed and # days to reopen/regain access following disaster/emergency; # health facilities closed and # days closed following emergency/disaster; # trauma counselors/mental health professionals available to assist following emergency/disaster; gallons emergency fuel; tons emergency food stock; # emergency shelters; # emergency generators; # gallons drinking water; # and type emergency equipment; # and type emergency medical personnel	A community disaster recovery plan exists; are the disaster mitigation and recovery plans integrated; plans are updated simultaneously; does the plan address: short- and long-term impacts and recovery needs (e.g., social, economic, emotional, and environmental); post-disaster debris management; sanitation; continued provision of shelter, food, medical, and other critical supplies throughout recovery; residential and business recovery of property; insurance claims; reunification of animals (pets and livestock); communication and media; inclusion of disaster resilience and lessons learned; economic response and recovery; occurrence of events post-disaster to raise funds, recognize impacts, grieve, remember, commemorate; trauma counseling available in aftermath of events; mechanisms to collect lessons learned for future planning and policy	Cox and Hamlen, 2015'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Matthews et al., 2014'; 'Sanders et al., 2015'; Thoms, 2016; DHS, 2016; Mitchell et al., 2013; UNISDR, 2017	Driver	Poor or outdated plans can increase sensitivity and exposure, and decrease community coping in the event of a hazard

Engagement and support of vulnerable groups	Social	Policy & Planning	Well-being	# of advocacy groups representing the needs of vulnerable populations; # of law firms that represent vulnerable groups at no/low cost; amount ($) funding and assistance allocated to help vulnerable residents	Are vulnerable groups included in community decisions and planning; Are vulnerable groups sufficiently engaged to be aware of disaster response measures;	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Parsons et al., 2016'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; Parsons & Morley, 2017; (Messias et al., 2012; Blackstone and Kailes, 2015)	Driver	Lack of engagement and participation from vulnerable groups may lead to incomplete or incorrect methods for decreasing vulnerability and increasing coping ability within the community
Availability and access to support services	Social	Services	Well-being	[all units are per 1,000 capita of vulnerable residents, or other appropriate measure] # and type of support services (Red Cross, Good Will, AGAPE, YMCA, YWCA, women and children's shelters, child services, homeless shelters, employment assistance, youth organizations, etc.); # and type of assistance programs and social welfare (medical, unemployment, disability, food assistance, etc.); # of affordable daycare and childcare services to allow adults to work; average distance from vulnerable populations areas to services; # of non-profits and organizations that contribute to community wellbeing by providing (money, food, services, care, volunteers, etc.); # of affordable English courses available for non-native English speakers; amount ($) annual funding to provide services	Are services reasonably accessible to areas with vulnerable populations (within walking distance, bus line, other affordable public transportation); are services consistent and reliable	Parsons et al., 2016'; 'Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; 'Matthews et al., 2014'; DHS, 2016; U.N., 2015; Parsons & Morley, 2017; (Paton et al., 2006)	Resource and Driver	Those without access to support services are more likely to have higher sensitivity and low coping ability as they are less likely to have the physical, monetary, and time resources necessary to respond to hazards (driver); adequate and equitable access to support services builds social and economic capital by providing for basic needs and allowing greater flexibility in resources which increases adaptive capacity (resource)

High quality education (pre-K through 12th grade)	Social	Services	Well-being	Average child-teacher ratio per school; amount ($) spent annually on K-12 education; average salary for K-12 teachers; school rankings or state test rankings; annual cost of tuition by school; graduation rate; special education offered; college acceptance rates: % children over age 3 not enrolled in school	Families do not need to leave the community (relocate) to access high quality schools; all public schools are equipped with computers and internet access; all public schools have sufficient resources to provide adequate classroom space, materials, and services; all children have access to good nutrition in schools (no child goes without a healthy breakfast or lunch regardless of availability to pay)	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; Cutter et al., 2014'; Cutter, 2016c; 'Arup (Rockefeller), 2014'; Mitchell et al., 2013; Parsons & Morley, 2017; Kontakosta & Malik, 2018; (Cavallo and Ireland, 2014; Ronan and Johnston, 2005)	Resource and Driver	Lack of availability and access to quality schools and educational opportunity can increase sensitivity and reduce coping ability (driver); adequate availability and access to quality schools and educational opportunity builds social and economic capital, workforce diversity, and increases desirability and adaptive capacity (resource)
Opportunity for post-high school education and training	Social	Services	Well-being	# of four-year colleges/universities within 30 miles; # of 2-year associate or technical degree programs within 30 miles; # and type of technical and training certification courses within 30 miles; illiteracy rate; % population unable to read English	Residents do not need to leave the community (relocate) to obtain access to educational and training opportunities; schools and training are affordable and accessible; GED, literacy, and basic skills courses are available and accessible	Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; 'Parsons et al., 2016'; U.N., 2015	Resource and Driver	Varying skill level and situational awareness may impact sensitivity and coping ability (driver); high education and skill levels build social capital, workforce diversity, and increase adaptive capacity (resource)

Sufficient and effective emergency response services (police, fire, medical, etc.)	Social	Services	Survival	# of police, fire, emergency medical response personnel per 1,000 residents (or other appropriate measure); # unfilled critical emergency response positions; amount ($) spent annually on emergency response; average salary of emergency responders by type; average response times for emergency calls; average distance to fire station, police station, emergency center	Emergency response personnel are trained and certified based on current standards and requirements; equipment meets current standards and is maintained and operational; sufficient equipment, facilities, and supplies exist and are maintained at appropriate levels of quantity and quality; emergency services are available and accessible to all	Arup (Rockefeller), 2014'; 'Parsons et al., 2016'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; Orencio & Fujii, 2013; UNISDR, 2017; Kontakosta & Malik, 2018; Parsons & Morley, 2017	Resource and Driver	Sufficient and effective emergency response series reduce exposure and sensitivity and increase coping (driver); investment in proper manpower and training increase build social capital by increasing trust, capacity for response, desirability, and creating a safe and stable environment, which can increase adaptive capacity (resource)
Community is trained on how to respond to emergency/disaster	Social	Services	Preparedness	# of annual community events focused on safety and emergency response training and education; # of locations offering courses in safety and emergency response (CPR, first aid, etc.); # emergency drills conducted annually to prepare for disaster; # events annually that engage vulnerable groups or most likely to be harmed in a disaster to ensure training and education (poor, non-English speaking, assisted living, prisons, retirement homes, etc.)	Emergency services participate in local drills; healthcare providers have emergency and disaster training; emergency training is offered in languages other than English as needed; vulnerable populations are engaged and educated on what to do in a disaster	Parsons et al., 2016'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; UNISDR, 2017; (Godschalk, 2003; Simmonovich and Sharabi, 2013)	Driver	Lack of awareness of resources and access to training can increase sensitivity and exposure and reduce coping in the event of a hazard

Sufficient access to quality healthcare	Social	Services	Well-being	% population without access to health insurance; # of healthcare providers by type per 1,000 people (or other appropriate measure); # of emergency healthcare providers per 1,000 people (or other appropriate measure); # of urgent care providers per 1,000 people (or other appropriate measure); # of pharmacies per 1,000 people (or other appropriate measure); # hospital beds per 1,000 people (or other appropriate measure); average distance to emergency medical facilities; average wait time for emergency room care; average number of care providers by type per 1,000 people (primary/family care, internal medicine, obstetrics and gynecology, optometry ophthalmology, dentist endodontist, specialty care, etc.); ; average distance to nearest health services center	Emergency healthcare is available to all; essential healthcare services are available for all maternal, newborn, child, and infectious diseases regardless of ability to pay; residents do not need to leave the area to receive basic healthcare; healthcare professionals and facilities are adequately staffed and equipped (medical supplies, equipment, beds, ambulances; etc.); regional health services are accessible and available to provide specialized care and or additional support; healthcare services provide preventive health services (screening, testing, exams, immunization, contraception, etc.) and community outreach; there is an accessible area for medical evacuation (airstrip, helipad, other); hospice and homecare services are available; women's healthcare family planning (reproductive health) are available, accessible, and affordable	Cox and Hamlen, 2015'; 'Arup (Rockefeller) , 2014'; 'Parsons et al., 2016'; Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'McManus et al., 2012'; Shen et al., 2011; Hiremath et al., 2013; DHS, 2016; ; U.N., 2015; UNISDR, 2017; Kontakosta & Malik, 2018; (Chandra et al., 2011; Plough et al., 2013; Norris et al., 2008; Birkmann et al., 2013; Cimellaro et al., 2010; Renschler et al., 2010)	Resource and Driver	Communities without equitable access to quality healthcare services are more likely to have higher sensitivity and low coping ability as they are less likely to have the physical, monetary, and time resources necessary to respond to disruption (driver); improved access to quality healthcare builds social and economic capital by providing for basic needs, allowing greater flexibility in resources, and increasing desirability, which increases adaptive capacity (resource)

Health	Social	Services	Survival	% population diagnosed with chronic health issues (cardiovascular, diabetes, cancer, respiratory, etc.); average life expectancy; birth rate; under 5 years-old mortality rate; maternal mortality rate; child and adult vaccination rate; % population not participating in leisure time physical activity; rate of drug and alcohol abuse; annual reported spousal abuse; annual reported child abuse; % obesity in adults and children; # STDs reported per year including HIV; % population that uses tobacco products	Population is physically healthy and sound; disparity in health is monitored based on community location and vulnerable populations; immunization is mandatory for all school-aged children attending public or private schools	Parsons et al., 2016'; 'Cox and Hamlen, 2015'; DHS, 2016; U.N., 2015; UNISDR, 2017	Resource and Driver	Higher levels of individual/households with poor physical capacity indicates high sensitivity and low coping ability (driver); higher levels of health and wellness build social capital by providing greater workforce stability, increasing community desirability, and increasing adaptive capacity (resource)
Mental health support	Social	Services	Survival	# psychiatric/psychological/counseling practitioners per 1,000 people (or other appropriate measure); suicide rate; amount ($) spent annually on assistance for mental health, addiction, abuse	Population is mentally healthy and sound; disparity in health is monitored based on community location and vulnerable populations; assistance in available to families in the aftermath of crisis and disaster	Cutter et al., 2014'; Cutter, 2016c; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; Orencio & Fujii, 2013; Hiremath et al., 2013; U.N., 2015; (Pietrzak et al., 2012; Springgate et al., 2011)	Resource and Driver	Higher levels of individual/households with poor emotional/mental capacity indicates high sensitivity and low coping ability (driver); higher levels of health and wellness build social capital by providing greater workforce stability, increasing community desirability, and increasing adaptive capacity (resource)

Adequate and available law enforcement and crime prevention	Social	Services	Survival	# violent crimes per year; # non-violent crimes per year; # homicides per year; # juvenile crimes per year; amount ($) spent annually on law enforcement and crime prevention; # fire-related deaths per year; 911 response time per call from initial call; # traffic related deaths per year; # sexual assaults per year; # hate crimes reported per year	Perceived safety is high; community has active neighborhood watch; public trusts police force and law enforcement	Parsons et al., 2016'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'McManus et al., 2012'; 'Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; Shen et al., 2011; U.N., 2015	Resource and Driver	High levels of crime and perception of danger increase exposure and sensitivity and reduce coping (driver); investment in proper manpower and training high levels of perceived safety increase social capital by increasing trust, desirability, and creating a safe and stable environment, which can increase adaptive capacity (resource)
Remoteness	Social	Services	Survival	Distance from community center to the nearest urban center/metropolitan statistical area; distance from community center to the nearest major highway; distance from community center to the state capitol; average household distance to nearest hospital; average household distance from community center; average distance between households	The nearest regional hub has the services (e.g., banking, health, dental, etc.) local residents need and is within 2 hours travel year-round	Parsons et al., 2016'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'Cox and Hamlen, 2015'; (Bowman and Parson, 2009)	Driver	Community physical isolation can increase exposure and sensitivity to hazards, reducing coping ability
Adequate services and amenities are available for permanent and seasonal residents and visiting occupants	Economic	Micro/Meso Economic efficiency	Survival	[all measures are per 1,000 people (or other appropriate measure] # grocery stores; # hotel/motels; # fueling stations; # banks/financial providers	Adequate repair and maintenance services; adequate goods, supplies, and equipment vendors; adequate retail stores and restaurants to meet resident's needs; residents do not need to leave the community to meet service and amenity needs	McManus et al., 2012; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'Cox and Hamlen, 2015'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; Orencio & Fujii, 2013; (Ozbay et al., 2007; Tierney, 2009; Rose	Resource and Driver	Those without access to services and amenities are more likely to have higher sensitivity and low coping ability as they are less likely to have the physical, monetary, and time resources necessary to respond to disruption (driver); improved access to services and amenities builds social and economic capital by providing for needs and allowing greater flexibility in

						and Krausmann, 2013; Wein and Rose, 2011)		resources, and greater desirability, which increases adaptive capacity (resource)
Livable wage	Economic	Macroeconomic Stability	Survival	% population at or below the poverty line by age, gender, race; % of population working more than 1 job; % of population income derived via external support (welfare, subsidy, etc.); % inactive businesses/farms; Gini coefficient/income distribution; # children living in poverty; % population receiving government financial assistance; # jobs lost due to natural disaster/disaster; median per capita income; amount ($) spent on ending poverty per year; # households entering poverty due to emergency/disaster	Most of the population can earn a livable wage working a single job	Cabell and Oelofse, 2012'; Palmisano et al., 2016'; 'Parsons et al., 2016'; Shen et al., 2011; Lynch et al., 2011; Ranger & Surminski, 2013; Venton 2014; DHS, 2016; U.N., 2015; Mitchell et al., 2013	Resource and Driver	Those without access to a livable wage are more likely to have higher sensitivity and low coping ability as they are less likely to have the physical, monetary, and time resources necessary to respond to disruption (driver); higher percent of livable wage builds social and economic capital by providing for needs and allowing greater flexibility in resources, and greater desirability, which increases adaptive capacity (resource)

Innovation and growth in businesses	Economic	Macroeconomic Stability	Well-being	% annual change in new, locally owned business; % privately owned businesses in operation for more than 5 years; % change GDP from new business; % growth in employment; # locally provided loans, risk-transfer or sharing programs to help new businesses	Stability or growth in new business; privately owned businesses can be sustained; the community encourages niche, craft, and micro-enterprises	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; 'Palmisano et al., 2016'; Rose & Krausmann, 2013; U.N., 2015; Mitchell et al, 2013; Parsons & Morley, 2017	Resource and Driver	Lack of growth or lack of stability in local business (businesses frequently fail to survive) creates higher sensitivity and lower coping in the event of hazards (driver); stable, long-term growth in new business increases social and economic capital, desirability, and adaptive capacity (resource)
Diverse economic structure, skills, and livelihood strategies	Economic	Micro/Meso Economic efficiency	Well-being	% and type of industry sectors present in the community (industrial, manufacturing, agricultural, etc.); % labor force engaged in the following (agriculture, farming, tourism, fishing, mining/extraction); % and type of skilled professionals (doctors, nurses, lawyers, dentists, veterinarians, scientists, etc.); ratio of highly skilled jobs to trade-level jobs; % farms receiving subsidies or paid not to produce	Economic base is diverse and does not depend on a single or only a few industries; balance between small and large businesses; there is an adequate number of highly skilled professionals to meet community needs; professionals stay within the community; critical skills are typically filled and not vacant; flexible strategies are developed to avoid dependence on single sectors or goods	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; Palmisano et al., 2016'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'Arup (Rockefeller), 2014'; 'Cox and Hamlen, 2015'; 'Matthews et al., 2014'; 'Cabell and Oelofse, 2012'; Rose & Krausmann, 2013; Hughes & Bushell, 2013; U.N., 2015; Mitchell et al., 2013;	Driver	Lack of diversity (reliance on one or few skills and livelihood strategies) can increase sensitivity and reduce coping in the event of a hazard

						UNISDR, 2017; Kontakosta & Malik, 2018; (Altieri, 1999; Ewell, 1999; Berkes et al., 2003; Luck et al., 2003; Swift et al., 2004; Folke, 2006; Jackson et al., 2007; Di Falco and Chavas, 2008; Chapin et al., 2009; Darnhofer et al., 2010; Sherrieb, et al., 2010)		
Desirability	Economic	Macroeconomic Stability	Well-being	Relative comparison of: property tax, sales tax, state income tax to other nearby communities; relative comparison of well-being (education, crime rates, healthcare services, public spending on community infrastructure and upkeep, etc. to other nearby communities)	Public finances are well-managed and reported to the community in a transparent way; public economic reports and audits are available to the public	Arup (Rockefeller), 2014'; 'Cox and Hamlen, 2015'	Resource and Driver	Poor value performance (prices, taxes, etc.) can lead to greater sensitivity and lower coping (driver); increased value performance builds social and economic capital and desirability, leading to increased adaptive capacity (resource)
Public-private partnership and investment	Economic	Macroeconomic Stability	Well-being	# and worth of significant public-private partnerships	There is shared investment in the community between public and private partners	Sharifi and Yamagata, 2014; 'Sharifi, 2016'	Resource	Public/private partnerships can leverage available resources and provide access to extended resources that can increase social and economic capital, and increase both capacity for response and adaptive capacity

Property ownership	Economic	Micro/Meso Economic efficiency	Well-being	% of population owning homes (outright or mortgage); % or population owning land (outright or mortgage); # families displaced (homes lost without compensation) due to natural disaster/disaster annually	The majority of residents own property as opposed to renting/leasing	Parsons et al., 2016'; 'Cutter et al., 2014'; Cutter, 2016c; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; Ranger & Surminski, 2013; Thoms, 2016; Venton, 2014; U.N., 2015; (Peacock et al., 2010; Tierney, 2009; Haveman and Wolff, 2005; Pendall et al., 2012)	Driver	Lack of property ownership (high levels of renting or leasing) can indicate lack of financial stability or lack of permanence in residents, which can lead to higher levels of sensitivity and lower coping in the event of a hazard
Age structure of working population	Economic	Macroeconomic Stability	Survival	% workforce by age bracket; % change in workforce by age bracket	The majority of the workforce is not close to retirement age; workforce is stable with a balanced mix of age groups	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; (Morrow, 2008)	Resource	Balanced and stable workforce age allows for greater potential diversity in work structure, skills, and livelihood, increasing social and economic capital and adaptive capacity
Stability of prices, incomes, property values	Economic	Macroeconomic Stability	Well-being	[% change in last 5 years in] property values; property taxes; median income; average household utility cost (water, electricity, gas, renewable, etc.); average cost of living; inflation rate; % population spending more than 30% income on housing and transportation costs (emphasis on low income families)	Property values, tax rates, cost of living are relatively stable	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; Shen et al., 2011; Lynch et al., 2011; DHS, 2016	Resource and Driver	Poor value performance (prices, taxes, etc.) can lead to greater sensitivity and lower coping (driver); increased desirability can lead to greater social and economic capital and increased adaptive capacity (resource)

Balanced market supply and demand	Economic	Macroeconomic Stability	Survival	Ratio of imported to exported goods; # and value of mutual aid agreements for major supply chains, etc. (agreements between public/private entities to pool resources, shift or re-route supply chains/transport when needed, share storage, etc.); Amount of emergency stockpile/back-up, excess capacity for critical goods and supplies (raw materials, fuel, food, etc.); ratio of imported (energy, food, industrial supply) to GDP as a measure of dependence on strategic import of goods into community	Supply and demand strategies are not sole-sourced and are sufficiently redundant/diverse to accommodate disruption; healthy reliance on local markets and resources; existence of back-up or stockpile for critical resources in the event of disruption to keep businesses running; existence of redundant capabilities for critical supply and demand; existence of excess labor when needed	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cabell and Oelofse, 2012'; Rose & Krausmann, 2013; Orencio & Fujii, 2013; Ranger & Surminski, 2013; Briguglio et al., 2009; UNISDR, 2017; (Holling, 2001; Gunderson and Holling, 2002; Milestad and Darnhofer, 2003; Folke et al., 2010; van Apeldoorn et al., 2011)	Resource and Driver	Imbalanced market structure (significant reliance on export or import, reliance on a single supplier or buyer) can lead to increased vulnerability and lower coping in the event of a hazard (driver); balanced and diverse market structures allow for growth in social and economic capital and greater adaptive capacity (resource)
Stable employment rate	Economic	Micro/Meso Economic efficiency	Well-being	% annual change in unemployment; % community jobs that are state or federal positions; % annual job growth; % jobless families with children under 15 years of age; 3-year average unemployment rate; % population over age 16 unemployed	Employment rates are stable; Employment is not significantly impacted by relocation of state and federal facilities	Cutter et al., 2014'; Cutter, 2016c; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; McManus et al., 2012; 'Parsons et al., 2016'; DHS, 2016; U.N., 2015; Kontakosta & Malik, 2018; (Rose	Driver	Unstable employment (significant variability in employment rates, significant increase in unemployment, or reliance on a single major employer) can lead to increased vulnerability and lower coping in the event of a hazard (driver); stable and diverse employment opportunity allows for growth in social and economic capital

						and Krausmann, 2013; Sherrieb et al., 2010)		and greater adaptive capacity (resource)
Strong integration between local and regional economies	Economic	Macroeconomic Stability	Well-being	% of businesses with international, national, regional, or state-wide presence/distribution	Strong collaboration/integration of local and regional markets; contingency contracts with suppliers & transporters; capacity for credit/assistance from network distribution and local/regional markets	Arup (Rockefeller), 2014'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cabell and Oelofse, 2012'; 'Cox and Hamlen, 2015'; Rose & Kruasmann, 2013; Ranger & Surminski, 2013	Resource and Driver	Lack of integration between local and regional economies can increase isolation, leading to greater sensitivity to hazards and lower coping ability (driver); integration and coordination with other local and regional economies can leverage available resources and provide access to extended resources that builds social and economic capital and may increase risk awareness, improve planning and mitigation actions, and increase both capacity for response and adaptive capacity (resource)

Urban sprawl/farmland conversion	Economic	Macroeconomic Stability	Well-being	% annual change in land use conversion by type (from one land use to another)	Impacts of urban sprawl and farmland conversion are monitored	Skog and Steinnes, 2016'	Resource and Driver	Significant increase in farmland conversion or other forms of land use change should be monitored to ensure that impacts do not increase sensitivity to hazard (driver); diversity in land use and strategic management of land use conversion can build social, economic, and environmental capital, leading to increase in adaptive capacity (resource)
Contingency funds/savings (private and public)	Economic	Micro/Meso Economic efficiency	Well-being	% of residents with active savings; % of municipal funding set aside for contingency/emergency; $ amount of financial or in-kind agreements with public/private entities to provide support/assistance in emergency/natural disaster/disaster	Existence of public and private financial reserve (internal and external funds) in case of contingency/emergency; estimates of worst-case scenarios for medium to high-risk natural disaster/disaster (storm, flood, earth quake, wildfire, etc.) and strategies to access needed resources based on estimates	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; Hughes & Bushell, 2013; Ranger & Surminski, 2013; Thoms, 2016	Resource and Driver	Lack of allocation of individual and community resources to respond to hazards can increase sensitivity and reduce coping (driver); adequate establishment of private and public contingency funds increases economic capital through availability and access to immediate resources and may reduce the need for outside help, increasing both capacity for response and adaptive capacity (resource)

Insurance	Economic	Micro/Meso Economic efficiency	Well-being	% homes not insured; % businesses/farms uninsured; % properties located in flood plain not insured by National Flood Insurance Program(NFIP); % of NFIP-participating community enrolled in Community Rating System (CRS) with a rating of 5 or better; # Repetitive Loss Properties; # Severe Repetitive Loss Properties; # acquired Repetitive Loss Properties; % farms without crop insurance; % financial institutions not insured by FDIC; amount ($) paid insurance claims due to natural disaster/disaster annually; # and value ($) of homes, businesses, farms lost/damaged by natural disaster/disaster; % loss agricultural output due to disaster annually	Properties and businesses are adequately insured; existence of property "buy-out" program to remove Repetitive Loss and Severe Repetitive Loss properties from flood hazard zones; Most recent Flood Insurance Rate Maps (FIRM) are publicly accessible	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cutter et al., 2014'; Cutter, 2016c; 'Cox and Hamlen, 2015'; Sempier et al., 2010; Ranger & Surminski, 2013; DHS, 2016; Mitchell et al., 2013; (Michel-Kerjan et al., 2012)	Resource and Driver	Lack of insured properties and businesses can increase sensitivity to hazards and reduce coping (driver); appropriate insurance coverage can increase economic and social capital by generating resources to aid in recovery and allowing other resources to be used more effectively in response, which increases adaptive capacity (resource)
Comprehensive planning and support for local business continuity	Economic	Micro/Meso Economic efficiency	Preparedness	% businesses with continuity/recovery plans that include communication, evacuation, emergency supplies, shelter, leadership/staff succession, contingency, relocation, re-financing, practice restarting, change procedures, supply re-routing, mutual aid agreements, and family assistance (including farms and agro-industry); # of local financial institutions that provide low-interest or no-interest financing mechanisms to businesses for mitigation and recovery; % businesses that have employee assistance programs during times of disruption	Business continuity plans address mitigation, response, and recovery and/or redevelopment; low-interest or no-interest financing mechanisms are available to businesses for mitigation and recovery; business leaders actively support small business continuity by providing assistance; understanding and estimation capability for worst-case damage/loss scenarios related to likely hazards (flood, storm, etc.); employee communication plans in place; current business plan and operations plan; understanding of worst-case damage/loss from likely hazards scenarios; agreements/contracts in	Arup (Rockefeller), 2014'; 'Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'; Rose & Krausmann, 2013; Orencio & Fujii, 2013; Sempier et al., 2010; Ranger & Surminski, 2013; LaDon et al., 2015; Mitchell et al., 2013; UNISDR, 2017	Driver	Businesses that do not have a plan for continued operation, access to needed resources, and recovery are generally more sensitive to hazards and have lower coping ability

					place with other businesses and suppliers in event of disaster; at least 3 months emergency operating funds; adequate insurance; backup generators/emergency supplies on hand			
Job density (proximity, commuting, etc.)	Economic	Micro/Meso Economic efficiency	Survival	% population that commutes more than 20 miles one way (high mileage commuters); % of high mileage commuters that are low income	Most jobs are located within 20 miles of residences; low income workers can afford to live within reasonable distance from jobs	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cox and Hamlen, 2015'	Resource and Driver	Lack of reasonable proximity to jobs that provide a livable wage (excessive commuting or commuting outside the community to find work) can increase sensitivity to hazards and reduce coping ability (driver); access and proximity of jobs that provide livable wages within the community build social and economic capital, and can increase adaptive capacity (resources)

Collective ownership of community resources	Economic	Micro/Meso Economic efficiency	Well-being	# of co-ops, # of community gardens; # of farmers markets; # of shared community spaces; # of community supported agriculture (CSA)	There is shared ownership/investment in community resources	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; 'Cutter et al., 2014'; Cutter, 2016c; Hughes & Bushell, 2013	Resource and Driver	Lack of shared investment in community resources can increase sensitivity and reduce coping (driver); shared investment and ownership in community resources increases social and economic capital through cohesion and leveraging of resources, which can increase adaptive capacity (resource)
Tourism	Economic	Micro/Meso Economic efficiency	Well-being	Number of annual tourists, % community revenues generated by tourism; % jobs dependent on tourism	Relative dependence on tourism	Palmisano et al., 2016'; U.N., 2015	Resource and Driver	Communities that rely primarily on tourism may have increased sensitivity to hazards and lower coping ability (driver); tourism balanced with other livelihood sources (diversity) can increase social and economic capital and may result in greater adaptive capacity (resource)
Asset operations and maintenance	Economic	Macroeconomic Stability	Well-being	Annual $ needed for operation and maintenance of WWTP, storm sewers, water and wastewater distribution networks, drinking water plants, roadways and bridges, buildings, electric distribution stations, gas/electric lines, information technology (broadband, cable, fiber)	Amount of funding needed to maintain critical assets and systems (public and private)	'Palmisano et al., 2016'; Thoms, 2016; DHS, 2016; U.N., 2015; UNISDR, 2017	Resource and Driver	Inadequate funding to maintain critical systems and assets leads to higher sensitivity and lower coping ability (driver); well maintained and operated system and assets increase social, economic, and environmental capital, reducing injury, loss, and time to recovery, and increasing adaptive capacity (resource)

Local businesses are included in community processes and decisions	Economic	Micro/Meso Economic efficiency	Well-being	# of businesses in the chamber of commerce, size/membership in chamber of commerce, local better business bureau membership	Chamber of Commerce or equivalent meets regularly; business leaders participate in community decisions and planning processes	Cox and Hamlen, 2015'	Driver	Failure to include businesses in community processes and decisions can lead to lack of awareness and incomplete or inaccurate decisions that increase sensitivity and may reduce coping
Well-managed public finances	Economic	Macroeconomic Stability	Well-being	Ratio of community annual revenue to debt; community credit rating; amount ($) community investments; amount ($) community savings; fiscal deficit to GDP ratio; external debt to GDP ratio	Public finances are well-managed and reported to the community in a transparent way	Arup (Rockefeller), 2014'; Cutter, 2016c; NAS, 2017; Ranger & Surminski, 2013; Briguglio et al., 2009; DHS, 2016; UNISDR, 2017	Resource and Driver	Poorly managed public finances can lead to increased sensitivity to hazards and lower coping ability (driver); well managed public finances increase social and economic capital by building trust, efficient use of resources, and extending access to external resources when needed (credit, loan, etc.), increasing adaptive capacity (resources)
Economic development planning	Economic	Macroeconomic Stability	Preparedness	Age of current community economic development plan (preferably within 5 years of current date)	Community economic development plan exists; plan looks forward to consider changes that might affect the tax base or the demand for specific services; coordinated with other local/regional governments	Matthews et al., 2014'; 'Cox and Hamlen, 2015'; UNISDR, 2017	Resource and Driver	Lack of comprehensive and coordinated economic development planning can increase sensitive and exposure, and reduce coping ability (driver); comprehensive and coordinated economic development planning can increase opportunity to build diversity and desirability, increasing social, economic, and environmental

								capital, leading to greater adaptive capacity (resource)
Adequate & affordable housing	Environment	Built	Survival	% deficit or excess in housing by type and average price; % available housing based on price and community income brackets; % homes vacant; % homes for rent; % vulnerable home types (trailers, etc.); % housing units built prior to 1970 or after 2000; # and % change in annual foreclosures; gentrification or displacement rate for lower income residents; housing affordability gap; % households with monthly housing costs that exceed 30% of monthly income; % of total households with at least 1 of 4 severe housing problems (housing unit lacks complete kitchen facilities; housing unit lacks complete plumbing facilities; household is severely overcrowded; and household is severely cost burdened); % homes subsidized by State or Federal government	Is there enough affordable housing to meet population needs; Is available housing of good quality; Is there an excess of housing	McManus et al., 2012; Parsons et al., 2016'; Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'Arup (Rockefeller), 2014'; 'Cox and Hamlen, 2015'; Shen et al., 2011; Lynch et al., 2011; DHS, 2016; U.N., 2015; (Kern, 2010; Tierney, 2009; Mileti, 1999; Theckethil, 2006)	Resource and Driver	Lack of affordable, quality housing increases sensitivity to hazards and lowers coping ability (driver); balanced availability and access to safe and affordable housing (avoiding major deficit or excess) builds social, economic, and environmental capital and may increase adaptive capacity (resources)

Building codes and enforcement (residential and commercial)	Environment	Built	Survival	% inspected buildings that meet current international building codes; % schools/childcare facilities that meet current building codes; # of enhanced building codes adopted to promote disaster resilience if community if subject to seismic, hurricane, or flood hazard; # schools and daycares with enhanced building codes to promote disaster resilience; % homes and businesses with enhanced building codes; # and type of incentives offered to encourage enhanced codes for hazard-prone areas	Do most buildings meet current codes; do codes reflect higher standards if in high risk areas for storms/ hurricanes/ earthquakes (protect against most severe scenarios), etc.; are codes routinely enforced; adherence to building codes that promote disaster resilience; existence of incentive-based mitigation measures (flood proofing; elevation; relocation; etc.); adequate # of certified building inspectors and staff to inspect and enforce codes	Sharifi and Yamagata, 2014; Sharifi, 2016'; Cox and Hamlen, 2015'; Orencio & Fujii, 2013; Sempier et al., 2010; DHS, 2016; Mitchell et al., 2013; UNISDR, 2017	Driver	Lack of safe housing and faculties due to inconsistent code compliance and enforcement increases sensitivity to hazards and can impact coping ability
Availability and access to secure and reliable information and communication technology systems (ICT) and networks	Environment	Built	Survival	% population without access to phone/cellular/mobile service; % population without access to internet; % population without access to cable or satellite (TV)	Use of secure networks for commerce, finance, medical, etc.; frequency and duration of disruption in services (cable, cellular, internet, phone, etc.); reverse 911 is available	Arup (Rockefeller), 2014'; Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; 'Sharifi and Yamagata, 2014; Sharifi, 2016'; Cox and Hamlen, 2015'; 'Parsons et al., 2016'; (Burger et al., 2013; Strawderman et al., 2012; UNDESA, 2007); Thoms, 2016; DHS, 2016; U.N., 2015	Driver	Lack of secure and reliable ICT and networks can increase sensitivity to hazards and reduce coping ability

Emergency communication systems (before, during, after event)	Environment	Built	Survival	# of warning sirens per 1,000 people (or other appropriate measure); % capability to alert population via mobile devices (texts, social media, etc.) before, during, and after an event; % capability to enable inbound flow of information from mobile devices to support crowd sourcing of data; % population that reports receiving warnings during drills	Sufficient warning sirens, alert systems to notify residents; alert methods are sufficiently redundant to reach residents (sirens, radio, TV, phone, etc.); the community has access to contingency communication systems and devices (HAM, hand-held radios, etc.)	Sharifi and Yamagata, 2014; 'Sharifi, 2016'; Thoms, 2016; Mitchell et al, 2013; UNISDR, 2017	Driver	Lack of awareness and reliable alert mechanisms increases exposure to hazards and may decrease coping ability
Critical infrastructure identification	Environment	Built	Survival	% critical infrastructure not currently identified on community maps (digital mapping such as GIS is preferred) [critical infrastructure are facilities and networks that are considered one of 16 recognized categories by the Department of Homeland Security - chemical, commercial, communication, information technology, manufacturing, dams, levees, defense, agricultural, energy, finance, government, healthcare, nuclear, transportation, water]; # and type of protective infrastructure systems (levees, dams, seawalls, etc.)	Can community officials and first responders immediately identify and convey the location of all critical infrastructure facilities and networks, as well as protective structures; 100% critical infrastructure and protective infrastructure systems are mapped, up to date, and available to first responders and public as appropriate; identification of airports, rail stations, helipads, etc. for emergency transport	Sharifi and Yamagata, 2014; Sharifi, 2016'; DHS, 2016; UNISDR, 2017	Driver	Inaccurate or incomplete identification and mapping of critical infrastructure can increase sensitivity to hazards and reduce coping ability
Critical infrastructure protection and maintenance	Environment	Built	Well-being	% critical infrastructure/systems and protective structures that require significant or moderate maintenance, repair, replacement; current amount ($) of critical deferred maintenance backlog; % critical systems, services, or resources without adequate alternative (backup) or spare capacity; % critical infrastructure without an emergency continuity plan; % protective infrastructure with current inspection and Emergency Action Plan (EAP); % protective infrastructure fully operational and prepared to handle most severe disaster scenario	Critical infrastructure and protective structures are regularly maintained and operational; critical infrastructure is regularly monitored; critical infrastructure, systems, and resources are protected from identified hazards; emergency plans and inspections are up to date	Arup (Rockefeller), 2014'; 'Sharifi and Yamagata, 2014; Sharifi, 2016'; Cox and Hamlen, 2015'; 'Cabell and Oelofse, 2012'; DHS, 2016; UNISDR, 2017; (Sundkvist et al., 2005; Darnhofer et	Resource and Driver	Inadequate protection and maintenance of critical infrastructure leads to higher exposure and sensitivity to hazards and can lower coping ability (driver); well maintained and protected critical infrastructure increase social, economic, and environmental capital, reducing injury, loss, and time to recovery, and increasing adaptive capacity (resource)

						al., 2010; Folke et al., 2010)		
Energy & Water efficiency and renewable energy	Environment	Built	Well-being	% public buildings meeting current energy and/or water efficiency standards/codes; % residential buildings meeting current energy and/or water efficiency standards/codes; % renewable energy based on total community energy supply; average megawatt hours per energy consumer; per capita energy and water consumption; energy and water intensity by economic/industrial sector	Relative levels of energy and water efficiency across commercial and residential areas, public and private sectors; availability and use of renewable energy	Sharifi and Yamagata, 2014; Sharifi, 2016'; Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; Palmisano et al., 2016;; Shen et al., 2011; DHS, 2016; U.N., 2015; UNISDR, 2017; (UNDESA, 2007)	Resource	Greater availability and access to efficient and renewable energy sources increases social, economic, and environmental capital and can increase adaptive capacity
Accessible, affordable, safe, and reliable power	Environment	Built	Well-being	% residents without access to power; % residents without access to municipal/utility-provided power; % residents without heating/cooling (HVAC); % population at risk from exposure to pollution from power generation/energy extraction	All residents have access to power; most residents have heating/cooling (HVAC); elderly have access to heating and cooling in areas at risk for extreme temperature	Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; DHS, 2016; U.N., 2015	Resource and Driver	Lack of access to safe and reliable power increases sensitivity to hazards and reduces coping ability (driver); equitable access to safe, affordable, and reliable power builds social, economic, and environmental capital and increases adaptive capacity (resource)

Assets located outside of hazard zones (floodplains, exposed coastal zones, landside areas, etc.)	Environment	Built	Survival	# residential structures located in high-hazard zones (floodplain, landslide, subsidence, storm surge, etc.); # residential structures located in high-hazard zones (floodplain, landslide, subsidence, storm surge, etc.); # schools and childcare facilities located in high-hazard zones; # medical facilities located in high-hazard zones; # of critical facilities/services (sub-stations, radio towers, emergency equipment storage, water treatment plants, etc.); % population within 10 miles of nuclear power plant, major dam, major levee, or other high impact structure; % population by age, gender, race residing in known areas that are prone to hazard	Critical infrastructure is not located in high-hazard areas; residential buildings are not located in high-hazard areas; commercial buildings are not located in high-hazard areas; active programs to remove or relocate properties in hazard zones; routine enforcement of zoning; community has a floodplain manager; community uses early warning systems for flood; zoning restrictions are enforced	Cox and Hamlen, 2015'; 'Sharifi and Yamagata, 2014; Sharifi, 2016'; 'Arup (Rockefeller), 2014'; Sempier et al., 2010; Shaw et al., 2009; Mitchell et al., 2013; UNISDR, 2017	Driver	Improper zoning and location of homes, businesses, or other structures within high hazard areas increases exposure and sensitivity to hazards, and reduces ability to cope
Retrofit, renewal, and refurbishment of the built environment	Environment	Built	Well-being	% community that is compromised by blight (vacant/abandoned property) - less than 4% of property base is desired	Community blight is low (vacant/abandoned property); there is an active program to identify and reduce blight	Sharifi and Yamagata, 2014; Sharifi, 2016'; Cutter et al., 2014'; Cutter, 2016c; NAS, 2017	Resource and Driver	Persistent blight increases sensitivity and exposure to hazards and may reduce coping ability (driver); reduction in blight and revitalization of vacant/abandoned properties increases social, economic, and environmental capital, and can increase adaptive capacity (resource)

Land use planning	Environment	Built	Well-being	Age of current land use planning documents and maps (preferably within 5 years); % farmland converted to other use; % critical ecosystem services identified; # green & blue infrastructure projects (greening roofs, urban gardens, green corridors for natural storm water attenuation, replace impervious surfaces with pervious; restoration of embankments, restoration of waterways, river and stream banks, etc.); # miles continuous bike trails; % areas considered "walkable" - able to work and live in proximity to essential services and amenities	Community land use planning uses appropriate zoning ordinances and codes to protect resources (property, people, services, etc.); ordinances and codes are routinely enforced; land use planning adequately addresses issues of blight, gentrification; low-income housing; accessibility to essential services, identification and avoidance of high risk areas; protection of ecosystem services	Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; 'Skog and Steinnes, 2016'; UNISDR, 2017	Resource	Land use planning and enforcement of zoning that is integrated with other community plans (economic development, disaster mitigation, etc.) can increase social, economic, and environmental capital and can increase adaptive capacity (resource)
Temporary shelter and relief availability	Environment	Built	Well-being	# of beds that can be provided to those in need of shelter (homeless, women & children, disaster); # of services that provide relief (homeless, women & children, disaster); # homeless adults and children	There is adequate shelter for those in need (homeless, women & children, disaster); there is adequate relief support for those in need (immediately available or otherwise accessible within 24 hours)	Sharifi and Yamagata, 2014; Sharifi, 2016'; Cutter et al., 2014'; Cutter, 2016c; Lynch et al., 2011; Shen et al., 2011; UNISDR, 2017	Resource and Driver	Lack of temporary shelter and resources dedicated to relief can increase exposure and sensitivity to hazards, lowering coping ability (driver); integrated efforts to identify and maintain resources for temporary shelter and relief increase social and economic capital, and can increase adaptive capacity during response and recovery (resource)
Most livestock owners understand local hazard risks and how to keep animals safe through alternate shelter, food supplies, or evacuation	Environment	Built	Preparedness	# farms/livestock owners that are not prepared for disaster	Livestock/farm owners have identified and invested in emergency response resources, equipment, and contingency power; backup supplies (food, water, medicine) and shelter are available; livestock vaccinations up to date	Cox and Hamlen, 2015'; Hughes & Bushell, 2013	Driver	Lack of emergency planning and preparation for livestock maintenance can increase exposure and sensitivity to hazards, and may reduce coping ability especially within the agricultural sector

Recreational opportunities encourage young adults and families to stay	Environment	Built	Well-being	# community recreational facilities/areas per 1,000 people (or other appropriate measure) [includes sport/health clubs, recreation centers, parks, playgrounds, skate ramps, green space, etc.]; square feet (acres, etc.) of public recreation facility space per capita (facilities and green space/parks); $ spent annually on public recreation; # libraries	Adequate number of recreational facilities and areas available for community use; facilities and areas are accessible to all; facilities and areas are well-maintained and safe; residents do not need to leave the community to access recreational opportunities	Cox and Hamlen, 2015'; 'Sharifi and Yamagata, 2014; Sharifi, 2016'; McManus et al., 2012; Shen et al., 2011; U.N., 2015; Kontakosta & Malik, 2018	Resource and Driver	Lack of recreational opportunity increases sensitivity and may impact coping due to lack of cohesion and community engagement (driver); opportunity for recreation through facilities or natural spaces increases social capital and economic capital by increasing desirability, creating new revenue/business, and fostering social cohesion and trust, increases environmental capital and adaptive capacity as resources can also be used for temporary shelter and relief (resource)
Access and evacuation routes	Environment	Built	Well-being	# major road egress point per 1,000 persons (or other relevant measure); Amount funding allocated to emergency evacuation procedures (crews, transportation, etc.); # airports; # rail lines; # helipads	Adequate road egress points to enter and leave the community based on population; adequate signage to identify routes; routes and information available to public via multiple communication systems (internet, maps, plans, etc.); emergency signage is posted and easily understandable (flood, avalanche, tsunami, etc.); multiple access routes into and out of the community; alternate access routes are available and maintained; plan in place to monitor evacuation, clear debris, assist with traffic control; remove	Cutter et al., 2014'; Cutter, 2016c; 'Cox and Hamlen, 2015'; Sempier et al., 2010	Driver	Lack of adequate access and evacuation routes (and identification and awareness of routes) can increase exposure and sensitivity to hazards and reduce coping ability, especially during evacuation, response, and recovery

					vehicles, provide public transportation, and complete emergency repair of roads and transportation systems; mutual aid agreements with other communities			
Industrial re-supply potential	Environment	Built	Well-being	# of rail miles per square mile; # of ports in area; # of multimodal transport hubs in area	Commercial rail is available to the community, other commercial transport and shipping modes available	Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; (Cutter et al., 2008)	Resource	Availability of means for industrial resupply increases social and economic capital, especially during response and recovery, and increases adaptive capacity
Adequate, accessible, reliable, safe, and affordable transport networks	Environment	Built	Well-being	# and type of transportation/mobility networks (bus, rail, etc.); % households within 1/4 mile of a transit stop; miles of bike lane; % population using transit (ridership); # primary ingress/egress routes (alternate means of access or evacuation); % of public transportation passenger terminals with intermodal connectivity and in compliance with ADA requirements	Transportation modes are affordable and reliable; networks are adequately connected; networks are accessible and consistently available; transportation infrastructure, equipment, and services are adequately maintained (roads, signage, bridges, rail line, buses, trains, stations, shelters, etc.) to ensure safety and operability; disruption to service is minimal (length and duration of disruption); existence of	Arup (Rockefeller), 2014'; 'Sharifi and Yamagata, 2014; Sharifi, 2016'; 'Cox and Hamlen, 2015'; Lynch et al., 2011; Sempier et al., 2010; DHS, 2016	Resource and Driver	Inadequate transport/mobility networks increases exposure and sensitivity to hazards, and decreases coping ability, especially during evacuation, response, and recovery (driver); equitable access to safe, reliable, and affordable means of transport increase social and economic capital, as community desirability and

					alternate routes for access/evacuation			adaptive capacity (resource)
Cultural and historical preservation, indigenous knowledge and traditions	Environment	General	Well-being	# cultural/archeological sites; # museums; public/private investment ($ annually) in cultural/heritage sites	Community legislation and policy protect cultural/historical resources; history and tradition is respected (existence of cultural/historical groups focused on protection, preservation, and education); maintenance of heirloom seeds and native species; engagement of elders; incorporation of traditional techniques with modern knowledge	Sharifi and Yamagata, 2014; Sharifi, 2016'; 'Palmisano et al., 2016'; 'Cabell and Oelofse, 2012'; Shen et al., 2011; UNISDR, 2017; (Gunderson and Holling, 2002; Cumming et al., 2005; Shava et al., 2010; van Apeldoorn et al., 2011)	Resource	Maintenance of land, facilities, and assets associated with local history and heritage increases social and environmental capital through learning, memory. cohesion, increased desirability, recreation, and shared space, which can increase adaptive capacity

Climate is considered in risk identification, assessment, and planning, and policy	Environment	General	Preparedness	% change in maximum, average, and minimum daily temperatures over 10 year period; % change in maximum, average, and minimum precipitation over 10 year period; % change in frequency and intensity of severe storms, floods, drought, wildfire, etc. over last 10 years; % change in reported damages (\$) resulting from severe storms, floods, drought, wildfire, earthquake, etc. over last 10 years; % change sea level over last 10 years (for coastal communities); # of sites designated as StormReady and/or TsunamiReady	Climate risk and impacts are considered for built and natural infrastructure, economy, safety, and wellbeing; community resources are allocated for assessment of climate impacts; monitoring of changes in frequency and intensity/severity of storms, flood, wildfire, drought, erosion, subsidence, infestation, and related damage and loss, etc.; coastal communities consider impacts of sea level rise and salinity intrusion	Sharifi and Yamagata, 2014; Sharifi, 2016'; 'Matthews et al., 2014'; Cox and Hamlen, 2015'; Hughes & Bushell, 2013; Shaw et al., 2009; Yoon et al., 2016; UNISDR, 2017	Driver	Failure to adequately monitor, assess, and integrate climate data (past, current, and future projections) into risk assessment and planning can result in underestimation of frequency and severity of hazards and lack of identification of social, economic, and environmental impacts - this increases exposure and sensitivity to hazards and lowers coping ability
Mapping capability	Environment	General	Preparedness	% critical assets currently mapped (infrastructure, critical services, evacuation routes, populations, high risk areas, etc.)	Accurate and up-to-date mapping of critical assets, infrastructure, services, evacuation routes, populations, hazard scenarios (flood, tidal surge, wind, etc.) exists and is available to the public; maps are updated regularly; GIS is used	Arup (Rockefeller), 2014'; Venton, 2014; UNISDR, 2017	Resource	The ability to apply integrated tools such as mapping capability (GIS, etc.) to risk assessment, planning, and policy increases social capital through trust, efficiency, and capacity for response, and can also increase economic and environmental capital through more efficient and effective use of resources and linked impacts during hazard/mitigation planning and strategies for adaptation or transformation, which can increase adaptive capacity

Waste management	Environment	General	Survival	% population without access to municipal waste management; % population without adequate sewage treatment (including septic fields); number of hazardous waste collection/treatment sites; % population burning trash; # of "non-permitted" landfills/waste repository sites; # hazardous spills reported in last year; # transpiration related spills/releases of hazardous materials in last year; # recycling services; # wastewater treatment facilities; # of wastewater treatment systems that did not meet permit requirements in the last year; # untreated discharges from wastewater treatment plants in last year; # beach closures in last year; # fishing/swimming advisories issued in last year; # of impaired water sources (rivers, aquifers, etc.); # of septic tanks and septic fields; % combined sewer/storm water systems; % facilities failing to meet air quality standards in last year; # air quality warnings/advisories to public in last year; % population exposed to excessive noise levels; # of reported medical respiratory incidents related to air quality in adults and children; carbon dioxide emissions intensity by economic sector/industry (tons/year)	The community has access to safe and sanitary waste disposal and management services; municipal waste is disposed of at a permitted facility; appropriate measures are in place for spill response and recovery; where trash burning is allowed, the community provides safety guidelines; recycling is available; municipal waste water treatment systems meet permit requirements; waste sites/repositories are adequately maintained and protected; wastewater treatment plants are in compliance with permits; water quality standards in lakes, rivers, and streams are adequately maintained; residents understand how to properly maintain septic tanks; storm water is adequately managed; air quality standards are maintained; air quality is consistently good; noise levels are acceptable	Palmisano et al., 2016; Cox and Hamlen, 2015'; 'Arup (Rockefeller) , 2014'; Shen et al., 2011; Lynch et al., 2011; Hiremath et al., 2013; U.N., 2015; UNISDR, 2017	Resource and Driver	Lack of safe and reliable waste disposal and sanitary services increases exposure and sensitivity to hazards and can decrease coping ability (driver); equitable access to safe and reliable waste management and sanitation services increases social capital through health, trust, and desirability, economic and environmental capital are also increased through prevision of jobs, and prevention of natural degradation, when services are present and reliably maintained, adaptive capacity is higher (resource)

Water supply and quality	Environment	General	Survival	% population without access to municipal drinking water (municipal, private wells, etc.); # municipal multiple water supply sources; % public drinking water systems that did not meet permit requirements in the last year; % population with only access to groundwater; % irrigation from groundwater; water supply stress index; # of waterborne illnesses reported in last year; # of annual disruptions to water supply; # of droughts and length and severity of drought conditions; # bottled water notices; # boil water notices; # swimming water notices; % water lost in conveyance	All residents have access to adequate supplies of safe drinking water; multiple water supply sources; water meets current and future (over next 20 years) needs (municipal, industrial, agricultural, etc.); water distribution and treatment facilities are well maintained; the community adequately protects source water areas, watersheds, reservoirs, springs, well heads; ; does the state have a Mutual Aid and Assistance Agreement in place through the Water/Wastewater Agency Response Network (WARN)	Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; Palmisano et al., 2016; Cox and Hamlen, 2015'; 'Arup (Rockefeller), 2014'; Lynch et al., 2011; Hughes & Bushell, 2013; DHS, 2016; Hiremath et al., 2013; U.N., 2015; UNISDR, 2017; (UNDESA, 2007)	Resource and Driver	Lack of long-term availability and access to safe drinking water increases exposure and sensitivity to hazards and lowers coping ability (driver); long-term availability and equitable access to safe drinking water through integrated demand-management and watershed planning increases social, economic, and environmental capital, and increases adaptive capacity (resource)
Redundancy and diversity in natural resources	Environment	Natural	Well-being	# and type of crops planted annually; # and type of water sources available for community use; # and type of energy sources available to the community (coal, natural gas, heating oil, nuclear, wind, solar, etc.); % annual change in land cover from natural to other use; % of total surface and groundwater sources used; water demand projections for agricultural, industrial, municipal sectors for next 10-20 years;	Adequate diversity and redundancy in natural resources (water, energy, land); consideration of impact associated with water rights; adoption of hazard resistant agriculture	Srinivasan et al., 2012; Cabell and Oelofse, 2012';'Cox and Hamlen, 2015'; Shen et al., 2011; Lynch et al., 2011; Orencio & Fujii, 2013; Hughes & Bushell, 2013; UNISDR, 2017	Resource and Driver	Lack of redundancy and diversity in resource availability and use increases sensitivity to hazard and can lower coping ability (driver); adequate redundancy and diversity in resource availability and use ensures access to resources under changing conditions and allows for greater flexibility over time which can increase social, economic, and environmental capital and adaptive capacity (resource)

Diversity in landscape elements	Environment	Natural	Well-being	% land use by type; % pervious surface in urban areas; % woodland, prairie, and natural space; % change in natural areas annually (loss of green space, including farm conversion)	Balanced community design (mixed use, compact, dispersed, green space, etc.); patchiness in agricultural areas; mosaic pattern of managed and unmanaged land; diverse forestry and cultivation practices; crop rotation; heterogeneity of features within the landscape; master plan and economic development are integrated to preserve landscape and natural assets	Palmisano et al., 2016; 'Sharifi and Yamagata, 2014; Sharifi, 2016'; Cabell and Oelofse, 2012'; Cutter et al., 2014'; Cutter, 2016c; NAS, 2017; UNISDR, 2017; (Altieri, 1999; Ewell, 1999; Berkes et al., 2003; Luck et al., 2003; Swift et al., 2004; Folke, 2006; Jackson et al., 2007; Di Falco and Chavas, 2008; Chapin et al., 2009; Darnhofer et al., 2010; Devictor et al., 2008)	Resource and Driver	Lack of diversity in land use and landscape elements can increase sensitivity to hazards and reduce coping ability (driver); adequate presence of green (natural) and gray (built) features allows for natural attenuation and natural buffers (water quality, flood, etc.), which increases social capital through presence of green spaces, economic capital through greater efficiency, and environmental capital through infrastructure protection and ecosystem services, which increases adaptive capacity (resource)
Managed exposure to disturbance	Environment	Natural	Well-being	# controlled burn events in last year; # controlled inundation events in last year; # forest fuel clearing events; # acres harvested through sustainable forest practices	Pest management that allows a certain controlled amount of invasion followed by selection of plants that fared well and exhibit signs of resistance; controlled burn to manage land cover; controlled flooding for nutrients and maintenance; environmental practices that reduce hazard risk	Cabell and Oelofse, 2012'; Orencio & Fujii, 2013; (Gunderson and Holling, 2002; Berkes et al, 2003; Folke, 2006)	Resource and Driver	Managed exposure increases health and availability of natural assets and buffers (resource); lack of managed exposure decreases natural coping and increases unwanted risk of disaster and potential for harm (wildfire, infestation, etc.) (driver)

Effectively managed ecosystems	Environment	Natural	Well-being	# and type of critical ecosystem services identified (forests, fisheries, mangroves, riparian zones, wetlands, reefs, lakes, rivers, beaches, aquifers, dunes, protective buffers, etc.); ($) allocated for protection of ecosystem services annually, % loss of natural systems and buffers in last year by type; % partnerships to maintain and protect critical natural assets and ecosystem services	Adequate monitoring and maintenance of biodiversity, critical habitat, and ecosystem services (rivers, lakes, forests, prairies, watersheds, beaches, riparian zones, natural flood protection systems, etc.); master plans, zoning, and economic development plans are coordinated to preserve natural buffers and assets; laws are in place and enforced to protect critical natural areas and ecosystem services	Arup (Rockefeller), 2014'; 'Sharifi and Yamagata, 2014; Sharifi, 2016'; Cox and Hamlen, 2015'; Srinivasan et al., 2012; Cabell and Oelofse, 2012'; NAS, 2017; DHS, 2016; UNISDR, 2017; (Ewell, 1999; Milestad and Darnhofer, 2003; Naylor, 2009; Darnhofer et al., 2010; van Apeldoon et al., 2011)	Resource and Driver	Failure to adequately monitor and maintain local ecosystems and services (natural buffers, water quality, parks, forests, etc.) can lead to resource degradation and increased exposure and sensitivity to hazards as well as reduced coping ability (driver); integrated and coordinated planning to protect and maintain ecosystems and services increases social capital through cohesion, health, and desirability and environmental capital by providing natural protection of facilities and assets, and increases adaptive capacity (resource)
Sustainable management of resources	Environment	Natural	Well-being	% population participating in resource conservation and recycling; % farms using natural herbicides and pesticides; % organic farms; # of landfills; tons of trash; mulch and compost service available; # recycling centers; % farms using sustainable and organic agriculture practices	Builds (does not deplete) soil and organic matter; recharges water; reduces need to import nutrients; reduces need to export waste; resources function adequately without need for excessive augmentation; agriculture and forestry maintain plant cover and incorporate more perennials; provide habitat for predators and parasitoids; and align production, harvesting, and extraction with	Cabell and Oelofse, 2012'; 'Sharifi and Yamagata, 2014; Sharifi, 2016';Cox and Hamlen, 2015'; DHS, 2016; U.N., 2015; (Sundkvist et al., 2005; Ewell, 1999; Jackson, 2002; Swift et al., 2004; McKey et	Resource	Sustainable management of resources that allows for minimization of degradation to soils, water, air, etc., and more efficient use of resources and services (minimization of solid waste to prevent the need for additional landfills, costs, etc.) increases social, economic, and environmental capital and increases adaptive capacity

					local ecological parameters	al., 2010; Holling, 2001; Gunderson and Holling, 2002)		
Public, commercial, and residential properties and services located outside of critical natural areas (natural buffers, wetlands, riparian zones, critical habitat, etc.	Environment	Natural	Well-being	# endangered and threatened species (plants and animals); # of designated critical habitat areas; % loss in critical species and habitat (plants and animals)	Threatened and endangered species are adequately monitored and protected; critical habitat is adequately monitored and protected;	Sharifi and Yamagata, 2014; Sharifi, 2016'; Cutter et al., 2014; Cutter, 2016c; NAS, 2017; Lynch et al., 2011; (Beatley and Newman, 2013)	Resource	Adequate monitoring and management of critical species and habitat helps to preserve community health, heritage, and diversity and can build social, economic, and environmental capital, increasing adaptive capacity (die-offs and loss of habitat due to degradation are typically precursors to systemic community degradation of capital)

Management of environmental impacts	Environment	Natural	Well-being	Amount ($) spent on restoration of natural, cultural, and historical resources by type in last year	Measures are in place to manage and prevent negative impacts to natural, cultural, and historical resources; funding is allocated for prevention and restoration	Sharifi and Yamagata, 2014; Sharifi, 2016'; Srinivasan et al., 2012; DHS, 2016	Resource and Driver	Lack of adequate management and restoration of natural, cultural, and historic resources can lead to increased exposure and sensitivity to hazards and lower coping ability (driver); maintenance and restoration of natural, cultural, and historical assets increases social, economic, and environmental capital, and can increase adaptive capacity (loss of natural, cultural, and historical assets through degradation and neglect are typically precursors to systemic community degradation of capital)
Availability and accessibility of high quality resources (air, energy, water, food, land, habitat; etc.)	Environment	Natural	Survival	% population at risk for loss of access to critical resources (depletion, degradation, loss, etc.); Amount of food and water available for emergency; Per capita water demand estimates and plans for acquisition/storage/treatment for next 20 years	The community is not at risk for loss of future resources due to degradation, depletion, or other factors); there no significant detrimental changes in the quality or quantity of natural resources (water, soil, land cover, air, habitat, landscape, view shed, aesthetics, noise, etc.)	Sharifi and Yamagata, 2014; Sharifi, 2016'; Cox and Hamlen, 2015'; 'McManus et al., 2012; Srinivasan et al., 2012; Shen et al., 2011; Orencio & Fujii, 2013; U.N., 2015; UNISDR, 2017	Resource	Long-term, equitable access to life-sustaining natural resources increases all forms of capital and is essential for supporting adaptive capacity (lack of availability and equitable access to these resources are typically precursors to systemic community degradation of capital)

Leaders/local government identify and protect environmentally sensitive areas and natural resources	Environment	Natural	Well-being	# of environmental enforcement actions in last year by type/statute; amount ($) in fines in last year; amount ($) spent on management on environmental management in last year	Adequate legislation, policy, and planning for environmental management and pollution control; adequate funding to manage environmental (natural, cultural, and historical) resources; enforcement of environmental laws and policies; management plans are current for environmental programs and permitting (noise, air quality, water quality, pollution control, waste management, sanitation, land use, etc.)	Cox and Hamlen, 2015'; Shen et al., 2011; DHS, 2016; UNISDR, 2017	Resource	Adequate government measures to maintain and enforce protecting of natural, cultural, and historic resources is essential to all forms of capital and adaptive capacity (failure to provide and enforce mechanisms for protection indicate a weak and ineffective government and can be seen as precursor to systemic community degradation of capital)

Appendix D: Journal Titles Produced in Literature Review

Journal Title/Source	**No. Initial Search**
Global environmental change	2
J. Infrastruct. Syst.	1
Land Use Policy	1
PLoS One	2
Sustainable Cities and Society	1
Accounting, Auditing, and Accountability Journal	1
Agriculture, ecosystems & environment	2
Ambio	2
American Behavioral Scientist	1
American journal of community psychology	1
American journal of public health	2
Annu. Rev. Environ. Resour.	1
Annual Review of Environment and Resources	2
Anthropocene	1
Applied Geography	3
Applied Research in Quality of Life	1
Asian Journal of environment and disaster Management	1
Australian Journal of Emergency Management	1
Australian Journal of Emergency Management	1
Benchmarking	1
Benchmarking: An International Journal	1
Biological Sciences	1
BioScience	1
Building Research and Information	1
Child development	1
Cities	3
Climate Change	2

Conservation Ecology	2
Disaster Prevention and Management	1
Disaster Prevention and Management: An International Journal	1
Disaster resilience: An integrated approach	1
Disasters	3
Earthquake Spectra	2
Ecological complexity	1
Ecological economics	1
Ecological Indicators	3
Ecology and Society	4
Economic Systems Research	1
Economic systems research: journal of the international Input-Output Association	1
Ecosystems	3
Energy for sustainable development	1
Energy Policy	1
Energy Procedia	1
Engineering Structures	1
Environment and Society	2
Environment international	1
Environment Monitoring and Assessment	1
Environment Systems & Decisions	3
Environmental Earth Sciences	1
Environmental Education Research	1
Environmental Hazards	2
Environmental Impact Assessment Review	2
Environmental Law	2
Environmental Management	5
Environmental Reviews	2
Environmental science & policy	1
Family process	1

Fisheries	3
Food Policy	1
Food Security	1
Forest Ecology and Management	1
Futures	1
Geoheritage	1
GeoJournal	1
Global environmental change	4
Habitat International	3
Human Ecology	1
Human Ecology Review	3
Intenational Journal of River Basin Management	1
International Journal of Disaster Reduction	3
International Journal of Climate Change Strategies and Management	1
International journal of agricultural sustainability	2
International journal of disaster risk reduction	3
Journal of Coastal Research	1
Journal of Urban Health	1
Journal of Business Economics and Management	1
Journal of Contingencies and Crisis Management	2
Journal of Current Issues in Globalization	2
Journal of environmental management	1
Journal of Environmental Planning and Management	4
Journal of Environmental Studies and Sciences	1
Journal of Management & Governance	1
Journal of Risk Research	2
Journal of sustainable agriculture	2
Journal of Sustainable Development	2
Journal of Toxicology and Environmental Health	1
Lancet	2

Land Economics	2
Land Use Policy	3
Landscape and urban planning	1
Landscape Ecology	1
logistics and transportation review	1
Measuring Business Excellence	1
Mitigation and Adaptation Strategies for Global Change	3
Natural hazards	7
Natural hazards review	3
Nature climate change	1
OECD Environment Working Papers	1
OECD Food, Agriculture and Fisheries Papers	1
OECD Regional Development Working Papers	1
OECD Working Papers on Public Governance	1
Patient-Provider Communication: Roles for Speech-Language Pathologists and Other Health Care Professionals	1
Philadelphia: Penn Institute for Urban Research.	1
Progress in Human Geography	1
Progress in Planning	1
Quality in Higher Education	1
Rand health quarterly	1
Reliability Engineering & System Safety	1
Remote Sensing of Environment	1
Risk Analysis	1
Social indicators research	3
Social psychology quarterly	1
Social Science Quarterly	1
Society & Natural Resources	2
Springer books	3
Sust. Dev	1
Sustainability	2

Sustainability Science	1
Sustainability: Science, Practice, & Policy	2
Technological Forecasting and Social Change	2
Trends in Ecology & Evolution	1
Urban Climate	1
Water Resources Management	1
Water Resources Research	1
WHOQoL Group	2
Wiley Interdisciplinary Reviews. Climate Change	1
World Development	1
Total	205

Appendix E: Literature Review Results

Also available in filterable/searchable format at: https://blindreview1.shinyapps.io/Search/

Journal/Source	From Google Scholar	Full-Text Review	Used in Appendix B	Reference
Annual review of ecology and systematics	1	1		Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual review of ecology and systematics*, 4(1), 1-23.
Current opinion in environmental sustainability	1	1		Leichenko, R. (2011). Climate change and urban resilience. Current opinion in environmental sustainability, 3(3), 164-168.
Family process	1	1	1	Walsh, F. (2007). Traumatic loss and major disasters: Strengthening family and community resilience. *Family process*, 46(2), 207-227.
Global Environmental Change		1		Hinkel, J. (2011). "Indicators of vulnerability and adaptive capacity:" Towards a clarification of the science–policy interface. *Global Environmental Change*, *21*(1), 198-208.
J. Infrastruct. Syst.		1		Johansen, C., Horney, J., Tien, I. (2016). Metrics for Evaluating and Improving Community Resilience. J. *Infrastruct. Syst*., *23*(2), 04016032.
Trends in Ecology & Evolution	1	1	1	Luck, G. W., Daily, G. C., Ehrlich, P. R. (2003). Population diversity and ecosystem services. *Trends in Ecology & Evolution*, 18(7), 331-336.
(Doctoral dissertation). Retrieved from https://scholarcommons.sc.edu/etd/1275	1	1		Burton, C. G. (2012). The development of metrics for community resilience to natural disasters. (Doctoral dissertation). Retrieved from https://scholarcommons.sc.edu/etd/1275
Agriculture, ecosystems & environment		1	1	Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, ecosystems & environment*, 74(1), 19-31.
Agriculture, ecosystems & environment		1	1	Jackson, L. E., Pascual, U., Hodgkin, T. (2007). Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agriculture, ecosystems & environment*, 121(3), 196-210.

Agriculture, Ecosystems & Environment		1	1	Swift, M. J., Izac, A. M., van Noordwijk, M. (2004). Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? *Agriculture, Ecosystems & Environment*, 104(1), 113-134.
AMBIO: A Journal of the Human Environment		1		Ernstson, H., Leeuw, S. E. V. D., Redman, C. L., Meffert, D. J., Davis, G., Alfsen, C., Elmqvist, T. (2010). Urban transitions: on urban resilience and human-dominated ecosystems. AMBIO: *A Journal of the Human Environment*, 39(8), 531-545.
AMBIO: A journal of the human environment		1		Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S. and Walker, B., (2002). Resilience and sustainable development: building adaptive capacity in a world of transformations. *AMBIO: A journal of the human environment*, *31*(5), pp.437-440.
American Behavioral Scientist	1	1	1	Cox, R. S., & Hamlen, M. (2015). Community disaster resilience and the rural resilience index. *American Behavioral Scientist*, 59(2), 220-237.
American journal of community psychology	1	1	1	Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., Pfefferbaum, R. L. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American journal of community psychology*, 41(1-2), 127-150.
American journal of public health		1	1	Plough, A., Fielding, J.E., Chandra, A., Williams, M., Eisenman, D., Wells, K.B., Law, G.Y., Fogleman, S. and Magaña, A. (2013). Building community disaster resilience: perspectives from a large urban county department of public health. *American journal of public health*, 103(7), 1190-1197.
Annu. Rev. Environ. Resour.		1		Eakin, H., & Luers, A. L. (2006). Assessing the Vulnerability of Social-Environmental Systems. *Annu. Rev. Environ. Resour*. 31, 365–94.
Annual Review of environment and resources		1		Parris, T. M., & Kates, R. W. (2003). Characterizing and measuring sustainable development. Annual Review of environment and resources, 28(1), 559-586.
Applied Geography		1		Frazier, T.G., Thompson, C.M., and Dezzani, R. J. (2014). A framework for the development of the SERV model: A Spatially Explicit Resilience-Vulnerability model. *Applied Geography*, 51, 158-172.

Arup International Development and The Rockefeller Foundation	1	1	1	Arup International Development and The Rockefeller Foundation. (2014). City Resilience Index: City Resilience Framework. London.
Asian Journal of Environment and Disaster Management	1	1	1	Shaw, R., & Team, I. E. D. M. (2009). Climate disaster resilience: focus on coastal urban cities in Asia. A*sian Journal of Environment and Disaster Management*, *1*, 101-116.
Australian Journal of Emergency Management		1	1	Parsons, M., & Morley, P. (2017). The Australian natural disaster resilience index. *Australian Journal of Emergency Management, The*, *32*(2), 20.
Biological Sciences		1	1	Devictor, V., Julliard, R., Couvet, D., Jiguet, F. (2008). Birds are tracking climate warming, but not fast enough. Proceedings of the Royal Society of London B: *Biological Sciences*, 275(1652), 2743-2748.
BioScience		1		Alberti, M., Marzluff, J. M., Shulenberger, E., Bradley, G., Ryan, C., Zumbrunnen, C. (2003). Integrating humans into ecology: opportunities and challenges for studying urban ecosystems. *BioScience*, 53(12), 1169-1179.
Cambridge University Press	1	1		Berkes F, Colding J, Folke C. (Eds). (2003). Navigating social–ecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge, UK.
Can. J. Civ. Eng.	1	1		Upadhyaya, J. K., Biswas, N., Tam, E. (2014). A review of infrastructure challenges: assessing stormwater system sustainability. *Can. J. Civ. Eng.*, 41, 483–492.
CARRI Research Report	1	1	1	Morrow, B. H. (2008). Community resilience: A social justice perspective (Vol. 4). Oak Ridge, TN: CARRI Research Report.
CARRI Research Report	1	1	1	Tierney, K. (2009). Disaster response: Research findings and their implications for resilience measures (Vol. 6). CARRI Research Report.
Cities		1		Collier, M. J., Nedović-Budić, Z., Aerts, J., Connop, S., Foley, D., Foley, K., Verburg, P. (2013). Transitioning to resilience and sustainability in urban communities. *Cities*, *32*, S21-S28.
Cities		1		Desouza, K. C., & Flanery, T. H. (2013). Designing, planning, and managing resilient cities: A conceptual framework. *Cities*, 35, 89-99.

Cities		1		Lu, P., and Stead, D. (2013). Understanding the notion of resilience in spatial planning: A case study of Rotterdam, The Netherlands. Cities, 35, 200-212.
Comptes Rendus Geoscience	1	1		Adger, W.N., & Vincent, K., (2005). Uncertainty in adaptive capacity. Comptes Rendus Geoscience, 337(4), pp. 399-410.
Conservation Ecology		1	1	Levin, S. (1999). Towards a science of ecological management. *Conservation Ecology*, 3(2).
DHS Mitigation Framework Leadership Group (MitFLG)	1	1	1	Department of Homeland Security (DHS). (2016). Draft Interagency Concept for Community Resilience Indicators and National-Level Measures. Mitigation Framework Leadership Group (MitFLG).
Disaster resilience: An integrated approach	1	1	1	Paton, D., McClure, J., Bürgelt, P. T. (2006). Natural hazard resilience: The role of individual and household preparedness. Disaster resilience: An integrated approach, 105-127.
Disasters		1	1	Messias, D. K. H., Barrington, C., Lacy, E. (2012). Latino social network dynamics and the Hurricane Katrina disaster. *Disasters*, 36(1), 101-121.
Disasters		1		Mochizuki, J., Keating, A., Liu, W., Hochrainer-Stigler, S., & Mechler, R. (2018). An overdue alignment of risk and resilience? A conceptual contribution to community resilience. *Disasters*, *42*(2), 361-391.
Disasters		1	1	Pingali, P., Alinovi, L., & Sutton, J. (2005). Food security in complex emergencies: enhancing food system resilience. *Disasters*, 29(s1).
Earthquake Spectra		1	1	Wein, A., & Rose, A. (2011). Economic resilience lessons from the ShakeOut earthquake scenario. *Earthquake Spectra*, 27(2), 559-573.
Ecological complexity		1		Graymore, M. L., Wallis, A. M., & Richards, A. J. (2009). An Index of Regional Sustainability: A GIS-based multiple criteria analysis decision support system for progressing sustainability. Ecological complexity, 6(4), 453-462.
Ecological economics		1		Dietz, S., & Neumayer, E. 2007. Weak and strong sustainability in the SEEA: Concepts and measurement. Ecological economics, 61(4), 617-626.
Ecological Indicators		1	1	Sharifi, A. (2016). A critical review of selected tools for assessing community resilience. *Ecological Indicators*, 69, 629-647.

Ecological indicators		1		Wang, Y., Lam, K. C., Harder, M. K., Ma, W. C., & Yu, Q. (2013). Developing an indicator system to foster sustainability in strategic planning in China: A case study of Pudong New Area, Shanghai. *Ecological indicators*, *29*, 376-389.
Ecology and Society		1	1	Cabell, J., & Oelofse, M. (2012). An indicator framework for assessing agroecosystem resilience. *Ecology and Society*, 17(1).
Ecology and society		1	1	Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T., Rockström, J. (2010). Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and society*, 15(4).
Ecology and Society		1	1	van Apeldoorn, D., Kok, K., Sonneveld, M., Veldkamp, T. (2011). Panarchy rules: rethinking resilience of agroecosystems, evidence from Dutch dairy-farming. *Ecology and Society*, 16(1).
Ecosystems		1	1	Cumming, G.S., Barnes, G., Perz, S., Schmink, M., Sieving, K.E., Southworth, J., Binford, M., Holt, R.D., Stickler, C. and Van Holt, T. (2005). An exploratory framework for the empirical measurement of resilience. *Ecosystems*, 8(8), 975-987.
Ecosystems		1	1	Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems*, 4(5), 390-405.
EGU General Assembly Conference Abstracts	1	1	1	Thoms, M. (2016). The Australian Natural Disaster Resilience Index. In *EGU General Assembly Conference Abstracts* (Vol. 18, p. 2435).
Energy for sustainable development	1	1	1	Hiremath, R. B., Balachandra, P., Kumar, B., Bansode, S. S., Murali, J. (2013). Indicator-based urban sustainability—A review. *Energy for sustainable development*, *17*(6), 555-563.
Energy Policy		1		Coaffee, J. (2008). Risk, resilience, and environmentally sustainable cities. *Energy Policy*, *36*(12), 4633-4638.
Energy Procedia		1	1	Sharifi, A., & Yamagata, Y. (2014). Resilient urban planning: Major principles and criteria. *Energy Procedia*, *61*, 1491-1495.
Engineering Structures		1	1	Cimellaro, G. P., Reinhorn, A. M., Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Engineering Structures*, 32(11), 3639-3649.

Environment international		1		Mayer, A. L. (2008). Strengths and weaknesses of common sustainability indices for multidimensional systems. Environment international, 34(2), 277-291.
Environment Systems and Decisions		1		Larkin, S., Fox-Lent, C., Eisenberg, D. A., Trump, B. D., Wallace, S., Chadderton, C., Linkov, I. (2015). Benchmarking agency and organizational practices in resilience decision making. *Environment Systems and Decisions*, 35(2), 185-195.
Environmental Education Research	1	1	1	Shava, S., Krasny, M. E., Tidball, K. G., Zazu, C. (2010). Agricultural knowledge in urban and resettled communities: Applications to social–ecological resilience and environmental education. *Environmental Education Research*, 16(5-6), 575-589.
Environmental Hazards		1	1	Rose, A. (2007). Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions. *Environmental Hazards*, 7(4), 383-398.
Environmental Impact Assessment Review		1	1	Matthews, E. C., Sattler, M., Friedland, C. J. (2014). A critical analysis of hazard resilience measures within sustainability assessment frameworks. *Environmental Impact Assessment Review*, 49, 59-69.
Environmental Impact Assessment Review		1		Mori, K., & Christodoulou, A. 2012. Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI). Environmental Impact Assessment Review, 32(1), 94-106.
Environmental Innovation and Societal Transitions	1	1		Rose, A. (2011). Resilience and sustainability in the face of disasters. *Environmental Innovation and Societal Transitions*, 1(1), 96-100.
Environmental science & policy		1		Wilhelmi, O. V., & Morss, R. E. (2013). Integrated analysis of societal vulnerability in an extreme precipitation event: a Fort Collins case study. *Environmental science & policy*, *26*, 49-62.
ERDKUNDE	1	1		Keck, M., Sakdapolrak, P. (2013). What is social resilience? Lessons learned and ways forward. ERDKUNDE. Vol. 67, No. 1, 5-19.
Ethnicity & disease	1	1	1	Springgate, B. F., Wennerstrom, A., Meyers, D., Allen III, C. E., Vannoy, S. D., Bentham, W., Wells, K. B. (2011). Building community resilience through mental health infrastructure and training in post-Katrina New Orleans. *Ethnicity & disease*, 21(3 0 1), S1.

Findings from community-based resilience analysis (CoBRA) assessments	1	1	1	Venton, C. C. (2014). Understanding community resilience: findings from community-based resilience analysis (CoBRA) assessments: Marsabit, Turkana and Kajiado counties, Kenya and Karamoja sub-region, Uganda.
Food Policy		1	1	Sundkvist, Å., Milestad, R., Jansson, A. (2005). On the importance of tightening feedback loops for sustainable development of food systems. *Food Policy*, 30(2), 224-239.
Global Environmental Change		1		Adger, W.N. (2006). Vulnerability. *Global Environmental Change*. 16, 268-281.
Global environmental change		1	1	Cutter, S. L., Ash, K. D., Emrich, C. T. (2014). The geographies of community disaster resilience. *Global environmental change*, 29, 65-77.
Global environmental change		1		Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global environmental change*, 18(4), 598-606.
Global Environmental Change		1		Engle, N.L. (2011). Adaptive capacity and its assessment. *Global Environmental Change* 21, 647-656.
Global Environmental Change		1		Milman, A., and Short, A. (2008). Incorporating resilience into sustainability indicators: An example for the urban water sector. *Global Environmental Change*, *18*(4), 758-767.
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Social Science Quarterly		1		Cutter, S. l., Boruff, B. J., Shirely, L. W. (2003). Social Vulnerability to Environmental Hazards. *Social Science Quarterly*, Vol 84, No. 2.

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Springer, Dordrecht		1		Krishnamurthy, P. K., & Krishnamurthy, L. (2011). Social vulnerability assessment through GIS techniques: a case study of flood risk mapping in Mexico. In *Geospatial Techniques for Managing Environmental Resources* (pp. 276-291). Springer, Dordrecht.
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TR news	1	1	1	Tierney, K., and Bruneau, M. (2007). Conceptualizing and measuring resilience: A key to disaster loss reduction. *TR news*, (250).
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United Nations Office for Disaster Risk Reduction (UNISDR)	1	1	1	United Nations Office for Disaster Risk Reduction (UNISDR). (2017). Disaster Resilience Scorecard for Cities Detailed Level Assessment.
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World Health Organization, Statistical Commission	1	1		U.N. Economic Council, S. (2016). Report of the inter-agency and expert group on sustainable development goal indicators. World Health Organization, Statistical Commission.
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Total	66	182	91	

Appendix F: Dam Failures

(see following pages)

Also available in filterable/searchable format at: https://blindreview1.shinyapps.io/dams/

Name	Year	State	Type	Primary Cause	Secondary Cause	Cost	Description of Damages	Fatalities	Explanation and Commentary	References
Lake Paran	1852	VT	earth	piping	unknown		Heavy destruction along Paran Creek. All dams, bridges, and structures reported destroyed downstream.	1	4 to 5 hour warning time prevented further loss of life	http://npdp.stanford.edu/dam_incidents
Kohanza Dam, Flint's Dam	1869	CT	unknown	foundation	ice		Destroyed homes, businesses, 3 bridges.	11	Dams broke at night with no warning	NRC, 2012; Association of State Dam Safety Officials (www.damsafety.org); https://connecticuthistory.org/frozen-reservoir-destroys-danbury-today-in-history/
Williamsburg Dam	1874	MA	earth masonry	piping	seepage, poor construction	1,000,000	Destroyed factories, 740 homes in Williamsburg, Leeds, Skinnerville, and Haydenville, deaths included 43 children under age 10) (NPDP estimates 143 deaths).	139	Occurred in early morning. Most heard no warning. The losses were so great that the mill towns eventually petitioned for assistance from the legislature in Boston. There was no precedent for the state government to provide direct relief to a city or town; residents in troubled towns usually received only a temporary abatement of taxes. The legislators were hesitant to break with tradition, but they eventually granted $120,000 to rebuild bridges and roads. Resulted in first state requirements for dam safety and design and construction standards. The dam failed due to seepage resulting in embankment and foundation failure, and collapse of the masonry core wall.	Sharpe, 2004; Association of State Dam Safety Officials (www.damsafety.org); http://www.massmoments.org/moment.cfm?mid=145; Wahl, 1998
Lynde Brook Reservoir Dam	1876	MA	earth gravity	breach	piping	1,000,000	unknown	0	Failure due to seepage along outlet conduit, creating a breach 200 feet long. $1,000,000 in property damage.	http://npdp.stanford.edu/dam_incidents
STAFFORDVILLE RESERVOIR	1877	CT	earth	seepage	unknown		unknown	0	The dam failed due to seepage along the outlet conduit.	http://npdp.stanford.edu/dam_incidents
BIBBINS POND	1884	CT	unknown	unknown	unknown	250,000	unknown	0	none	http://npdp.stanford.edu/dam_incidents

Mud Pond	1886	MA	unknown	foundation	poor construction	250,000	Heavily damaged or destroyed a dozen shops and industries along Greenwater Brook.	7	Rebuilt, new dam failed in 1968	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
South Fork Dam	1889	PA	earth zoned	overtopping	hydrologic event, poor maintenance	17,000,000	Almost the entire city was destroyed (1600 homes, 280 businesses demolished);(more than 1 in every 5 residents of Johnstown died). Of victims: 99 entire families, 396 children under the age of 10, and 755 unidentified victims. 45% of the victims whose ages were known were under 20. (NPDP estimates $6,000,000 in damages).	2209	Weakened structurally through modification and lack of maintenance. The dam had a deficient outlet and spillway, had been improperly maintained, and was overtopped and washed out during heavy rains. In previous years, many "alarms" had been sounded regarding the imminent failure of the dam. Under the misguided belief that this final alarm was just another "false alarm", many people in Johnstown did not seek higher ground. By the time the floodwater reached Johnstown, it was no longer water, but rather included much of the debris from the 14-mile long Valley between the South Fork Dam and Jonestown. The debris flow was reportedly up to 1/2-mile wide and may have been as tall as 40 feet above ground in places. There was no safe refuge in town.	NRC, 2012; McCullough, 1987; JAHA, 2012; Association of State Dam Safety Officials (www.damsafety.org); http://madridengineering.com/johnstown-flood-engineering-failure/; Wahl, 1998
SPRING LAKE	1889	RI	earth	unknown	unknown		unknown	0	A portion of the dam just above the waste pipe was washed away.	http://npdp.stanford.edu/dam_incidents

Walnut Grove Dam	1890	AZ	rockfill	poor construction	spillway	800,000	Destroyed town of Seymour (pop: <10); huge economic losses in Wickenburg; washed out new 25'-high diversion dam 12 miles downstream. (NPDP estimates 85 deaths).	70	The dam was 110 feet high, 400 feet long at the top, 140 feet base width (note height-to-width ratio), top width of 10 feet. It was rockfill and poorly sealed so that it leaked badly. The total operable outlets consisted of two 20-inch pipes. A 5 ft by 5 ft (or 3 ft by 5 ft depending on which engineering article you believe) flume in the bottom of the dam was inoperable, but would have not saved the dam if it had been opened. (Source: Jim Liggett, Cornell University); inadequate spillway that was able to pass only about 4% of the flood flow at the time of failure; spillway terminated at the toe of dam and probably led to undermining. Poor design & construction	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
BROAD BROOK RESERVOIR	1890	CT	concrete	unknown	unknown	50,000	5 dams failed; 2 railroad trestles and 6 highway bridges damaged; Total damage $50,000.	0	5 dams failed; 2 RR trestles and 6 highway bridges damaged; Total damage $50,000	http://npdp.stanford.edu/dam_incidents
Mud Pond	1890	VT	earth	unknown	unknown		unknown	0	There was no engineer, and the dam failed eight days after completion.	http://npdp.stanford.edu/dam_incidents
CHAMBERS	1891	CO	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Lynx Creek	1891	AZ	concrete arch	breach	poor construction		unknown	0	Height of dam was 28 feet at time of failure (designed to reach 50 feet). Failed during first flood (during construction). No fatalities. Breach was 35 feet long and down to bed rock. Poor construction - mortar too lean.	http://npdp.stanford.edu/dam_incidents
MAHANOY TOWNSHIP DAM NO 2	1892	PA	earth	unknown	unknown		Dam was under repair when the failure occurred. The cause of the failure is not known. One fatality and considerable damage occurred as a result.	1	Dam was under repair when the failure occurred. The cause of the failure is not known. One fatality and considerable damage occurred as a result.	http://npdp.stanford.edu/dam_incidents

Long Valley	1892	CA	earth	overtopping	hydrologic event		unknown	0	Dam was carried away by flood caused by heavy rains.	http://npdp.stanford.edu/dam_incidents
Mountjoy Hill Reservoir	1893	ME	earth	unknown	unknown		Severe damage	4	Action of frost, or the light embankment, or water following the pipes (seepage along the drain pipe). Much damage was done, and four lives were lost.	http://npdp.stanford.edu/dam_incidents
Goodrich Reservoir	1896	OR	earth	unknown	unknown		Family of 7 drowned, farmhouse washed away.	7	family of 7 drowned, farmhouse washed away	http://npdp.stanford.edu/dam_incidents
Staunton Dam	1896	VA	gravity	overtopping	hydrologic event		5 fatalities and significant property damage as a result of the flood.	0	5 fatalities and much property damage as a result of the flood.	http://npdp.stanford.edu/dam_incidents
Alcyon Lake Dam	1896	NJ	earth gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
LOWER MELZINGAH DAM	1897	NY	earth masonry	overtopping	hydrologic event	30,000	Failure due to freshet flowing over crest of both dams. Seven fatalities and $30,000 property damage.	7	2 dams failed. Failure due to freshet flowing over crest of both dams. Seven fatalities and $30,000 property damage.	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
BOYDSTOWN	1897	PA	earth	overtopping	hydrologic event		unknown	0	After a heavy rain, approximately 100 feet of the embankment washed out. According to Ref.1259, embankment washed out either from overtopping or percolation along iron pipe line.	http://npdp.stanford.edu/dam_incidents
ST ANTHONY FALLS UPPER LOCK & DAM	1899	MN	concrete gravity	foundation	ice		unknown	0	Ice pressure contributed to sliding or overturning.	http://npdp.stanford.edu/dam_incidents
Austin Dam	1900	TX	rockfill	overtopping	hydrologic event, foundation	1,400,000	100 houses, powerhouse destroyed. (NPDP estimates 8 deaths and $500,000 in damages).	18	No warning despite 7 hours of overtopping. Engineers were surprised by amount of siltation and effects of hydraulic uplift and erosion which undercut the toe.	Association of State Dam Safety Officials (www.damsafety.org); https://www.researchgate.net/publication/291164788_Powerpoint_Lecture-Texas_Austin_Dam_Failure-1900; http://damfailures.org/lessons-learned/; http://npdp.stanford.edu/dam_incidents

Grand Rapids Detached Dike No 2	1900	MI	earth gravity	overtopping	hydrologic event	1,000,000	Not sure of the cause of the overtopping. Not sure of height. Water was 25 ft deep. Caused $100,000 damage. According to Ref.1259, 1 fatality and $1,000,000 damage.	1	Not sure of the cause of the overtopping. Not sure of height. Water was 25 ft deep. Caused $100,000 damage. According to Ref.1259, 1 fatality and $1,000,000 damage.	http://npdp.stanford.edu/dam_incidents
ASHLAND RESERVOIR	1901	PA	earth	overtopping	hydrologic event, upstream dam failure		Caused by failure of two upstream dams. See Haupt Estate Dams 1 and 2. A fourth dam belonging to the town of Ashland may also have been damaged.	0	Caused by failure of two upstream dams.	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
BISON PARK	1901	CO	earth	unknown	unknown		unknown	0	Reservoir on Pikes Peak for supplying water to Victor washed away due to inadequate spillway. All 70 million gallons of water in the reservoir escaped. No details as to nature or cause of failure.	http://npdp.stanford.edu/dam_incidents
Randall's Pond	1901	RI	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org);
Lake Housatonic	1902	CT	concrete gravity	unknown	unknown		unknown	0	Muskrats were burrowing under the foundation.	http://npdp.stanford.edu/dam_incidents
ASHLAND RESERVOIR	1902	RI	unknown	overtopping	unknown		partial failure due to high water break	0		http://npdp.stanford.edu/dam_incidents
unknown	1902	TN	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org);
Utica Reservoir	1902	NY	unknown	unknown	unknown		unknown	0		Association of State Dam Safety Officials (www.damsafety.org);
Oakford Park	1903	PA	earth masonry	overtopping	hydrologic event		unknown	23		Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
BOYDSTOWN	1903	PA	earth	overtopping	hydrologic event, spillway		unknown	0	Rebuilt after the failure in 1897. According to Ref. 1259, failed by overtopping. Inadequate spillway.	http://npdp.stanford.edu/dam_incidents

Fort Pitt	1903	PA	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Haledon Reservoir Dam	1903	NJ	earth gravity	overtopping	hydrologic event		Number of mills flooded and forced to shut down.	0	Number of mills flooded and forced to shut down.	http://npdp.stanford.edu /dam_incidents
PANGUITCH LAKE	1903	UT	other	overtopping	wave action		unknown	0	Failed while still under construction. Wave action from heavy wind caused dam to fail.	http://npdp.stanford.edu /dam_incidents
Winston Lake Dam	1904	NC	other brick	unknown	unknown		unknown	9	Brick dam. Failed one year after storage increase. Wall overturned, unable to withstand increased water pressure; poor design. 9 people killed.	http://npdp.stanford.edu /dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
AVALON	1904	NM	earth rockfill	breach	hydrologic event, piping		unknown	0	Rebuilt, failed again during flood of unprecedented magnitude, by water forcing a passage through the dam.	http://npdp.stanford.edu /dam_incidents
Lake Vera	1905	CA	other buttress	unknown	unknown		unknown	0	Short spillway with insufficient capacity caused overtopping washing out 14' in height from top of dam.	http://npdp.stanford.edu /dam_incidents
REEDER	1905	CO	earth	overtopping	hydrologic event, breach		unknown	0	Overtop - breach in middle	http://npdp.stanford.edu /dam_incidents
TUPELO BAYOU SITE 1	1905	AK	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
CHAMBERS	1907	CO	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
Hauser	1908	MT	other steel	unknown	unknown		Failure caused owner's power company to fail and sell out	0	In operation for one year prior to failure. Replaced with concrete dam.	Association of State Dam Safety Officials (www.damsafety.org);
Fergus Falls Hydro Dam	1909	MN	unknown	unknown	unknown	15,000	Washed out 4 downstream dams; damaged 2 mills	0	Failure of 1-year old dam washed out Red River Mill Dam ($10,000 loss) & destroyed Woolen Mill Dam ($5,000 loss). Advanced warning saved Dayton Hollow Dam, 5 miles south, as owner & president of Otter Tail Power Company had time to open the flood gates. Of the demolished dams, only Central Dam near South Cascade was rebuilt.	Association of State Dam Safety Officials (www.damsafety.org);

Ashley Dam	1909	MA	unknown	unknown	unknown		unknown	0	Piping failed during first filling.	Association of State Dam Safety Officials (www.damsafety.org);
Ashley Dam	1909	MA	unknown	unknown	unknown		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Black Rock	1909	NM	earth rockfill	unknown	unknown		unknown	0	Failure by piping through abutment; undermined by passage of water under cap of lava rock which flanked dam and extended beneath spillway. Portion of spillway dropped 7 feet; some fill at south end washed out. Main part of dam uninjured. Repaired now known as Black Rock.	http://npdp.stanford.edu /dam_incidents
DANSVILLE RESERVOIR DAM	1909	NY	earth	breach	undermining		unknown	0	Undermining when water stood about 14 against flashboards. Breach: deck slap snapped.	http://npdp.stanford.edu /dam_incidents
Humphrey's Lake Dam	1909	MD	unknown	unknown	unknown		unknown	0		Association of State Dam Safety Officials (www.damsafety.org);
LAKE GEORGE	1909	CO	earth	overtopping	unknown		unknown	0	First of two overtopping incidents.	http://npdp.stanford.edu /dam_incidents
JUMBO	1910	CO	earth	piping	seepage		unknown	0	Serious seepage began in 1907. This dam is also listed as having NPDP ID No. 2439. According to NPDP Ref No.1040, section of west embankment washed out completely in 1911. Strong possibility that failure was result of foundation piping.	http://npdp.stanford.edu /dam_incidents
RIVERSIDE	1910	CO	earth	cracking	hydrologic event, wave action		unknown	0	Partial failure due to the cracking of the concrete paving and the sloughing of the embankment. According to NPDP Ref no 4918, concrete facing broke up due to wave action with subsequent erosion of earth beneath the concrete.	http://npdp.stanford.edu /dam_incidents
White River	1910	WI	earth gravity	foundation	hydrologic event		unknown	0	Failure of earthfill section and powerhouse during flood. Rebuilt.	http://npdp.stanford.edu /dam_incidents

Bayless Pump & Paper Mill	1911	PA	concrete gravity	foundation	hydrologic event, poor maintenance	3,000,000	Water picked up debris and stacks of pulp wood, estimated to be as much as 700,000 cords, from the Bayless lumber yard. These logs became deadly weapons as the water hit the town of Austin. After the waters raged through Austin, they hit the nearby town of Costello. Between 1910 and 1920, the town lost half of its population. (NPDP estimates 80 deaths).	88	Bayless Pulp and Paper Company made cost-cutting modifications to the dam that contributed to a minor structural failure in January 1910. Company allowed the rains to fill the dam to its maximum capacity. On September 30, 1911, the Bayless Pulp and Paper Company Dam gave way under the pressure. Coursing down Freeman Run, the water picked up debris and stacks of pulp wood, estimated to be as much as 700,000 cords, from the Bayless lumber yard. These logs became deadly weapons as the water hit the town of Austin. After the waters raged through Austin, they hit the nearby town of Costello. Between 1910 and 1920, the town lost half of its population. dam was loaded before the concrete had completely set, allowing for the opening of cracks and excessive pressures under the dam. As a result, in January 1910, the dam dropped down about 6 inches and slid about 18 inches at the spillway. The dam was left in this condition until it failed suddenly by sliding	Association of State Dam Safety Officials (www.damsafety.org); http://explorepahistory.com/hmarker.php?markerId=1-A-3D; http://npdp.stanford.edu/dam_incidents
White River	1926	WI	earth gravity	overtopping	gate		unknown	0	Due to debris at gates, pipeline was dynamited to allow added flow. Later sandstone foundation found to be eroded.	http://npdp.stanford.edu/dam_incidents
Hatfield	1911	WI	earth gravity	overtopping	hydrologic event, upstream dam failure	23,000,000	Business section of Black River Falls destroyed.	0	Failure of this dam preceded/caused by failure of Dells (Wisconsin Dells) dam. Insufficient spillway. Business section of Black River Falls destroyed.	http://npdp.stanford.edu/dam_incidents
Institute Pond	1911	VT	earth	unknown	unknown		homes damaged	0		http://npdp.stanford.edu/dam_incidents
MILITARY PARK	1911	CO	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents

VALENTINE FISH HATCHERY DAM	1911	NE	earth	unknown	unknown		unknown	0	Dam failed on first filling as a result of settlement of fill under concrete spillway.	http://npdp.stanford.edu /dam_incidents
Ansonia Brass & Copper Co. Dam	1912	CT	unknown	foundation	undermining	150,000	unknown	0		Association of State Dam Safety Officials (www.damsafety.org);
Brokow	1912	WI	timber crib	overtopping	hydrologic event	80,000	unknown	0		Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu /dam_incidents
Wausau Detached	1912	WI	gravity	overtopping	hydrologic event	75,000	damage to power plant	0	One of eight dams washed out by this flood (Brokaw [original], Callon, Kelly, Lindauer's, Merrill, Rothchild, Schofield). Height unknown. Flood washed out 125 feet of dam. $75,000 damage to dam and power plant.	http://npdp.stanford.edu /dam_incidents
Brokaw	1912	WI	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
CARLISLE RAW WATER INTAKE	1912	PA	stone masonry	foundation	ice		unknown	0	Overturned due to ice pressure	http://npdp.stanford.edu /dam_incidents
City Reservoir	1912	TN	unknown	unknown	unknown		25 million gallons of water released	0		Association of State Dam Safety Officials (www.damsafety.org);
Merrill	1912	WI	gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
OWASCO LAKE OUTLET DAM	1912	NY	masonry	unknown	unknown		little damage	0		http://npdp.stanford.edu /dam_incidents
ROCKPORT POND DAM	1912	NY	stone masonry	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
Davis	1914	CA	earth rockfill	seepage	poor construction		unknown	0	Seepage through backfill noted soon after first water in reservoir, repairs attempted but unsuccessful. On June 27 dam 1 ft from full, failure on June 28. Water users complained backfill not adequately puddled exposed cut confirmed poor backfill.	http://npdp.stanford.edu /dam_incidents

LAKE GEORGE	1914	CO	earth	overtopping	unknown		unknown	0	Second of two overtopping incidents.	http://npdp.stanford.edu/dam_incidents
OWENS DAM	1914	CA	earth	unknown	unknown		unknown	0	leakage around outlet structure	http://npdp.stanford.edu/dam_incidents
Stony River Dam	1914	WV	gravity	foundation	hydrologic event, undermining		unknown	0	Foundation failure shortly after completion. Undermined, cutoffs not carried sufficiently deep.	http://npdp.stanford.edu/dam_incidents
Lyman	1915	AZ	earth zoned	unknown	unknown	500,000	unknown	8		Association of State Dam Safety Officials (www.damsafety.org); Wahl 1998; http://npdp.stanford.edu/dam_incidents
POINT OF ROCK	1915	CO	earth	overtopping	wave action		unknown	0	Concrete slope paving failed due to five foot wave action.	http://npdp.stanford.edu/dam_incidents
SAND CREEK	1915	CO	earth	piping	seepage		unknown	0	Piping, foundation seepage. Break in the dam on the east side of the outlet of Sand Creek Reservoir, with a loss of about 1,500 acre feet of water.	http://npdp.stanford.edu/dam_incidents
unknown	1916	WV	unknown	overtopping	hydrologic event		unknown	60		Association of State Dam Safety Officials (www.damsafety.org)
unnamed	1916	WV	unknown	overtopping	hydrologic event	600,000	Extensive damage; esp. to rail, telephone, and coal company	44		Association of State Dam Safety Officials (www.damsafety.org)
Lower Otay	1916	CA	concrete rockfill	overtopping	unknown	1,500,000	NPDP estimates $250,000 in damages	30	Failed on first filling. Dam operator opened outlet gate which failed to slow rising levels. He decided to send notification of dam failure by courier and telephone. Most residents took advantage of the warning.	Association of State Dam Safety Officials (www.damsafety.org); https://pubs.usgs.gov/wsp/0426/report.pdf; Wahl, 1998
John Thompson's Mill Dam	1916	TN	rockfill	breach	hydrologic event	50,000	Many buildings, crops, and livestock destroyed, railroad damage	24	The dam broke following nine inches of rainfall in five hours, sending a wall of water 25 feet high crashing down the river.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
Lake Toxaway	1916	NC	earth	unknown	unknown	50,000	unknown	0		Association of State Dam Safety Officials (www.damsafety.org)

LAKE SHERBURNE	1916	MT	earth	unknown	unknown		unknown	0	Floating logs displaced hand placed riprap (apparently during construction). Excavation for spillway initiated slow slide of considerable extent on left abutment above spillway. Over the years, hillside moved slowly downward toward dam, deforming and lifting spillway structure.	http://npdp.stanford.edu/dam_incidents
Lookout Shoals	1916	NC	earth masonry	overtopping	hydrologic event		unknown	0	West embankment washed out after a flood.	http://npdp.stanford.edu/dam_incidents
Sweetwater Main	1916	CA	gravity	overtopping	hydrologic event, breach		unknown	0	Earthfill dyke at north end of structure was overtopped and breached which broke the concrete core wall. Break was 75 feet wide and 30 feet deep. A puddled core saddle dyke some distance from dam was overtopped and swept away.	http://npdp.stanford.edu/dam_incidents
unknown	1916	NC	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
unknown	1916	NC	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
unknown	1916	CA	unknown	unknown	unknown		released 13 billion gallons	0	The dam at Sweetwater Reservoir fails releasing 13 billion gallons of water. Dam constructed in 1888.	Association of State Dam Safety Officials (www.damsafety.org)
Wateree	1916	SC	concrete earth	overtopping	hydrologic event		unknown	0	West embankment washed out after a flood.	http://npdp.stanford.edu/dam_incidents
West Brook Reservoir # 3	1916	NY	unknown	unknown	unknown		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Mammoth Dam	1917	UT	earth	unknown	unknown		Extensive damage to Rio Grande railroad, several coal mines and settlements.	1	Dam poorly constructed; carelessly repaired, modified, and operated.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
COON RAPIDS	1917	MN	earth gravity	unknown	unknown		unknown	0	hole eroded under dam - no collapse	http://npdp.stanford.edu/dam_incidents

Masonry Dam (Boxely)	1918	WA	masonry	unknown	unknown		Destroyed RR line & village of Eastwick	0	Excessive seepage through glacial moraine abutment caused mud flow about 1 mi. from reservoir. Destroyed RR line & village of Eastwick.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu /dam_incidents
MINATARE	1920	NE	earth	unknown	unknown		unknown	0	Partial failure. Wave action broke and entered concrete slabs, thus washing out gravel and earth. This caused the slabs to settle.	http://npdp.stanford.edu /dam_incidents
BARTON	1922	ID	earth	unknown	unknown		unknown	0	Considerable moisture was noted on downstream slope in May 1922, and in June, a localized slide occurred. Following slide, downstream slope continued to be saturated whenever reservoir was kept full for any length of time.	http://npdp.stanford.edu /dam_incidents
OVERHOLS ER	1923	OK	earth	overtopping	hydrologic event, spillway		unknown	0	Insufficient spillway capacity. Flood overtopped dam and washed out 300 ft of west end embankment, to the depth of the base of the dam.	http://npdp.stanford.edu /dam_incidents
Saltville Muck Dam (Mathieson Alkali Works Plant Waste) Dam	1924	WV	unknown	unknown	unknown		plant waste dam failed sending tons of waste into Palmertown and blocking portions of the Holston River; many homes destroyed	19	"Palmertown tragedy" A plant waste dam failed sending tons of waste into Palmertown and blocking portions of the Holston River. “…tons of waste raced through the tiny community of Palmertown. Pieces of the dam and boulders of muck blocked the North Fork of the Holston River, sending the flood upstream into the even smaller community of Chinch Row.” Source: “The 1924 Saltville muck dam disaster” Roaknoke Times, 12/24/2004; Muck dam in Saltville burst on Christmas Eve, covering the village of Palmertown with a thick, white caustic liquid that killed 19 people and demolished many homes.	Association of State Dam Safety Officials (www.damsafety.org)
MANITOU	1924	CO	rockfill	unknown	unknown		unknown	0	Partial failure, was disintegrating and converted into gravel fill.	http://npdp.stanford.edu /dam_incidents

BULLY CREEK	1925	OR	earth	spillway	ice		unknown	0	Ice blocked outlet gate, Condemned in 1916. Dam was abandoned uncompleted at the time of failure.	http://npdp.stanford.edu/dam_incidents
French Landing	1925	MI	earth gravity	unknown	unknown		unknown	0	Failed before reservoir was filled. According to NPDP Ref No 4112, erosion of gravely soil in the foundation caused a break in the embankment.	http://npdp.stanford.edu/dam_incidents
MISSION LAKE	1925	KS	earth	unknown	unknown		unknown	0	Settlement and overtopping. Dam had an insufficient spillway. According to NPDP Ref No 4288, exceptionally heavy rains caused flooding the overtopping of dam. A break developed adjacent to the spillway. Effective flood fight controlled the breach so 500 million gallons were still stored in the reservoir.	http://npdp.stanford.edu/dam_incidents
Moyie	1925	ID	concrete gravity	spillway	hydrologic event, undermining		unknown	0	Spillway undermined, flood cut by-pass around and washed out abutment. Reference indicates that except for abutment, dam remained intact. However, headline of ENR article noted by reference states that these two dams failed due to undermining of abutments.	http://npdp.stanford.edu/dam_incidents
Sheffield Dam	1925	CA	earth	foundation	settlement, earthquake		unknown	0	6.5 earthquake; led to increasing interest in using instruments to study the performance of dams	NRC, 2012; Seed et al., 1970
Great Falls	1926	TN	concrete gravity	overtopping	hydrologic event		destruction of and extensive damage to homes	0	Failed following heavy rains, likely due to overtopping. Numerous homes swept away by floodwaters. No deaths known to be reported, but extensive and costly damages.	http://npdp.stanford.edu/dam_incidents
SCNONAME 23001	1926	SC	gravity	foundation	undermining		unknown	0	Failure due to undermining of abutment.	http://npdp.stanford.edu/dam_incidents
Lake Hemet	1927	CA	gravity	overtopping	hydrologic event, breach		extensive property loss	1	Auxiliary earth dyke was overtopped and breached. Escaping water cleaned off good quality rock foundation.	http://npdp.stanford.edu/dam_incidents
George Lake Dam	1927	NJ	earth gravity	unknown	unknown		unknown	0	timber-crib rock fill structure with a concrete core wall, failed	http://npdp.stanford.edu/dam_incidents

Mackville Pond	1927	VT	stone masonry	breach	hydrologic event		major damage	0	The dam breached through the right abutment. Major damage downstream both from flood and probably dam failure. The dam is a stone and concrete dam approximately 20 feet in height. Pond size: 18 acres. Age of dam: 27 years (estimated). It is located near/in the town of Hardwick.	http://npdp.stanford.edu/dam_incidents
MAQUOKETA MILLDAM	1927	IA	gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Sweetwater Main	1927	CA	gravity	overtopping	unknown		unknown	0	Dam overtopped causing erosion of south abutment.	http://npdp.stanford.edu/dam_incidents
St. Francis Dam	1928	CA	concrete arch	foundation	poor construction	15,000,000	1,240 homes & other buildings destroyed; 23,500 acres of farmland flooded; 4 railroad bridges, 8 miles of railroad track, unknown miles of roads; 10 bridges (NPDP estimates $20,000,000 damages)	450	Collapsed upon being filled for first time. Modifications to height had been made to increase capacity without modifying the base. Start of intense efforts to improve dam safety in California, especially with respect to new dam construction. Multiple investigations. Insufficient review by independent experts and foundation of the dam was weak. 1929, California passed a dam safety act which placed all dams within the state, except those owned by the federal government, under supervision of the state engineer. The supervision includes design, construction, operation, alteration, and repair. Other states were slower to follow.	NRC, 2012; Rogers, 2006; Association of State Dam Safety Officials (www.damsafety.org); USBR, 2005; http://npdp.stanford.edu/dam_incidents
Crater Lake	1928	CA	earth rockfill	unknown	unknown		unknown	0	Spillway became clogged with drift, causing dam to be overtopped and breached. Inadequate spillway capacity, possibly due to obstruction by debris.	http://npdp.stanford.edu/dam_incidents
Lafayette	1928	CA	earth rockfill	unknown	unknown		unknown	0	Foundation slide during construction	http://npdp.stanford.edu/dam_incidents
NARRAGUINNEP MAIN DAM	1928	CO	earth	unknown	unknown		unknown	0	First of two failure incidents at this dam. Reference indicates failure due to sloughing of upstream slope and leakage.	http://npdp.stanford.edu/dam_incidents

SCOFIELD	1928	UT	earth	unknown	unknown		unknown	0	Partial failure due to piping through settlement cracks. This dam was built to replace Mammoth Dam which failed in 1917 at a different site. USBR replaced this dam with a new and larger Scofield dam 800 feet downstream on Price River below the existing unsafe dam. According to Ref. No. 1040, complete failure was preceded by large crest settlements and transverse cracks near abutments.	http://npdp.stanford.edu/dam_incidents
Balsam	1929	NH	earth	unknown	unknown	500,000	unknown	0		http://npdp.stanford.edu/dam_incidents
Abenaki Dam	1929	NH	earth	overtopping	ice	3,500,000		0		
Alexander Dam	1930	HI	earth	piping	seepage	80,000	Rapid failure during construction killed workers	6	First earthen dam constructed using physio-chemical soil stabilization. Failed during construction. (HI has history of poor performance with hydraulic fill due to water channels and voids in compacted fill - volcanic soils). Failure likely occurred due to lack of internal drainage.	Association of State Dam Safety Officials (www.damsafety.org); Cato and Rogers, 2016; http://npdp.stanford.edu/dam_incidents
LAKE VERMILION DAM	1930	IL	earth	unknown	unknown		unknown	0	Failure due to sliding on the base. There were many visible old cracks, and the concrete, made of local gravel, was thought to be deficient in coarse aggregate. Reservoir status: drained the reservoir at the pumping station. The failure did not cause a shortage in the water supply because a higher dam was built a few years before this, and the dam was used to reduce suction lift and provide storage near the pumping plant.	http://npdp.stanford.edu/dam_incidents
LAKE VERMILION DAM	1930	IL	earth	foundation	poor construction		unknown	0	Failure due to sliding on the base. There were many visible old cracks, and the concrete, made of local gravel, was thought to be deficient in coarse aggregate.	http://npdp.stanford.edu/dam_incidents

Eastwick Railroad	1932	WA	earth other fill	overtopping	spillway, debris		destroyed railroad line and village of Eastwick	7	During storm, erosive wave action on upstream slope put dam in danger. To eliminate hazard, owner cut additional spillway. Later storm followed, making the extra spillway inadequate. Open section was topped, eroding side toward main fill embankment.	Association of State Dam Safety Officials (www.damsafety.org); Notable Dam Failures in Washington State (http://www.ecy.wa.gov/programs/wr/dams/Reports/damfailure-ws.pdf); http://npdp.stanford.edu/dam_incidents
Little Juniper	1932	CA	earth	breach	hydrologic event, spillway		unknown	0	During storm, erosive wave action on upstream slope put dam in danger. To eliminate hazard, owner cut additional spillway. Later storm followed, making the extra spillway inadequate. Open section was topped, eroding side toward main fill embankment. Breach failure.	http://npdp.stanford.edu/dam_incidents
Mud Lake	1932	CA	earth masonry	breach	seepage		unknown	0	Dam washed out on both sides of rock masonry structure located in fill. Breached section on each side was backfilled. Leakage along face of masonry probably caused breach in dam.	http://npdp.stanford.edu/dam_incidents
Rye Grass Swale	1932	CA	earth	unknown	unknown		unknown	0	Dam failed by breaching. Numerous rodent holes in breached section.	http://npdp.stanford.edu/dam_incidents
Castlewood	1933	CO	rockfill	overtopping	hydrologic event	750,000	unknown	2		http://npdp.stanford.edu/dam_incidents
Bostwicks Pond Dam	1934	NJ	earth	overtopping	hydrologic event		significant damage	0	A flood washed out several small earth dams along the Cohansey River in southwestern New Jersey. Floodwaters converged on the city of Bridgeton, causing significant damage.	http://npdp.stanford.edu/dam_incidents
LAKE LUDLOW CLUB DAM	1935	NY	earth rockfill	overtopping	hydrologic event		unknown	3	The dam was overtopped and failed. Three fatalism as a result of the failure.	http://npdp.stanford.edu/dam_incidents
Francis, Lake	1935	CA	earth	spillway	piping		unknown	0	Blowout failure under concrete spillway weir structure during period of heavy spillway flow. Spillway failure thought to be due to piping in soft saturated foundation.	http://npdp.stanford.edu/dam_incidents

HERRIN RESERVOIR 2 DAM	1935	IL	earth	overtopping	hydrologic event		unknown	0	Dam overtopped and washed out.	http://npdp.stanford.edu/dam_incidents
PLEASANT VALLEY	1935	CO	earth	unknown	unknown		unknown	0	rodents	http://npdp.stanford.edu/dam_incidents
TROPIC	1935	UT	earth	overtopping	spillway, poor construction		damage to Forest Service resources, bridges, and roads	0	No adequate spillway protection from erosion. Unapproved poorly reinforced wood and log spillway erodes and fails dam. 180 acre feet of water. Reconstructed in 1936 with approved plans. Property damage included significant Forest Service resources and bridges and roads.	http://npdp.stanford.edu/dam_incidents
Black Rock	1936	NM	earth rockfill	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Lake Shaftsbury	1936	VT	earth gravity	overtopping	hydrologic event		unknown	0	The dam failed during a flood event.	http://npdp.stanford.edu/dam_incidents
Miller Pond	1936	VT	earth	overtopping	hydrologic event, upstream dam failure		unknown	0	The dam failed during a flood event. Reportedly caused by the failure of upstream Shaftsbury Lake Dam (VT00103).	http://npdp.stanford.edu/dam_incidents
Rye Grass Swale	1936	CA	earth	overtopping	hydrologic event, spillway		unknown	0	Rim levee of dam overtopped, failed during flood. Breached section through right portion of levee. Inadequate spillway capacity. Second of three incidents at this dam.	http://npdp.stanford.edu/dam_incidents
WEARE RESERVOIR DAM	1938	NH	earth gravity	overtopping	spillway		unknown	4	Earth embankment overtopped and failed due to insufficient discharge capacity. 4 people were standing on the bridge watching flood wave when the bridge collapsed and were killed.	http://npdp.stanford.edu/dam_incidents
Loup Loup Dam (Wagner Dam)	1938	WA	earth	overtopping	hydrologic event, spillway	75,000	Destroyed 25 homes and left 75 people homeless. Destroyed 1/2 mile of state highway.	1	50 foot high hydraulic fill dam failed when emergency spillway was undercut during a flood.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
Brokaw	1938	WI	earth	foundation	hydrologic event, erosion	700,000	unknown	0		http://npdp.stanford.edu/dam_incidents

BOLTON LAKE	1938	CT	earth	overtopping	hydrologic event, breach		unknown	0	During a Hurricane in September 1938 the dam was overtopped and breached in two places. Upper Bolton Lake Dam, about 3,500 ft. upstream was also breached.	http://npdp.stanford.edu/dam_incidents
DIXON DAM	1938	IL	gravity	unknown	unknown		unknown	0	washed out	http://npdp.stanford.edu/dam_incidents
Fredonia	1938	CA	earth	breach	hydrologic event, spillway		unknown	0	Dam was overtopped and breached during snow runoffs in spring 1938. Section of dam washed out. Cause of failure: no spillway. During repairs, a natural spillway was included in the dam.	http://npdp.stanford.edu/dam_incidents
Horse Lake	1938	CA	earth	overtopping	hydrologic event, spillway		unknown	0	Dam was overtopped during spring runoff, section of dam was washed out. Cause of failure believed to be inadequate spillway capacity. This is the first of two failures at this dam.	http://npdp.stanford.edu/dam_incidents
Lee Lake	1938	CA	earth	overtopping	hydrologic event, spillway		unknown	0	Excessive flooding caused excess flow to pass over emergency unlined spillway. Emergency spillway eroded down by flow. Combination of inadequate capacity of main spillway and lack of protection of erosive foundation in emergency spillway caused failure.	http://npdp.stanford.edu/dam_incidents
Rye Grass Swale	1938	CA	earth	breach	hydrologic event, spillway		unknown	0	Rim levee again breached due to overtopping. Inadequate spillway capacity. Third of three incidents at this dam.	http://npdp.stanford.edu/dam_incidents
Slate Creek	1938	CA	concrete arch	breach	hydrologic event, spillway		unknown	0	Dam was overtopped and breached near outlet. Section of dam washed out. Cause of failure: no spillway provision. Dam was not rebuilt.	http://npdp.stanford.edu/dam_incidents
UPPER BOLTON LAKE	1938	CT	earth	overtopping	hydrologic event, poor construction		unknown	0	Was first washed out during hurricane of 1938. Overtopped - faulty construction and rebuilt.	http://npdp.stanford.edu/dam_incidents
BEAVER MEADOWS	1939	PA	earth	overtopping	hydrologic event, spillway		some damage	0	Temporary spillway overwhelmed. Spillway erosion from snow melt flood. Reservoir status: full. Some	http://npdp.stanford.edu/dam_incidents

									downstream damage (not specified).	
PARIS DAM	1939	AK	earth	overtopping	hydrologic event		unknown	0	Heavy rains washed dam out while it was still under construction (75% complete).	http://npdp.stanford.edu/dam_incidents
Breakneck Dam	1940	NJ	earth gravity	unknown	unknown		unknown	0	Dam was breached and a substantial portion of the embankment was lost, but the brick arch culvert remained intact. Reports of damage in the downstream area were not available.	http://npdp.stanford.edu/dam_incidents
FAIRMONT	1940	CO	earth	overtopping	hydrologic event, spillway		unknown	0	Overtop - owner sandbag spillway.	http://npdp.stanford.edu/dam_incidents
BOLTON LAKE	1941	CT	earth	unknown	unknown		damage to property	0	Faulty construction appears to be the cause of the collapse, which resulted in damage to property.	http://npdp.stanford.edu/dam_incidents
GOODENOUGH #2	1941	CO	earth	unknown	unknown		unknown	0	Rodent hole washed out.	http://npdp.stanford.edu/dam_incidents
Jim Falls	1941	WI	earth gravity	overtopping	hydrologic event		unknown	0	Right embankment failed due to overtopping during flood of record.	http://npdp.stanford.edu/dam_incidents
Lac Vieux Desert	1941	WI	concrete gravity	overtopping	hydrologic event, foundation		unknown	0	Overtopping failure of embankment.	http://npdp.stanford.edu/dam_incidents
Norton Brook	1942	VT	earth	unknown	unknown		temporary loss of water supply	0	The dam breached full depth through dike section. No downstream damage reported except temporary loss of Vergennes water supply. The dam is an earth dam approximately 34 feet in height. Pond size: 15 acres. Age of dam: 7 years. It is located near/in the town of Bristol.	http://npdp.stanford.edu/dam_incidents
WILLOW CREEK	1942	UT	earth	unknown	unknown		some property damage	0	Abutment seepage gypsum dissolution. 600 acre feet released. Reservoir status: 600 acre feet. Some property damage (not specified).	http://npdp.stanford.edu/dam_incidents

HULET	1943	ID	earth	seepage	wave action, settlement		serious property damage	0	Full at time of failure, emptied in 2 hours. Waves 40 feet high in narrow canyons below dam. Instantaneous break for full length of dam. Saturation. Serious property damage. According to NPDP Ref.No.1040, dam failed completely after many years of saturation of downstream slope and leakage through upper portion of dam.	http://npdp.stanford.edu /dam_incidents
GRINDSTONE RIVER	1944	MN	gravity	overtopping	hydrologic event		unknown	0	Right earthen abutment was overtopped and washed out during a flood following a heavy rainstorm.	http://npdp.stanford.edu /dam_incidents
Wewoka Dam	1945	OK	unknown	overtopping	hydrologic event		unknown	8	April 13-14: 14.6 inches of rain at Seminole. 80 people forced from homes, town under 4' of water *	Association of State Dam Safety Officials (www.damsafety.org)
Barbours Pond Dam	1945	NJ	earth	overtopping	hydrologic event		extensive property damage	0	The dam failed following a 9 inch rainfall in the area. Floodwaters overtopped a reservoir immediately downstream, causing extensive property damage.	http://npdp.stanford.edu /dam_incidents
JOHNSON DAM	1945	NE	earth	seepage	unknown		unknown	0	This is the second of two incidents at this dam. Failure the result of loss of filter through riprap (not sure if this applies to both incidents).	http://npdp.stanford.edu /dam_incidents
BLACK RIVER	1947	MN	unknown	overtopping	hydrologic event		unknown	0		http://npdp.stanford.edu /dam_incidents
WACO LAKE	1947	TX	unknown	foundation	hydrologic event, erosion		unknown	0	Erosion of shale foundation under apron and part of overflow section, resulting in loss of apron and part of dam.	http://npdp.stanford.edu /dam_incidents
Blandin	1948	MN	rockfill	unknown	unknown		unknown	0	Piping failure of foundation of rockfilled timber crib. Rebuilt with concrete gravity dam.	http://npdp.stanford.edu /dam_incidents
Kern Brothers Dam (Harney)	1949	OR	earth rockfill	unknown	unknown		unknown	0	Failure due to excessive settlement of fill.	http://npdp.stanford.edu /dam_incidents
Lake Algonquin	1949	NY	concrete gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents

Little Juniper	1949	CA	earth	breach	hydrologic event, spillway		unknown	0	Dam breached during heavy floods. Breaching could have been caused by inadequate spillway capacity. When dam was rebuilt, allowed for additional spillway capacity.	http://npdp.stanford.edu/dam_incidents
Lake Dawn Dam	1950	WA	earth	overtopping	hydrologic event	4,000	1 home destroyed, $4000 damage	0	Heavy Rains caused overtopping and failure of earthen dam.	Association of State Dam Safety Officials (www.damsafety.org)
CALHOUN LAKE DAM	1950	IL	earth	overtopping	hydrologic event, spillway		unknown	0	Failed at previously undermined and damaged step spillway during flood event.	http://npdp.stanford.edu/dam_incidents
Merced Falls	1950	CA	concrete gravity	overtopping	hydrologic event, spillway		unknown	0	Earth levee overtopped during flood flow. Washout portion stripped clean to slate foundation. Inadequate spilling capacity.	http://npdp.stanford.edu/dam_incidents
Stockton Creek	1950	CA	earth	cracking	piping, settlement		unknown	0	Failed at abutment, probably along contact or crack. According to NPDP ref No.1360, dam failed by breaching next to right abutment. Possible that piping occurred through embankment crack, due to differential settlement. Nature of fill material made it susceptible to cracking from stains set up by differential settlement	http://npdp.stanford.edu/dam_incidents
Vaux dams	1951	MT	unknown	unknown	unknown		family killed	?	Chronicled in Calamities & Miracles (Feb. 2008), by Richard P. Warren	Association of State Dam Safety Officials (www.damsafety.org)
unknown	1951	KS	unknown	unknown	unknown		unknown	11	Less than 2 hours notice.	http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
FRENCHMAN DAM	1952	MT	rockfill	breach	hydrologic event		unknown	0	Runoff from melting snow. A dike section was overtopped early morning April 15, 1952. Later that day, dam breached.	http://npdp.stanford.edu/dam_incidents
GENEVA DAM	1952	IL	gravity	unknown	unknown		unknown	0	Deterioration of the wood planking, and its absence in some locations, caused the failure.	http://npdp.stanford.edu/dam_incidents

Horse Lake	1952	CA	earth	unknown	unknown		unknown	0	Dam breached in same location as in 1938 (this is the second of two failures at this dam). Dam did not overtop. Cause of failure believed to be due to rodent holes, allowing for a piping failure.	http://npdp.stanford.edu/dam_incidents
Huffman Antelope	1952	CA	earth	foundation	hydrologic event		unknown	0	Dam failed by breaching during period of heavy snow melt runoff. Dam was not overtopped. Breach approximately in center of dam.	http://npdp.stanford.edu/dam_incidents
Toreson	1953	CA	earth	foundation	corrosion		unknown	0	Dam failed by breaching. Failure very fast. Cause unknown. This incident also appears in Lessons From Dam Incidents USA ASCE/USCOLD. According to this reference cause of failure was chemical drainage corrosion outlet pipe.	http://npdp.stanford.edu/dam_incidents
GRINDSTONE RIVER	1954	MN	gravity	overtopping	hydrologic event		unknown	0	According to case file, the right earthen abutment was overtopped and washed out during a flood following a heavy rainstorm. Also incident in 1944.	http://npdp.stanford.edu/dam_incidents
Crow Creek	1955	SD	earth	overtopping	hydrologic event, spillway		unknown	0	Flood waters undermined the spillway which created great damage to the concrete on the spillway.	http://npdp.stanford.edu/dam_incidents
Harris Pond Dam	1955	RI	earth	foundation	hydrologic event		town flooded	0	Failure of earthen embankment; disaster inspired city’s current flood control system.	Association of State Dam Safety Officials (www.damsafety.org)
MILLARD POND	1955	CT	masonry	overtopping	hydrologic event		unknown	0	In 1955 the dam was seriously damaged by a flood.	http://npdp.stanford.edu/dam_incidents
Three Mile Flat Res	1955	OR	earth	unknown	unknown		unknown	0	Dam breached relatively slowly. Failure of dam attributed to work of badgers and rodents.	http://npdp.stanford.edu/dam_incidents
Schoellkopf Station	1956	NY	unknown	unknown	unknown	620,000	destruction of two-thirds of the Schoellkopf Station at Niagara Falls	1		http://npdp.stanford.edu/dam_incidents
Baker Pond	1956	VT	earth	unknown	unknown		none	0	The dam breached at pipe spillway. No damages reported downstream.	http://npdp.stanford.edu/dam_incidents

Goodrich Reservoir	1956	OR	earth	piping	seepage		unknown	0	Limited piping due to seepage caused a void and abnormal weight of ice or ice pressure over void caused failure.	http://npdp.stanford.edu/dam_incidents
White Rapids Left Causeway	1956	MI	concrete gravity	foundation	poor construction		unknown	0	a reinforced concrete pier failed at a point which imbedded a hinge pin common to two Tainter gates, causing the common ends of the gates to pull free. A possible contributing cause was the fact that four hinge pin reinforcing loops were originally installed where the design called for six.	http://npdp.stanford.edu/dam_incidents
Jackson Bluff	1957	FL	earth gravity	breach	hydrologic event		unknown	0	According to Atlanta Regional Office Dam Failures breach of approximately 1200 feet of embankment during normal pool as a result of heavy rains.	http://npdp.stanford.edu/dam_incidents
LEECH LAKE DAM	1957	MN	concrete gravity	overtopping	hydrologic event, upstream dam failure		unknown	0	Failure of a sheetpile cofferdam led to failure of this dam.	http://npdp.stanford.edu/dam_incidents
SCSOWL CREEK SITE07	1957	OK	earth	unknown	unknown		unknown	0	Erosion tunnel emptied reservoir.	http://npdp.stanford.edu/dam_incidents
SCSOWL CREEK SITE13	1957	OK	earth	unknown	unknown		unknown	0	Failure tunnel travelled along right side of conduit.	http://npdp.stanford.edu/dam_incidents
ECHO LAKE	1958	CT	rockfill	piping	poor maintenance		unknown	0	Dam had to be breached so it could be drained, but the contractor screwed up on the repair work and the dam washed out. Piping had been seen in the four days prior to failure.	http://npdp.stanford.edu/dam_incidents
ROUNDY	1958	UT	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Currant Creek	1959	OR	earth	unknown	unknown		unknown	0	Inadequate foundation preparation.	http://npdp.stanford.edu/dam_incidents
Electric Light Pond	1960	NY	unknown	unknown	unknown		unknown	1		Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
ABENIKI LAKE DAM	1960	NH	earth	overtopping	hydrologic event, erosion	900,000	unknown	0	The dam failed as a result of high waters caused by spring thaw and heavy rains.	http://npdp.stanford.edu/dam_incidents

LAKE TANGLEWOOD DAM	1960	TX	earth	overtopping	hydrologic event		damage to Palo Duro State Park	0	Floodwaters overtopped the closure section and washed out a 100-foot portion of the dam. This caused considerable damage to Palo Duro State Park downstream.	http://npdp.stanford.edu/dam_incidents
MAUCH CHUNK LAKE (PA462)	1960	PA	earth	unknown	unknown		unknown	0	Failure was due to rotting and wear from ice and lack of maintenance.	http://npdp.stanford.edu/dam_incidents
PENN FOREST	1960	PA	concrete earth	piping	unknown		unknown	0	Partial failure. Sinkhole occurred in upstream slope of dam.	http://npdp.stanford.edu/dam_incidents
SCSLITTLE WEWOKA CREEK SITE17	1960	OK	earth	unknown	unknown		unknown	0	Small initial leak observed at 8a.m. gradually eroded into tunnel, and by evening reservoir was empty.	http://npdp.stanford.edu/dam_incidents
CRYSTAL LAKE	1961	CT	earth	unknown	unknown		unknown	0	The dam was over 100 years old and had been leaking for some time. It failed suddenly	http://npdp.stanford.edu/dam_incidents
WACO LAKE	1961	TX	unknown	unknown	unknown		unknown	0	Failure occurred during construction when a section sagged 19 feet vertically and slipped 23 feet downstream.	http://npdp.stanford.edu/dam_incidents
WASHINGTON COUNTY LAKE DAM	1962	IL	earth	unknown	unknown		unknown	0	Piping type failure during initial filling.	http://npdp.stanford.edu/dam_incidents
Spaulding Pond (Mohegan Park)	1963	CT	earth	overtopping	hydrologic event, piping	6,000,000	NPDP estimates $3,053,000 in damages	6	From New York Times, 10/22/00: “Norwich hopes to remove dams on Yantic” No warning.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993

Baldwin Hills	1963	CA	earth	cracking	piping, settlement	1,106,433	destroyed 65 houses, miles of streets, water pipes, sewers & gas lines, damaged 210 houses & apartments	5	Advanced warning enabled evacuation; signaled end of urban-area earthen dams in CA. (1.5 hours warning). Dam caretaker identified crack in wall, notification of operator and engineer preceded mapping of evacuation zone and community alert. Police went door to door. emergency services were mobilized for rescue. Took over 20 years for town to recover. Population at risk 16,500); subsidence caused by exploitation of oil field under dam exacerbated by reinjection of waste brine - area was also atop a fault, inadequate piping	Association of State Dam Safety Officials (www.damsafety.org); http://framework.latimes.com/2013/12/13/the-1963-baldwin-hills-dam-collapse/#/0; http://web.stanford.edu/~meehan/la/baldwin.htm; Dekay and McClelland, 1993; Wahl, 1998; http://npdp.stanford.edu/dam_incidents
Little Deer Creek	1963	UT	earth	overtopping	hydrologic event, piping		Summer cabins damaged	1	No warning.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
LAMBERT	1963	TN	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
White Rapids Left Causeway	1963	MI	concrete gravity	poor construction	gate		unknown	0	a reinforced concrete pier failed at a point which imbedded a hinge pin common to two Tainter gates, causing the common ends of the gates to pull free. A possible contributing cause was the fact that four hinge pin reinforcing loops were originally installed where the design called for six. Hold back plates were installed on these piers and on all of the other piers to prevent any further occurrence.	http://npdp.stanford.edu/dam_incidents

Swift Irrigation Dam and Lower Two Medicine Dam	1964	MT	earth rockfill	overtopping	hydrologic event	62,000,000	NPDP estimates 19 killed and $18,500,000 in damages	30	Most fatalities occurred on Blackfeet reservation. Replaced by concrete-arch dam with emergency action plan and process. Less than 1.5 hours notice.	Association of State Dam Safety Officials (www.damsafety.org); http://www.greatfallstribune.com/story/news/local/2014/05/25/50th-anniversary-1964-flood/9563135/; http://www.greatfallstribune.com/story/money/2014/06/01/swift-two-medicine-dams-quickly-replaced/9777069/; http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
Lower Hell Hole Dam	1964	CA	earth rockfill	foundation	hydrologic event	160,000,000	Destroyed 2 suspension bridges and 1 steel girder state highway bridge	0	Record rains during construction; 410-foot high zoned rockfill structure on the Rubicon River; a 200’ high section of the embankment failed upon record rains during construction; 30,000 af flood	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
LOWER MONUMENTAL LOCK AND DAM	1964	WA	concrete gravity	breach	hydrologic event, upstream dam failure		unknown	0	earthfill cofferdam overtopped by flood. Project flooded when sheetpile cell collapsed and the downstream earthfill cofferdam was breached.	http://npdp.stanford.edu/dam_incidents
MEDICINE CREEK	1964	NE	earth	overtopping	hydrologic event		unknown	0		http://npdp.stanford.edu/dam_incidents
SCSCHEROKEE SANDY SITE08A	1964	OK	earth	piping	seepage		unknown	0	Tunnel gradually eroded following path of initial leakage. About 48 hours required (after observation of initial leak) for release of main volume of reservoir through gradually eroded failure tunnel.	http://npdp.stanford.edu/dam_incidents
SCSUPPER RED ROCK CREEK SITE48	1964	OK	earth	unknown	unknown		unknown	0	Reservoir emptied through erosion tunnel before failure was discovered on 11/18/64, probably about 24hrs after initial leak.	http://npdp.stanford.edu/dam_incidents
SKAGWAY	1965	CO	rockfill	overtopping	hydrologic event		unknown	2	The dam failed during a flood in 1965.	http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
ALTO PASS RESERVOIR DAM	1965	IL	earth	unknown	unknown		unknown	0	Failed on first filling by piping along CMP drop inlet outlet pipe.	http://npdp.stanford.edu/dam_incidents

FRANKTOWN PARKER FPM1	1965	CO	earth	overtopping	hydrologic event		unknown	0	Overtopped during flooding.	http://npdp.stanford.edu/dam_incidents
Mosinee	1965	WI	timber crib	overtopping	hydrologic event		unknown	0	Collapse of timber crib needle dam during flood. Replaced by rockfill dam section.	http://npdp.stanford.edu/dam_incidents
Emery	1966	CA	earth	foundation	corrosion		unknown	0	Chemical action and corrosion of the outlet pipe caused failure. Old dam was removed and subsequently replaced by an earthfill embankment (designed and constructed to modern standards).	http://npdp.stanford.edu/dam_incidents
LAKE LATONKA	1966	PA	earth	unknown	unknown		livestock drowned	0	Piping through the embankment under the concrete spillway resulting in the collapse of the spillway. Two cows, two horses and a sheep drowned.	http://npdp.stanford.edu/dam_incidents
Lake North	1966	NE	earth	unknown	unknown		unknown	0	South and north dikes abutting diversion dam breached.	http://npdp.stanford.edu/dam_incidents
LAKE O THE HILLS	1966	AK	earth rockfill	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
FAIRHAVEN DAM	1967	MN	gravity	overtopping	hydrologic event, spillway		unknown	0	The concrete spillway and earthen embankment washed out only several weeks after the spillway had been constructed.	http://npdp.stanford.edu/dam_incidents
FRD NO 1	1967	KS	earth	unknown	unknown		unknown	0	Three piping failures occurred just above the contact surface of the trench excavations in the foundation of the closure section. The three failure channels were each underlain by approx 4 ft of impervious embankment lying over the natural ground material at the base of the dam. Immediately above this impervious blanket was the nonhomogeneous embankment material consisting of interconnected lenses, pockets and layers of gravel between alternate layers of well compacted impervious layers. Failure occurred thru this nonhomogeneous 3 to 5 ft thickness which extended thru	http://npdp.stanford.edu/dam_incidents

									the dam in the 3 failure locations.	
North Star Sand & Gravel Dams	1967	WA	unknown	overtopping	hydrologic event, spillway		Washed out GN railroad and derailed passing train	0	40 foot high dam washed out due to lack of spillway. 25 foot high dam rebuilt, also failed	Association of State Dam Safety Officials (www.damsafety.org)
SCSUPPER RED ROCK CREEK SITE42	1967	OK	earth	unknown	unknown		unknown	0	Small leak observed at 5p.m. on 6/20/67. 24 hours later, reservoir was found empty from failure. Erosion tunnel ran along right side of conduit upstream of dam, then crossed over and ran along left side.	http://npdp.stanford.edu /dam_incidents
Fort Meade	1967	FL	earth	unknown	unknown		250,000 m3 of phosphate clay slimes, 1.8 million m3 of water, fish kill	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Lee Lake	1968	MA	unknown	unknown	unknown		6 homes destroyed, 20 damaged. (NPDP estimates 2 deaths).	6	No warning.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu /dam_incidents; Dekay and McClelland 1993
Virden Creek Dam	1968	IA	unknown	unknown	unknown		unknown	1		Association of State Dam Safety Officials (www.damsafety.org)
Bridgeway Lake Dam	1968	MI	earth	overtopping	hydrologic event, erosion		unknown	0	The dam failed due to overtopping and erosion. This was a first filling failure.	http://npdp.stanford.edu /dam_incidents

WYOMING DEVELOPMENT COMPANY NO. 1	1969	WY	earth	unknown	unknown	1,000,000	flooded 10,000 acres of cropland	0	This earth embankment collapsed suddenly, flooding 10,000 acres of cropland. Approximately 9,400 acre feet of water was dumped into Sybille Creek. The breach occurred above the outlet works.	http://npdp.stanford.edu/dam_incidents
HUMBOLDT MILLDAM	1969	IA	concrete	overtopping	hydrologic event		unknown	0	The island was overtopped and washed out during a large flood.	http://npdp.stanford.edu/dam_incidents
Spruce Lake	1969	VT	earth	unknown	unknown		none	0	The dam breached at pipe spillway. No damages reported downstream.	http://npdp.stanford.edu/dam_incidents
MURPHY	1970	WI	earth	overtopping	hydrologic event, spillway		unknown	0	The dam was overtopped. There was debris in the spillway.	http://npdp.stanford.edu/dam_incidents
Pillar Rock Dam	1970	WA	concrete gravity	overtopping	hydrologic event, culvert		3 homes and fish cannery destroyed	0	Logging roadfill culvert blocked by debris, overtopped and failed, caused 25 foot high concrete gravity dam to fail.	Dam Safety Officials (www.damsafety.org)
SCSUPPER CLEAR BOGGY CREEK SITE50	1970	OK	earth	unknown	unknown		unknown	0	Bottom of breach well above foundation, so failure was wholly confined to embankment. Vertical walled breach.	http://npdp.stanford.edu/dam_incidents
SHEEP CREEK DAM	1970	ND	earth	overtopping	hydrologic event, spillway		unknown	0	Deformation, conduit. On day of incident, reservoir was filled with heavy rains for the first time; spillway went into operation. Failure is believed to have been caused by leaks from joints in the spillway pipe.	http://npdp.stanford.edu/dam_incidents
BULLOCK DRAW	1971	UT	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
San Fernando Dam	1971	CA	earth other fill	foundation	settlement, earthquake		unknown	0	Quake caused slide in upstream slope that lowered crest	Dam Safety Officials (www.damsafety.org);
Sid White Dam	1971	WA	earth	unknown	unknown		Debris dumped into town of Riversde	0	Earthen dam failed, causing second dam to fail and dump debris into town of Riverside.	Dam Safety Officials (www.damsafety.org);
Fort Meade	1971	FL	earth	unknown	unknown		9 million m3 of clay water released, large fish kill	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;

Canyon Lake Dam	1972	SD	earth	overtopping	hydrologic event, spillway	160,000,000	1,335 homes and 5,000 automobiles destroyed (NPDP estimates 33 deaths).	238	In the aftermath, interim and long-range programs were initiated and millions of federal dollars were spent in Rapid City and the surrounding stricken communities, including a flood-plain management program. (33 lives lost. According to file folder, dam failed near primary spillway structure. Also states that 300 were killed, but not all deaths were due to dam failure.) 34-year-old earth embankment; Dam size: 20' high, 500' long; Impoundment size: 40 acre reservoir, holding 132 million gallons "The safety inspection and repair program was spurred by the collapse of a dam built & operated by the city near Rapid City, S.D., in 1972. More than 200 persons died and damages ran in the millions of dollars." Washington Post 7/15/1978. Less than 1 hour notice.	NRC, 2012; Association of State Dam Safety Officials (www.damsafety.org); https://pubs.usgs.gov/fs/fs-037-02/; http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
Buffalo Creek	1972	WV	earth other fill	poor construction	hydrologic event	65,000,000	502 houses, 44 mobile homes, destroyed, 1000 cars and trucks , several roads and bridges destroyed; 943 homes damaged -- flood of wastewater. (NPDP estimates $50,000,000 in damages).	125	Series of 3 non-permitted dams built of low grade soils and mining debris. Less than 1 hour warning. Population at risk 5000. National Guard called in to rescue and recover. Despite possible signs of danger, the Pittston mining company refused to alert residents. In 1973, the West Virginia Legislature passed the Dam Control Act, regulating all dams in the state. However, funding was never appropriated to enforce the law. In 1992, an official with the state Division of Natural Resources estimated there were at least 400 hazardous non-coal dams in West Virginia, many of which were owned by the state. heavy rainfall; dams built from	WV Ad Hoc Commission of Inquiry, 1873; Erikson, 1978; National Dam Inspection Act, Public Law 92-367; http://wv.ng.mil/pages/about/history/1972-buffalo_creek/1972_buffalo_creek.html; Dekay and McClelland, 1993; Wahl, 1998; Association of State Dam Safety Officials (www.damsafety.org)

									mining waste products and poor soil caused embankment failure	
Anzalduas	1972	TX	earth	unknown	unknown		unknown	4		http://npdp.stanford.edu/dam_incidents
LAKE O THE HILLS	1972	AK	earth	foundation	erosion		One child (10-year old) drowned from the floodwaters and a road was washed out as a result.	1	Due to internal erosion. One child drowned from the floodwaters and a road was washed out as a result.	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
Barcroft Dam	1972	VA	earth masonry	overtopping	hydrologic event		unknown	0	Excessive rainfall during Tropical Storm Agnes was measured at a station 1.75 miles upstream from the dam.	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
BROWDER	1972	TN	earth	unknown	unknown		unknown	0	A controlled breach of the dam was performed following the discovery of a piping leak.	http://npdp.stanford.edu/dam_incidents
WHITEWATER BROOK DAM	1972	NH	earth gravity	breach	hydrologic event, spillway		unknown	0	The earth embankment was breached in an area adjacent to the concrete spillway. Much erosion and damage occurred to and along the spillway channel and on the downstream face. Initial cause of the failure was thought to be separation alongside of the spillway.	http://npdp.stanford.edu/dam_incidents
Box Lake	1973	UT	earth	overtopping	hydrologic event	5,000,000	unknown	0		http://npdp.stanford.edu/dam_incidents

CARLANNA LAKE	1973	AK	rockfill	overtopping	hydrologic event	3,200,000	unknown	0	The dam failed following two days of heavy rains.	http://npdp.stanford.edu/dam_incidents
LITTLE MUSKEGO	1973	WI	earth	overtopping	hydrologic event, foundation	15,000	unknown	0	An unusually heavy rain resulted in the overtopping and failure of a low portion of the right dike.	http://npdp.stanford.edu/dam_incidents
BLOTT	1973	WI	earth	overtopping	hydrologic event, breach		unknown	0	The earth dikes were overtopped and breached.	http://npdp.stanford.edu/dam_incidents
Braddock Lake Dam	1973	NJ	earth gravity	overtopping	hydrologic event		unknown	0	Overtopped	http://npdp.stanford.edu/dam_incidents
Carlanna Creek Dam	1973	AK	unknown	overtopping	hydrologic event, erosion		unknown	0	Break followed two days of heavy rains. Floodwaters went into the downtown area and forced the evacuation of 50 residents of a trailer court. No injuries or deaths were reported. Failure due to overflow and erosion on one of the abutments, as well as age and design deficiencies.	http://npdp.stanford.edu/dam_incidents
CAULK LAKE DAM	1973	KY	earth	unknown	unknown		unknown	0	The failure of this dam is thought to be the result of loss of soil strength due to seepage pressure or saturation by seepage.	http://npdp.stanford.edu/dam_incidents
CENTER CREEK NO. 1	1973	UT	earth	overtopping	spillway, piping		unknown	0	The spillway became plugged, and the dam was overtopped. Piping along the outlet pipe may have contributed to this event.	http://npdp.stanford.edu/dam_incidents
HORSESHOE LAKE	1973	CO	earth	unknown	unknown		unknown	0	This dam was breached in the area of the rubble masonry high level gate outlet. It is believed that leaks in the rubble masonry outlet, which was used for an emergency spillway, piped embankment material into the outlet channel.	http://npdp.stanford.edu/dam_incidents
IRELAND #5	1973	CO	earth	overtopping	hydrologic event, spillway		unknown	0	Overtopped during flooding. Reference 1256 records incident as spillway breach.	http://npdp.stanford.edu/dam_incidents
LOWER LATHAM	1973	CO	earth	unknown	unknown		unknown	0	A small discharge through the emergency spillway may have led to a piping situation between the earthfill and the concrete spillway section.	http://npdp.stanford.edu/dam_incidents
NEWTON GULCH	1973	CO	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents

ROUNDY	1973	UT	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
THOMAS	1973	CO	earth	overtopping	hydrologic event		unknown	0	Overtop.	http://npdp.stanford.edu/dam_incidents
Upper Moore Pond	1973	VT	earth	unknown	unknown		none	0		http://npdp.stanford.edu/dam_incidents
WILCOX	1973	UT	unknown	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Davis Lake Dam_Okanogan Co.	1974	WA	earth rockfill	overtopping	hydrologic event		unknown	0	The dam was overtopped and failed. A small section of the dam eroded down to the ground.	http://npdp.stanford.edu/dam_incidents
FOOL CREEK NO 1	1974	UT	earth	unknown	unknown		little damage	0		http://npdp.stanford.edu/dam_incidents
OBERON LAKE NO. 1	1974	CO	earth	overtopping	hydrologic event, spillway		unknown	0	Dam was overtopped and middle portion of dam was completely washed out. The spillway was inadequate to handle the large quantities of runoff	http://npdp.stanford.edu/dam_incidents
RIDGETOP	1974	TN	earth	breach	hydrologic event		unknown	0	Failure from overtopping. Not a full breach. Severe slides on downstream slope. Six inches of rain in one day.	http://npdp.stanford.edu/dam_incidents
SADDLE LAKE DAM	1974	NY	earth	unknown	unknown		unknown	0	The dam failed due to piping. The joints of a 24 inch corrugated metal pipe that were not watertight, causing the piping failure and subsequent embankment slope failure by sloughing.	http://npdp.stanford.edu/dam_incidents
STONERIDGE	1974	ID	earth	overtopping	hydrologic event, spillway		unknown	0	Dam was overtopped and middle portion of dam was completely washed out. The spillway was inadequate to handle the large quantities of runoff experienced during the week of January 11, 1974.	http://npdp.stanford.edu/dam_incidents
Deneen Mica	1974	NC	earth	overtopping	hydrologic event		38,000 m3 tailings released	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Lakeside Dam	1975	SC	earth	overtopping	hydrologic event		unknown	1		http://npdp.stanford.edu/dam_incidents
DRESSER NO.4 DAM (FAILED)	1975	MO	earth rockfill	unknown	unknown		unknown	0	Catastrophic failure that created a breach 300 feet wide in the levee.	http://npdp.stanford.edu/dam_incidents

KARVAL	1975	CO	earth	unknown	unknown		unknown	0	Outlet pipe corroded releasing entire reservoir.	http://npdp.stanford.edu/dam_incidents
Mike Horse	1975	MT	unknown	overtopping	hydrologic event, culvert		Thousands of tons of mine tailings washed downstream & killed most aquatic life in upper 10 miles of Blackfoot River	0	Dam built in 1941. Part of the dam washed out when culvert became clogged during heavy rains. Thousands of tons of mine tailings washed downstream & killed most aquatic life in upper 10 miles of Blackfoot River	Association of State Dam Safety Officials (www.damsafety.org)
Twin Falls Auxilliary Spillway	1975	MI	unknown	unknown	unknown		unknown	0	Failure of a section of the upstream cofferdam during spillway renovation.	http://npdp.stanford.edu/dam_incidents
Walter Bouldin	1975	AL	unknown	piping	unknown		unknown	0	Dam built in 1967; reconstructed and stands today.	Association of State Dam Safety Officials (www.damsafety.org)
Walter Bouldin	1975	AL	concrete gravity	unknown	unknown		unknown	0	The failure occurred after part of the upstream side of the embankment near the crest slid into the water. Outrushing water destroyed part of the fill and eroded the foundation to 50 feet below the reservoir bottom. The dam may have failed due to piping in the downstream shell. Flooding did not occur as the most of the force of the wall of water was dissipated along a 5 mile long canal below the dam.	http://npdp.stanford.edu/dam_incidents
Silverton	1975	CO	earth	unknown	unknown		116,000 tonnes released, tailings flow slide polluted nearly 100 miles (160 km) of the Animas river and its tributaries; severe property damage; no injuries	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Mike Horse	1975	MT	earth	overtopping	hydrologic event		150,000 m3 release	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
unknown	1976	CO	unknown	unknown	unknown		unknown	144	An unnamed dam on the Big Thompson River experienced an event. The dam did not fail. Less than 1 hour warning.	http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993

Teton Dam	1976	ID	earth zoned	foundation	erosion	1,322,000,000	NPDP estimates 14 killed and $900,000,000 in damages	11	Wall at base of dam was composed of volcanic rock with large fractures that were to be filled with grout. Fractures were too numerous to fill adequately. Leaks appeared on north side of dam that led to erosion. Designed by the U.S. Bureau of Reclamation, failed just as it was being completed and filled for the first time. Law enforcement was not notified until after attempts had been made to stop leakage; phone calls to initially impacted residents (7 deaths) were made less than an hour before the collapse. 45 minutes warning. Population at risk 2000. Subsequent flooding impacted another 22,000 people (4 deaths) who had approximately 2 hours and 15 minutes warning.	NRC, 2012; USBR, 2011b; Association of State Dam Safety Officials (www.damsafety.org); http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/narrative.html; Dekay and McClelland, 1993; Wahl, 1998; http://npdp.stanford.edu/dam_incidents
New-found Creek Dam (Bear Wallow)	1976	NC	earth	overtopping	hydrologic event	500,000	unknown	4	No warning.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
Mud Mountain Lake	1976	WA	rockfill	unknown	unknown		2 children	2		http://npdp.stanford.edu/dam_incidents
IDYLWILDE	1976	CO	concrete gravity	overtopping	hydrologic event		unknown	0	Heavy rainfall on a portion of the Big Thompson watershed caused extreme flooding conditions. As a result, the dam was completely destroyed.	http://npdp.stanford.edu/dam_incidents
LAKE NANCY DAM	1976	NY	earth	overtopping	spillway		unknown	0	Concrete spillway undermined and failed.	http://npdp.stanford.edu/dam_incidents
SEYMOUR RESERVOIR DAM	1976	IA	earth	unknown	unknown		minor damage	0		http://npdp.stanford.edu/dam_incidents

LAUREL RUN	1977	PA	earth	overtopping	hydrologic event	330,000,000	washed out highways and railroads. The downtown area of Johnstown, Pennsylvania was left several feet deep in mud. 6 houses destroyed, 19 homes damages. (NPDP estimates 40 deaths).	76	Washed out highways and railroads. The downtown area of Johnstown, Pennsylvania was left several feet deep in mud. Some flood victims were protected under the National Flood Insurance Program; President declared the Johnstown, Pennsylvania, area a major disaster area after a flood struck 136 communities within eight counties and killed 76 people, injured or caused sickness to 2,700, and damaged an estimated $117 million worth of property within the city and $213 million in areas outside the city. A wide variety of assistance was available to individual victims and State and local governments. Twelve agencies were responsible for 27 programs. Other agencies became involved through mission assignments by the Federal Disaster Assistance Administration. A local flash flood warning system could have alerted authorities to the disaster much sooner. An improved communications system could have provided better and quicker emergency assistance to the disaster area. It took up to 3 weeks to establish communications. The establishment of the 100-year floodplain may be inadequate as the criteria for floodplain management ordinances. No warning.	Association of State Dam Safety Officials (www.damsafety.org); https://www.gpo.gov/fdsys/pkg/CZIC-hg9983-u55-1978/html/CZIC-hg9983-u55-1978.htm; Wahl, 1998;http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993

Kelly Barnes Dam	1977	GA	earth	breach	piping	2,800,000	Loss of 39 lives. (9 houses, 18 house trailers and 2 college buildings destroyed.)	39	Earth dam built over rock crib dam. The Board could not determine a sole cause of the November 6, failure. It does conclude that a combination of factors caused the failure. The most probable causes are a local slide on the steep downstream slope probably associated with piping, an attendant localized breach in the crest followed by progressive erosion, saturation of the downstream embankment, and subsequently a total collapse of the structure. Governor established "Task Force on Dam Safety"; Corps of Engineers assigned the mission of organizing and leading a Federal technical investigation. 15 minutes warning. Population at risk 250.	NRC, 2012; Sanders and Sauer, 1979; https://ga.water.usgs.gov/publications/ToccoaFIBReport/; Wahl, 1998; http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
unknown	1977	MO	unknown	overtopping	hydrologic event		unknown	20	Less than 1 hour notice.	http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
Cedar Hills Lake Dam	1977	NC	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Deer Lake Dam	1977	NC	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Gossett Lake Dam	1977	NC	earth	overtopping	hydrologic event, spillway		unknown	0	Primary spillway was plugged with erodible soil. Emergency spillway carrying all flow.	http://npdp.stanford.edu/dam_incidents
MIDDLEBROOK	1977	TN	earth	overtopping	hydrologic event		unknown	0		http://npdp.stanford.edu/dam_incidents
Modest Creek Dam	1977	VA	earth	overtopping	hydrologic event, spillway		unknown	0	Located in a rural area it was 2 days before the failure was discovered.	http://npdp.stanford.edu/dam_incidents
Winter	1977	WI	gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Woodfin Reservoir Dam	1977	NC	earth	poor construction	hydrologic event		unknown	0	Concrete spillway chute washed out during flood. Original spillway design had been altered after initial construction, reducing capacity of the spillway control section	http://npdp.stanford.edu/dam_incidents

									and reducing the storage capacity of the reservoir.	
SANDY RUN	1977	PA	earth	breach	hydrologic event	200,000,000	See Laurel Run	0	The flood flows breached Sandy Run Dam and another water supply dam and washed out highways and railroads. The downtown area of Johnstown, Pennsylvania was left several feet deep in mud. (see Laurel Run)	Association of State Dam Safety Officials (www.damsafety.org); https://www.gpo.gov/fdsys/pkg/CZIC-hg9983-u55-1978/html/CZIC-hg9983-u55-1978.htm; Wahl, 1998;http://npdp.stanford.edu/dam_incidents
Homestake	1977	NM	earth	unknown	unknown		30,000 m3 released	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
COON CREEK 41	1978	WI	earth	unknown	unknown	590,000	unknown	0		http://npdp.stanford.edu/dam_incidents
Bartlett	1978	AZ	other arch	unknown	unknown	5,200	unknown	0		http://npdp.stanford.edu/dam_incidents
Allegan City Dam	1978	MI	earth	overtopping	piping		unknown	0	The dam failed as a result of overtopping and piping.	http://npdp.stanford.edu/dam_incidents
BAD AXE 12	1978	WI	earth	unknown	unknown		unknown	0	A flow of 5 cfs exited from the base of the right abutment downstream of the dam when the flood control pool was half-full. This was the first time the pool was filled to this level. The partial failure of the right abutment was due to water moving in stress-relief cracks and joints.	http://npdp.stanford.edu/dam_incidents
CAMP ERNST DAM	1978	KY	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
DIAMOND MILLS PAPER COMPANY DAM	1978	NY	gravity	unknown	unknown		unknown	0	deterioration of side channel spillway; outlets inoperable and no maintenance performed in past 10 yrs.	http://npdp.stanford.edu/dam_incidents
DURHAM	1978	WY	earth	overtopping	unknown		unknown	0	Complete failure of the dam due to overtopping.	http://npdp.stanford.edu/dam_incidents

MCCARTY LAKE DAM	1978	TX	earth	overtopping	hydrologic event, breach		unknown	0	The embankment was overtopped by floodwaters resulting in a breach at the right abutment, partial breaching at five separate locations and severe erosion along about 90 percent of its length. Considerable erosion damage also occurred in the spillway channel.	http://npdp.stanford.edu/dam_incidents
MONASHKA CREEK DAM	1978	AK	earth	foundation	hydrologic event, erosion		unknown	0	Three inches of rain had fallen on October 16, 1978 in the drainage (area), resulting in the dam's failure.	http://npdp.stanford.edu/dam_incidents
Myron Isabel Dam	1978	CO	unknown	piping	animal		Insignificant	0		Association of State Dam Safety Officials (www.damsafety.org)
OTTER	1978	TN	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
REYNOLDS NO. 1	1978	WY	earth	overtopping	hydrologic event		unknown	0	A partial failure of the dam occurred sometime during the spring of 1978 as a result of overtopping.	http://npdp.stanford.edu/dam_incidents
SARNIA DAM	1978	ND	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
SEWALLS SOUTH CHANNEL DAM	1978	NY	gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Swimming Pool Dam	1979	NY	earth	overtopping	hydrologic event		road washed out	4		http://npdp.stanford.edu/dam_incidents
MARTIN PLANT COOLING WATER RESERVOIR	1979	FL	earth	unknown	unknown	4,500,000	unknown	0	The dam failed due to piping in the foundation soils. Complete breach and emptying of the reservoir.	http://npdp.stanford.edu/dam_incidents
FERTILE MILL DAM	1979	IA	earth	unknown	unknown		unknown	0	A section of the earth dike washed out, possibly due to piping or a seepage-induced slope failure.	http://npdp.stanford.edu/dam_incidents
GOSHEN	1979	UT	earth	overtopping	hydrologic event		unknown	0	The dam overtopped and failed due to flooding caused by an approximately 0.6 inch rainfall on a 15 inch snowpack all at once.	http://npdp.stanford.edu/dam_incidents

Gropps Lake Dam	1979	NJ	earth	unknown	unknown		unknown	0	The dam collapsed as a result of both movement of the spillway structure along the abutment and the spillway apron being washed out.	http://npdp.stanford.edu/dam_incidents
HUTTOS LAKE DAM	1979	SC	earth	overtopping	hydrologic event, breach		unknown	0	The dam was overtopped and breached.	http://npdp.stanford.edu/dam_incidents
LITTLE FALLS	1979	WI	unknown	unknown	unknown		unknown	0	Two gates became inoperable after concrete shifted. Poor quality concrete was used.	http://npdp.stanford.edu/dam_incidents
MAPLE GROVE	1979	CO	other rubber	unknown	unknown		unknown	0	The fabric-dam was punctured by an unknown, sharp object. It was determined to be most likely due to vandalism.	http://npdp.stanford.edu/dam_incidents
Millsboro Pond Dam	1979	DE	earth	unknown	unknown		unknown	0	Due to melting snow and heavy rain, the water level of the pond rose considerably, increasing seepage through the dam's fill and creating washouts behind the culvert abutments and under the 16 foot long sheeting (which was supporting box-culvert walls). The upstream face of the embankment to the left of the spillway (looking downstream) has been eroded to a rather steep slope	http://npdp.stanford.edu/dam_incidents
United Nuclear Corp	1979	NM	unknown	unknown	unknown		Uranium tailings - 93 million gallons of liquid contaminated with low-level radiation & ~ 1100 T of solid waste spread ~ 100 miles downstream	0	Washington Post 1987 ASDSO West Conf Proc, p. 183 UNC shut down operations April 1982.	Association of State Dam Safety Officials (www.damsafety.org)
VANCE LAKE DAM	1979	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Wiggins Mill Pond Dam	1979	DE	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Church Rock	1979	NM	earth	unknown	unknown		370,000 m3 of radioactive water, 1,000 tonnes of contaminated sediment, Contamination of Rio Puerco sediments up to 110 km downstream	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;

Prospect Dam	1980	CO	earth	piping	unknown	150,000	unknown	0	Less than 30 minutes warning.	http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993
Clear Creek #2	1980	AZ	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
EAST LEMMON	1980	SD	earth	overtopping	hydrologic event		unknown	0	Following an 8 inch rainfall in approximately 3 to 4 hours, the dam failed due to overtopping.	http://npdp.stanford.edu/dam_incidents
Fairfield Swamp Pond	1980	VT	earth	unknown	unknown		unknown	0	The dam breached under the core wall and pipe spillway.	http://npdp.stanford.edu/dam_incidents
Lake Como Dam	1980	DE	earth	overtopping	unknown		unknown	0	The downstream half of the embankment eroded away by as much as five feet when the dam was overtopped on July 29, 1980.	http://npdp.stanford.edu/dam_incidents
PHELPS DODGE TAILINGS DAM NO. 3X	1980	NM	unknown	unknown	unknown		2 million cu yds tailings spilt into Mangas Creek.	0	Section 700 ft wide and down to the top of the starter dam failed in slightly more than 3 minutes releasing 2.5 million cubic yards of slimes. (Tyrone Tailings Dam No 3)	http://npdp.stanford.edu/dam_incidents
PICKWICK	1980	MN	earth	overtopping	hydrologic event		unknown	0	A large flood, many times greater than a 100 year event, occurred as a result of a heavy rainfall of short duration, which was preceded by a week of intermittent rainfall. The flood inundated the dam and the entire valley floodplain.	http://npdp.stanford.edu/dam_incidents
SAINT JOHN	1980	ID	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
SNOW BIRD LAKE DAM	1980	NY	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
TANNERSVILLE RESERVOIR #1 DAM	1980	NY	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Tyrone	1980	NM	earth	unknown	unknown		2 million m3 tailing released, inundated farmland	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Coal waste impoundment	1981	KY	unknown	unknown	unknown		unknown	1		Association of State Dam Safety Officials (www.damsafety.org)
Great Works	1981	ME	timber crib	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents

JOHNSTON CITY LAKE DAM	1981	IL	earth	poor maintenance	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Ages	1981	KY	earth	overtopping	hydrologic event		96,000 m3 coal refuse slurry released,1 person was killed, 3 homes destroyed, 30 homes damaged, fish kill in Clover Fork of the Cumberland River	1		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;

BUSHY HILL POND	1982	CT	earth	overtopping	hydrologic event, breach	276,000,000	15,000 homes and 400 commercial and industrial establishments were damaged. The flood also resulted in damages to 31 dams, state and local roads, bridges, dams, and utility infrastructure.	11	Heavy rains in Connecticut dumped more than 10 inches of water. The resulting flooding washed out or partially breached 19 dams. (Bushy Hill Lake, Clarks Pond, Deer Lake Scout Reservation, multiple others). 17 dams failed. The regional headquarters, a Federal service of the National Oceanic and Atmospheric Administration (N.O.A.A.), is housed in a basement suite of offices near a creek. By late Saturday, water was pouring through the walls, soaking cables, deactivating computer terminals and forcing the workers to flee. There was not the same sense of apprehension and state of personal alert that normally accompanies a thunderstorm or a hurricane. "'A relatively calm period of weather in New England" has created a generation complacent and inexperienced about the brutal force possible when water rises up and rages from its allotted course." (Dr. David Curtis, one of the senior hydrologists). Dr. Curtis believes that the building of dams and dikes earlier in the century lulled many people, including officials, into a false sense of security -not realizing, as he put it, that "nature is clever and can circumvent our best flood measures." In this case, dozens of tiny streams filled up below the dams - tributaries that were not thought to need control. Although the center put out a flood warning as early as Friday, the public was simply not accustomed to responding in the way it normally does to a snow or hurricane alert, he	http://www.floodsafety.noaa.gov/states/ct-flood.shtml; http://www.nytimes.com/1982/06/13/nyregion/the-flood-of-82-why-did-it-happen; htmlhttp://www.ct.gov/deep/cwp/view.asp?A=2705&Q=470890; http://articles.courant.com/2002-06-06/news/0206062166_1_tropical-storm-connecticut-river-flood; Dekay and McClelland, 1993;http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993

									said. 'They did not move their cars," Dr. Curtis said. "They did not move furniture. And I think they did not even take us seriously enough." 2-3 hours warning. Population at risk 400.	

Lawn Lake and Cascade Lake Dam	1982	CO	earth	foundation	erosion	31,000,000	Flood waters destroyed 18 bridges, damaged road systems, inundated 177 businesses (75 percent of Estes Park's commercial activity) and damaged 108 residences.	3	62 percent of the merchants who were affected by the flood either lost their business or moved away without rebuilding. Those who stayed faced a long, harrowing and expensive cleanup process. 30 minute warning. Population at risk 5000. "…of the 103 business owners within the zone of high flooding on July 15, 1982, 62% of them have moved away or no longer are engaged in business." (From the following link, now broken: www.estesnet.com/82flood/Lawn%20Lake%20Story%20p7.htm) Rocky Mt. News, 6/18/84 "Fingers Still Pointing in Estes Park Flood"	Association of State Dam Safety Officials (www.damsafety.org); http://www.reporterherald.com/ci_21071062/1982-flood-changed-downtown-estes-park; https://www.nps.gov/romo/planyourvisit/upload/flood_2009.pdf; Jarrett and Costa, 1984; Dekay and McClelland, 1993; Wahl, 1998; http://npdp.stanford.edu/dam_incidents
JOHNSON POND	1982	CT	earth	overtopping	hydrologic event	50,000	unknown	1	See other 1982 CT floods	http://npdp.stanford.edu/dam_incidents
LEESVILLE DAM	1982	CT	concrete	overtopping	hydrologic event		unknown	1	See other 1982 CT floods	http://npdp.stanford.edu/dam_incidents
Howard Dam	1982	ID	earth	overtopping	hydrologic event, upstream dam failure	2,100,000	unknown	0		http://npdp.stanford.edu/dam_incidents
HOLBROOK POND	1982	CT	unknown	overtopping	hydrologic event	100,000	unknown	0	See other 1982 CT floods	http://npdp.stanford.edu/dam_incidents
MILL POND	1982	CT	earth masonry	overtopping	hydrologic event	100,000	unknown	0	See other 1982 CT floods	http://npdp.stanford.edu/dam_incidents
CRYSTAL LAKE	1982	CT	earth	overtopping	hydrologic event	5,000	unknown	0		http://npdp.stanford.edu/dam_incidents
Alexander Lake Dam	1982	WA	unknown	unknown	unknown		Caused damage at fish hatchery and homes in Gorst	0	Spillway undermined and failed during heavy rains.	Association of State Dam Safety Officials (www.damsafety.org)
DEER LAKE	1982	CT	masonry	overtopping	hydrologic event		unknown	0	See other 1982 CT floods	http://npdp.stanford.edu/dam_incidents
GORTON POND	1982	CT	unknown	overtopping	hydrologic event		unknown	0	See other 1982 CT floods	http://npdp.stanford.edu/dam_incidents
Mud Lake	1982	CA	earth	breach	wave action, erosion, settlement		unknown	0	Breach, no evidence of overtopping. According to NPDP Ref No 1883, most likely cause of failure was erosion of the upstream slope and crest by wave action.	http://npdp.stanford.edu/dam_incidents

									Another incident occurred at this dam in 1932.	
UPPER MILLPOND	1982	CT	earth masonry	overtopping	hydrologic event		unknown	0	See other 1982 CT floods	http://npdp.stanford.edu/dam_incidents
DMAD	1983	UT	earth	unknown	unknown		unknown	1	1-12 hours notice.	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org); Dekay and McClelland 1993
BEAVER LAKE DAM	1983	IL	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Condit	1983	WA	concrete gravity	piping	hydrologic event		unknown	0	Failed by piping during heavy rain.	http://npdp.stanford.edu/dam_incidents
INDIAN LAKE DAM	1983	KY	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
LAKEVIEW RESERVOIR DAM	1983	MS	earth	unknown	unknown		none	0		http://npdp.stanford.edu/dam_incidents
Mallison Falls	1983	ME	concrete gravity	overtopping	hydrologic event, spillway		unknown	0	Timber crib spillway section unraveled during flow over spillway.	http://npdp.stanford.edu/dam_incidents
BASS HAVEN LAKE DAM	1984	TX	earth	poor maintenance	unknown		unknown	1	While attempting to repair a low flow pipe, the owner cut the dam and water was allowed to flow through the cut. Erosion and a slide ensued, causing the dam to fail and resulting in one fatality.	http://npdp.stanford.edu/dam_incidents
Grettum Flowage	1984	WI	unknown	unknown	unknown	310,000	unknown	0		http://npdp.stanford.edu/dam_incidents
BALLARDS DAM	1984	NY	timber crib	overtopping	hydrologic event, spillway		unknown	0	Top portion of embankment, and east control gate were washed out during a flood. Portion of concrete-capped timber crib spillway dam collapsed.	http://npdp.stanford.edu/dam_incidents
IRELAND #5	1984	CO	earth	breach	spillway		unknown	0	Dam breached due to erosion under the spillway.	http://npdp.stanford.edu/dam_incidents
Kingsbury	1984	VT	concrete gravity	breach	hydrologic event		unknown	0	The dam failed during a flood event at approximately 5:30 AM. It breached at the right abutment.	http://npdp.stanford.edu/dam_incidents

MENNO DAM	1984	SD	earth	foundation	hydrologic event		unknown	0	The combination of the saturated conditions inadequate freeboard and a steep downstream slope all contributed to the failure. After the incident it was reported that both spillways had been operating for several days before the failure and the embankment crest appeared to have settled some. The breach removed approximately the center one-third of the embankment and eroded well into the foundation.	http://npdp.stanford.edu/dam_incidents
Roxboro Municipal Lake Dam	1984	NC	earth	unknown	unknown		unknown	0	Spillway slab had no underdrainage. The State had noted signs of piping and required the owners to have their engineers submit a repair plan months before the failure. The repair plan had been approved, but owners had not implemented the plan.	http://npdp.stanford.edu/dam_incidents
Columbia Diversion Dam	1985	SC	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Cuero	1985	TX	concrete gravity	poor maintenance	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Flowage Lake Dam	1985	MI	earth	seepage	unknown		unknown	0	The engineer reported that the seepage rate was increasing with each visit, but that he never saw evidence of piping.	http://npdp.stanford.edu/dam_incidents
Johnny's Creek	1985	AL	unknown	overtopping	hydrologic event		Hundreds evacuated	0		Association of State Dam Safety Officials (www.damsafety.org)
Niagara	1985	VA	concrete gravity	overtopping	hydrologic event, erosion		unknown	0	Overtopping and erosion of embankment section.	http://npdp.stanford.edu/dam_incidents
RICHARDET DAM	1985	MO	earth	breach	unknown		unknown	0	The breach of the dam was caused by a slide scarp intercepting the water level in the lake.	http://npdp.stanford.edu/dam_incidents
RIVERVIEW DAM	1985	IL	earth	unknown	unknown		unknown	0	The dam failed through the concrete overflow spillway during an annual runoff event.	http://npdp.stanford.edu/dam_incidents

Olinghouse	1985	NV	earth	unknown	unknown		25,000 m3 released	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Upriver Dam Forebay	1986	WA	concrete gravity	overtopping	spillway	11,000,000	damage to facility	0	Lightning struck the transmission line from the powerhouse. Loss of load caused wicket gate closure and immediate onset of increased pool levels. Power to the spillway gates could not be established and the dam overtopped. Lightning struck hydropower facility, turbines shut down. Water rose behind dam while trying to restart. Backup power systems failed, could not raise spillway gates in time	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
14 dams (Barryton, White Cloud, Hart Lake, Danaher Lake, Hesperia, Carson City, Childsdale, Cat Creek, Bruce Nordland)	1986	MI	unknown	overtopping	hydrologic event, upstream dam failure		Total flood damages: $227 million to homes, businesses, public property, roads, bridges and crops in 17 of 22 counties between lakes Michigan and Huron.	0	Belding Dam is one that failed though it didn't occur until January. The investigating engineer stated that the failure was a delayed response to the flooding. This was one of several dams that failed during this flood event	Association of State Dam Safety Officials (www.damsafety.org)
Barryton Dam	1986	MI	earth gravity	overtopping	hydrologic event		unknown	0	This was one of eleven dams that failed during this flood event (see 14 dams - 1986 MI)	http://npdp.stanford.edu/dam_incidents
CEDAR LAKE	1986	OK	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Danaher Lake Dam	1986	MI	earth gravity	overtopping	hydrologic event		unknown	0	This was one of eleven dams that failed during this flood event (see 14 dams - 1986 MI)	http://npdp.stanford.edu/dam_incidents
Hart Lake	1986	MI	earth	overtopping	hydrologic event		unknown	0	This was one of eleven dams that failed during this flood event (see 14 dams - 1986 MI)	http://npdp.stanford.edu/dam_incidents
Hesperia Dam	1986	MI	earth	overtopping	hydrologic event		unknown	0	This was one of eleven dams that failed during this flood event (see 14 dams - 1986 MI)	http://npdp.stanford.edu/dam_incidents
Luther Pond Dam	1986	MI	earth gravity	overtopping	hydrologic event		unknown	0	This was one of eleven dams that failed during this flood event (see 14 dams - 1986 MI)	http://npdp.stanford.edu/dam_incidents

Rainbow Lake Dam	1986	MI	earth	overtopping	hydrologic event		unknown	0	This was one of eleven dams that failed during this flood event (see 14 dams - 1986 MI)	http://npdp.stanford.edu/dam_incidents
SCSUPPER RED ROCK CREEK SITE20	1986	OK	earth	foundation	erosion		unknown	0	The dam failed by internal erosion through the embankment on or about October 3, 1986. The failure occurred along a path approximately 40 feet left of the principal spillway barrel.	http://npdp.stanford.edu/dam_incidents
SIMPSON DAM; ALVIN	1986	ND	earth	breach	hydrologic event, piping		unknown	0	A partial breach of the embankment occurred along the low level drawdown pipe. The breach occurred following a short duration, high intensity storm which dumped from 2.75 to 4.5 inches of rainfall in approximately a 2 hour period. Apparently, seepage and piping were also involved in the dam's failure.	http://npdp.stanford.edu/dam_incidents
TRIAL LAKE	1986	UT	earth	piping	seepage		unknown	0	Evidence of overtopping from warm rain on snow and spillway clogged by snow. The dike apparently failed as a result of deterioration, seepage/piping, and overtopping.	http://npdp.stanford.edu/dam_incidents
White Cloud Dam	1986	MI	earth gravity	overtopping	hydrologic event		unknown	0	This was one of eleven dams that failed during this flood event (see 14 dams - 1986 MI)	http://npdp.stanford.edu/dam_incidents
Tomkins Lake	1987	TN	unknown	overtopping	hydrologic event	30,000	unknown	0		http://npdp.stanford.edu/dam_incidents
Belding	1987	MI	gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Hatfield	1987	WI	earth gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Jay	1987	ME	concrete gravity	overtopping	hydrologic event		unknown	0	Washout of 100 foot section due to flooding.	http://npdp.stanford.edu/dam_incidents
SCSLITTLE WASHITA RIVER SITE13	1987	OK	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Montcoal No.7	1987	WV	earth	unknown	unknown		87,000 cubic meters of water and slurry released	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;

BOG BROOK	1988	WI	unknown	overtopping	hydrologic event, animal	100,000	unknown	0	Beavers plugged the principal outlet, working and washing out the emergency spillway.	http://npdp.stanford.edu/dam_incidents
BISCHEL	1988	WI	unknown	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
MARSCHKE LAKE DAM	1988	MO	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
QUAIL CREEK	1988	UT	earth	piping	seepage		unknown	0	Discolored water was observed flowing around an observation pipe.	http://npdp.stanford.edu/dam_incidents
Wallace Lake Dam	1988	NC	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
WEST DAM AT POTSDAM	1988	NY	gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Tennessee Consolidated No.1	1988	TN	earth	unknown	unknown		250,000 m3 tailings released	0	dam wall failure from internal erosion, caused from failure of an abandoned outlet pipe	http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Riverview	1988	FL	earth	unknown	unknown		acid spill, Thousands of fish killed at mouth of Alafia River.	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Evans and Lockwood Dams	1989	NC	earth	overtopping	hydrologic event, erosion	10,000,000	children died	2		Association of State Dam Safety Officials (www.damsafety.org); http://www.judicial.state.sc.us/opinions/displayOpinion.cfm?caseNo=24732; http://npdp.stanford.edu/dam_incidents
Quail Creek	1989	UT	unknown	foundation	piping, poor construction	12,000,000	$12 million in damages	0	3/7/89 report to Gov. Bangerter concluded that failure cause was the lack of seepage protection of materials placed on the foundation. Design assumption that foundation had very low permeability was incorrect and remedial grouting may have aggravated the problem of seepage water against unprotected foundation materials.	Association of State Dam Safety Officials (www.damsafety.org)
Lake Spaulding No. 3 Auxiliary	1989	CA	concrete arch	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents

NIX LAKE DAM	1989	TX	earth	breach	hydrologic event		unknown	0	A resident adjacent to the dam reported strong winds and noise that sounded like a tornado	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
Point A	1989	AL	earth gravity	overtopping	spillway		unknown	0	Serious leak developed past spillway sluice gate.	http://npdp.stanford.edu/dam_incidents
Stancil	1989	MD	earth	unknown	unknown		38,000 m3 tailings released	0	dam failure during capping of the tailings after heavy rain	http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Kendall Lake Dam	1990	SC	earth	overtopping	hydrologic event		3 children	4	USACE inspected the dam in 1979 and found it to be unsafe.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
Chinook Water District Dam	1990	WA	earth	overtopping	hydrologic event, spillway	100,000	unknown	0	During heavy rains on Thanksgiving weekend, a flood occurred that exceeded the capacity of the project's customized spillway. The embankment was overtopped and the spillway was undermined leading to the failure of the dam.	http://npdp.stanford.edu/dam_incidents
Beaver Pond	1990	VT	earth	overtopping	hydrologic event		unknown	0	The dam was overtopped and failed during a flood event.	http://npdp.stanford.edu/dam_incidents
BREWER GOLD COMPANY DAM 1	1990	SC	earth other fill	unknown	unknown		Failure of this tailings dam introduced cyanide and heavy metals into the Lynches River, which seriously damaged the aquatic life of the river.	0	Failure of this tailings dam introduced cyanide and heavy metals into the Lynches River, which seriously damaged the aquatic life of the river.	http://npdp.stanford.edu/dam_incidents
C. D. Clark Dam	1990	AL	unknown	overtopping	hydrologic event, spillway		Washed out 50 yards of northbound U.S. Highway 29	0	Lake Tholocco, a 600-acre lake on the Fort Rucker reservation near Ozark, was also drained because of excessive flow through its emergency spillway	Association of State Dam Safety Officials (www.damsafety.org)
Chinook dam	1990	WA	unknown	overtopping	hydrologic event, spillway		~$100K damage to facility	0	Heavy rains overtopped embankment & undermined spillway, leading to failure.	Association of State Dam Safety Officials (www.damsafety.org)
HESTER LAKE DAM	1990	MO	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents

Holly Brooke Lake Dam	1990	AL	unknown	overtopping	hydrologic event		6 families evacuated	0	Water level on the 55-acre pond impounded by the dam was lowered	Association of State Dam Safety Officials (www.damsafety.org)
Kingsbury	1990	VT	concrete gravity	breach	hydrologic event		damaged road and power house	0	The dam failed during a flood event for the second time in six years. The dam failed in the early AM hours on June 5, 1990. It breached at the right abutment, washing out a town road and damaging a power house.	http://npdp.stanford.edu/dam_incidents
LAKE CARROLL SEDIMENTATION POND 2 DAM	1990	IL	earth	breach	hydrologic event		unknown	0	The incident was caused by a rainfall/flooding event. Four inches of rain fell. The breach occurred at the same place that was overtopped in March 1990.	http://npdp.stanford.edu/dam_incidents
Lake Lonnie Dam	1990	GA	unknown	unknown	unknown		swept away cars and moved several mobile homes off their foundations (young girl swept under floodwaters; rescued by her Mother)	0	21.6’ height, est. 67AF storage capacity. Midnight failure	Association of State Dam Safety Officials (www.damsafety.org)
Landrum Lake Dam	1990	NC	earth	breach	hydrologic event		road washed out and trailer	0	The failure appears to be due to structural causes during a heavy rainfall.	http://npdp.stanford.edu/dam_incidents
LELAND	1990	WI	earth	overtopping	hydrologic event, breach		unknown	0	The dam failed following a six-inch rain event. The dam was overtopped and breached.	http://npdp.stanford.edu/dam_incidents
Magnolia Shores Lake dam	1990	AL	unknown	controlled breach	hydrologic event		unknown	0	To prevent a break in the dam, a channel was dug around the dam to lower the water and the lake was then drained by a controlled breach of the dam.	Association of State Dam Safety Officials (www.damsafety.org)
Niagara	1990	VA	concrete gravity	unknown	unknown		unknown	0	Failure of wooden timbers covering upstream end of closure opening through base of dam.	http://npdp.stanford.edu/dam_incidents
TIMPERLEY WILDLIFE DAM	1990	NE	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Seminary Hill Reservoir	1991	WA	unknown	foundation	unknown	3,000,000	2 homes destroyed, many homes damaged, $3 million in damage.	0	Failure along weak rock zone in hillside caused massive slide that breached reservoir. 3 M gallons of water released in 3 minutes. No warning.	Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents; Dekay and McClelland 1993

HESTER LAKE DAM	1991	MO	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
KISATCHIE LAKE DAM	1991	LA	earth	breach	hydrologic event, spillway		unknown	0	Dam failed after heavy rains. Breached at concrete spillway structure.	http://npdp.stanford.edu/dam_incidents
LAKE CENTER DAM	1991	TX	earth	unknown	unknown		minor damage	0		http://npdp.stanford.edu/dam_incidents
BILK CREEK RESERVOIR	1992	NV	earth	overtopping	hydrologic event, spillway		damage to farm and ranch land	0	Unusual amounts of precipitation and runoff led to the failure. No damage to the embankment itself; however, the spillway bed was semi-consolidated sandstone and began head cutting and cut back into the reservoir.	http://npdp.stanford.edu/dam_incidents
LA BLONDE	1992	WI	earth	overtopping	hydrologic event, spillway		unknown	0	Debris plugged the principal outlet, working and washing out emergency spillway. The dam washed out in the area of the emergency spillway.	http://npdp.stanford.edu/dam_incidents
WYOMING HEREFORD RANCH NO. 2	1992	WY	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
ISP MINERALS DAM	1992	MO	earth other fill	overtopping	hydrologic event, poor maintenance		The erosion feature on the waste pile was approximately 55 feet high, 50 feet wide at the top, and 20 feet wide at the base. It is estimated that 6000 to 8000 tons of material eroded from the pile. Approximately half of the material was transported to Big Creek.	0	The pipe between the second and third settling ponds became clogged during the night of 6/3-4/92. Water was entering the pond at the rate of 400 gallons per minute. The water filled the pond and overtopped the berm on the north side of the waste pile and flowed down the 50 to 60 foot high slope. The water and waste material was temporarily stored behind a rock dike between the pile and Big Creek. Eventually, the water overtopped the dike and flowed into Big Creek. Rainfall may have contributed to the failure, but ISP's operational procedure was the primary cause.	http://npdp.stanford.edu/dam_incidents

Iowa Beef Processors Waste Pond No.1	1993	WA	earth	breach	hydrologic event, spillway	5,000,000	releasing 300 acre-feet of wastewater	0	Melting of record snowpack filled the animal waste pond and overtopped the earthen embankment. The lack of an emergency spillway combined with large numbers of animal burrows were also factors in the breaching of the dam. Failure of 15-ft high embankment releasing 300 acre-feet of wastewater.attributed to heavy snowmelt entering animal burrows near embankment crest, and eroding dam.	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
BRIGGSVILLE	1993	WI	earth	poor construction	unknown	300,000	unknown	0		http://npdp.stanford.edu/dam_incidents
ROCK	1993	WI	earth	overtopping	hydrologic event, breach	250,000	road damage	0	A flood overtopped the dam and a roadway downstream. The dam was breached.	http://npdp.stanford.edu/dam_incidents
CAMBRIA	1993	WI	earth gravity	overtopping	hydrologic event, gate	200,000	unknown	0	The dam failed as a result of a failure to operate the gates during a flood.	http://npdp.stanford.edu/dam_incidents
Annapolis Mall SWM Pond	1993	MD	earth	piping	hydrologic event, spillway		unknown	0	The dam failed during a storm event. Complete failure of the dam was likely due to piping of embankment fill from along the large corrugated steel pipe spillway conduit.	http://npdp.stanford.edu/dam_incidents
Bean Blossom Lake	1993	IN	earth	unknown	unknown		unknown	0	Earthen dam failed under the pressure of heavy rains. Water from the 17-acre lake flowed over Anderson Road and forced one man to leave his home.	Association of State Dam Safety Officials (www.damsafety.org)
Bend Hydro (MirrorPond)	1993	OR	other	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
BOCKELMAN LAKE DAM	1993	MO	earth	breach	hydrologic event		property damage	0	The embankment was completely breached, and the creek was flowing through the structure.	http://npdp.stanford.edu/dam_incidents
FAIRCHILD	1993	WI	gravity	overtopping	hydrologic event		unknown	0	A minor flood caused the embankment to be overtopped.	http://npdp.stanford.edu/dam_incidents
FREDDIES LAKE DAM	1993	MO	earth	overtopping	hydrologic event		unknown	0		http://npdp.stanford.edu/dam_incidents

Hatfield	1993	WI	earth gravity	overtopping	hydrologic event		unknown	0	Heavy rains on Friday, June 18 and Saturday, June 19 caused significant flooding on the Black River on Sunday, June 20, 1993. This was a one hundred plus year flood event. Late Sunday morning, a portion of the embankment on the power canal between Hatfield and Black River Falls failed.	http://npdp.stanford.edu/dam_incidents
PARTRIDGE LAKE	1993	WI	earth	poor construction	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Stanislaus Forebay West	1993	CA	earth rockfill	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
STEVENS LAKE DAM	1993	MO	earth	overtopping	hydrologic event		unknown	0	The dam overtopped and completely failed, draining the lake in approximately one hour and forty minutes. When the dam failed, there was 11.5 inches of precipitation within the previous 18 hours. The rain had finally ceased 2 hours before the dam failed. At the time of the failure, the upstream end of the lake was receiving water that was flowing overland at depths to 8 feet.	http://npdp.stanford.edu/dam_incidents
Treasure Lake	1993	KY	unknown	overtopping	hydrologic event		residents of 5 houses stranded; large sections of 2 roads, underground phone lines, trees washed out	0	32’-high dam, 15-acre lake 30’ x 10’ section collapsed (Hassert, Ky Post, 1/07)	Association of State Dam Safety Officials (www.damsafety.org)
WEST FORK OF BIG CREEK C1 DAM	1993	MO	earth	overtopping	hydrologic event		unknown	0	The embankment overtopped and failed sometime during January 3-4, 1993.	http://npdp.stanford.edu/dam_incidents
Gibsonton	1993	FL	earth	unknown	unknown		Fish killed when acidic water spilled into Archie Creek	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
ARROWHEAD LAKE	1994	PA	earth	poor construction	unknown	325,000	unknown	0		http://npdp.stanford.edu/dam_incidents
ABLE ACRES LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents

ANDREWS LAKE DAM	1994	GA	unknown	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
BARNESVILLE RESERVIOR DAM	1994	GA	earth	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
BROWNS MILLPOND LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
Buck	1994	VA	concrete gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
CADE LAKE NUMBER 3 DAM	1994	TX	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
CARDINAL LAKE DAM	1994	GA	unknown	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
CLOUD LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
COFFIN LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
Crisp County (Warwick)	1994	GA	earth gravity	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
ELEVA ROLLER MILL	1994	WI	gravity	piping	biological growth		unknown	0	Massive tree stump roots caused piping failure.	http://npdp.stanford.edu/dam_incidents
ESPERANZA FARMS LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
Faraday Diversion	1994	OR	concrete gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
FISHPOND	1994	PA	earth	breach	spillway		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
FLAT CREEK LAKE DAM	1994	GA	earth	breach	spillway		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
Flint River	1994	GA	earth gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
GARANT LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	The dam breached as a result of heavy rains and flooding.	http://npdp.stanford.edu/dam_incidents
GOMULAK AND PROFITT	1994	WI	earth	breach	hydrologic event, spillway		unknown	0	A flood caused full breach at emergency spillway.	http://npdp.stanford.edu/dam_incidents
GOOSE LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
HARPER LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents

HOLOKA LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
HORSEHEAD CREEK LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
HORTMANS POND DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
HOUSTON LAKE DAM	1994	GA	earth gravity	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
KENNEDY LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
KERSEY LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
Ladysmith	1994	WI	timber crib	overtopping	hydrologic event, breach		unknown	0	The abutment (and embankment) breached due to an extreme flood (greater than 100 year) event that caused overtopping and erosion. Rainfall in the area was between 10 and 17 inches.	http://npdp.stanford.edu/dam_incidents
LAKE CLOPINE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
LAKE TINKLE DAM	1994	TX	earth	unknown	unknown		none	0		http://npdp.stanford.edu/dam_incidents
LAKE YOHOLA DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
LIES LAKE DAM	1994	GA	unknown	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
LOCH HIGHLAND LAKE (LOWER)	1994	GA	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
LUCY GILES DAM	1994	GA	unknown	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
MCGILL LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
MCKEMIE LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
MCKEMIE LAKE NORTH DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
MCKNIGHT LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents

MERRITT LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
Morris Sheppard	1994	TX	other buttress	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
MOSSY LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
Muckafoonee Creek Dam	1994	GA	earth gravity	breach	hydrologic event, erosion		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
MULKEY LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
PACE LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
PACE LAKE DAM SOUTH	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
PHILLIPS POND DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
REEVES LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
SAXEGOTHA MILLPOND DAM	1994	SC	unknown	overtopping	hydrologic event, gate		unknown	0	The owner of the dam (new owner since last inspection) was apparently unaware that he needed to open the dam's gates to pass floodwaters.	http://npdp.stanford.edu/dam_incidents
SCNONAME 32028	1994	SC	earth	overtopping	hydrologic event, upstream dam failure		unknown	0	Approximately 5.5 inches of rain fell in the dam's watershed. Two upstream dams failed in succession early in the morning on 6/28/94. Flood waters from those failures overtopped and failed Lake Pauline Dam at approximately 5:30 AM on June 28, 1994.	http://npdp.stanford.edu/dam_incidents
SHELLHOUSE LAKE DAM	1994	GA	unknown	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
Sherry Lake Dam	1994	WA	timber crib	overtopping	hydrologic event		unknown	0	Timber crib dam failed due to overtopping.	http://npdp.stanford.edu/dam_incidents
SHIPP LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
SILBERMAN LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
STATHAM LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
THARPE LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents

WHATLEY LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
WHITEWATER CREEK LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
WILKINSON LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
WOLHWENDER LAKE DAM	1994	GA	unknown	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
YARA LAKE DAM	1994	GA	earth	breach	hydrologic event		unknown	0	Dam breached.	http://npdp.stanford.edu/dam_incidents
Hopewell Mine	1994	FL	earth	unknown	unknown		Nearly 1.9 million m3 of water from a clay settling pond	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Payne Creek Mine	1994	FL	earth	unknown	unknown		6.8 million m3 of water from a clay settling pond	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Fort Meade	1994	FL	earth	unknown	unknown		76,000 m3 of water released	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
IMC-Agrico	1994	FL	earth	unknown	unknown		Release of gypsum and water into groundwater	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Timberlake Dam	1995	VA	earth	overtopping	hydrologic event		unknown	2		Association of State Dam Safety Officials (www.damsafety.org); http://npdp.stanford.edu/dam_incidents
APPERT LAKE DAM	1995	ND	earth	overtopping	hydrologic event, seepage		unknown	0	A series of rains preceded a one-half inch rain on Saturday, July 15, 1995. These rains kept the dam near full and allowed seepage to soften the embankment. The rain on July 15 was enough so that the embankment was finally overtopped near its lowest point, the tallest area of the embankment, and it gave way.	http://npdp.stanford.edu/dam_incidents

Barnes Dam	1995	MI	earth	overtopping	hydrologic event		unknown	0	The owner of the dam reported an intense flood of 11 inches of rain in 5 hours (1% chance, 24 hour rainfall [design storm] is approximately 4.8 inches). The dam failed as a result.	http://npdp.stanford.edu/dam_incidents
BOYD RESERVOIR	1995	NV	earth	piping	hydrologic event, breach		unknown	0	Failure as a result of piping through the earthen embankment. Apparently, rain on snow pack caused the stream inflow to increase to the point where the dam was breached.	http://npdp.stanford.edu/dam_incidents
EUREKA HOLDING POND DIKE	1995	MT	earth	overtopping	hydrologic event		unknown	0	On the night of June 8, 1995, with the storage pond at a level of approximately one foot above the normal high water elevation, a significant thunderstorm event was experienced in the Eureka area.	http://npdp.stanford.edu/dam_incidents
Folsom Dam Gate Failure	1995	CA	unknown	unknown	unknown		Minor damage to dam & spillway	0		Association of State Dam Safety Officials (www.damsafety.org)
FRENCHMAN CREEK	1995	CO	earth	piping	spillway		unknown	0	The spillway foundation failed due to piping. A sinkhole also developed in the right abutment.	http://npdp.stanford.edu/dam_incidents
HAZEL LAKE	1995	WI	earth	poor construction	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
LAKE GARY DAM	1995	MS	earth	spillway	upstream dam failure		unknown	0	Flows from the upper lake caused a spillway failure of the lower lake.	http://npdp.stanford.edu/dam_incidents
Lake Lynn Dam	1995	NC	earth	overtopping	hydrologic event		unknown	0	The dam failed during heavy rains on June 19, 1995.	http://npdp.stanford.edu/dam_incidents
LAKEWOOD VILLAGES DAM	1995	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Moose Lodge Dam	1995	NC	earth	overtopping	hydrologic event		unknown	0	This dam failed as a result of heavy rains on June 19, 1995.	http://npdp.stanford.edu/dam_incidents
MOUNT MORRIS	1995	WI	earth gravity	overtopping	hydrologic event		unknown	0	13 inches of rain had fallen on the Wautoma area, including Mt. Morris. The area experienced persistent rains over a two week period. The dam was drawn down about 1 1/2 feet prior to the event. The dam was undergoing reconstruction at the time of	http://npdp.stanford.edu/dam_incidents

									the incident. The cofferdam was in use.	
Oceanview Farms Waste Lagoon	1995	NC	unknown	unknown	unknown		22-25 million gallons of hog waste spilled into tributaries of New River; millions of fish killed; coastal wetland contaminated & closed to shell-fishing	0		Association of State Dam Safety Officials (www.damsafety.org)
Timber Lake Dam	1995	VA	earth	overtopping	hydrologic event, breach		unknown	0	The dam breached due to overtopping during the evening/night of June 22, 1995. Heavy rains were reported as high as 13 inches.	http://npdp.stanford.edu/dam_incidents
TROY	1995	ID	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Walker Mill	1995	TN	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Ware Shoals	1995	SC	gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Wolcott Pond	1995	VT	earth	overtopping	hydrologic event		unknown	0	The dam failed during a flood event.	http://npdp.stanford.edu/dam_incidents
Meadow Pond (or Bergeron Pond) Dam	1996	NH	concrete	unknown	unknown	8,000,000	unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
AURORA WEST DAM	1996	IL	gravity	overtopping	hydrologic event		unknown	0	This is one of many dams that were affected by the 1996 flood event/record rainstorm.	http://npdp.stanford.edu/dam_incidents
Boeing Creek North Stormwater Pond	1996	WA	earth	overtopping	hydrologic event, spillway		unknown	0	Three heavy snowfalls followed by heavy rain and warming temperatures caused the failure of utilities at NW 175th and 6th NW, resulting in a collapse of the intersection.	http://npdp.stanford.edu/dam_incidents
BROOKVILLE WATERWORKS	1996	PA	earth	overtopping	hydrologic event, breach		unknown	0	Embankment erosion and breach of dam caused by four feet of overtopping during area wide flooding.	http://npdp.stanford.edu/dam_incidents
Bruceton Mills Dam	1996	WV	concrete masonry	overtopping	hydrologic event		unknown	0	The dam was completely overtopped during a snowmelt event.	http://npdp.stanford.edu/dam_incidents

CANYON LAKE	1996	MT	earth	overtopping	hydrologic event		unknown	0	The dam was overtopped during snow melt from the mountains.	http://npdp.stanford.edu/dam_incidents
CASA MONTE DAM	1996	TX	unknown	breach	hydrologic event, undermining		unknown	0	Breach of dam due to a combination of overtopping and undermining during flood conditions.	http://npdp.stanford.edu/dam_incidents
CRANBERRY CREEK	1996	WI	earth	piping	hydrologic event		unknown	0	Apparent piping failure at CMP outlet during high flows due to snowpack melt and rains.	http://npdp.stanford.edu/dam_incidents
Highland Lake Dam	1996	ME	concrete	overtopping	hydrologic event		unknown	0	The dam failed in conjunction with a 20 inch rain event.	http://npdp.stanford.edu/dam_incidents
MALLARD LAKE	1996	TN	earth	piping	animal		unknown	0	The dam was covered in kudzu, which initially made it difficult to determine the exact cause of failure. The failure is believed to be due to piping from animal activity under the kudzu or instability, or a combination of both.	http://npdp.stanford.edu/dam_incidents
Nine Mile	1996	WA	concrete gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
ROBERTS TANK DAM	1996	TX	earth	overtopping	hydrologic event		unknown	0	The dam failed during a 2-inch rainfall event.	http://npdp.stanford.edu/dam_incidents
VERNON MARSHREF. FLOWAGE	1996	WI	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
10 dams, including Charmaine, Galahad, Tristan, Urland	1997	TX	unknown	overtopping	hydrologic event		unknown	0	35 dams have failed in TX in the past 10 years. In the past year, 10 dams collapsed near Woodville, 2 failed in the Nueces River watershed.	Association of State Dam Safety Officials (www.damsafety.org)
East Head Pond Dam	1997	MA	earth gravity	poor maintenance	piping		unknown	0	The dam failed, apparently due to deterioration, seepage, or piping.	http://npdp.stanford.edu/dam_incidents
FORSYTH RESERVOIR	1997	GA	earth	breach	hydrologic event, spillway		unknown	0	During heavy rains, the reservoir refilled and the concrete shell spillway activated. The shell was undermined and collapsed. This was a partial breach of the dam.	http://npdp.stanford.edu/dam_incidents
Hamilton Dam	1997	MI	earth gravity	breach	hydrologic event		unknown	0	Precipitation estimates of 5 to 8 inches of rain in 5 hours over the basin. The right abutment breached.	http://npdp.stanford.edu/dam_incidents

HOLLAND DAM SITE A	1997	TX	other buttress	poor maintenance	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
JOHNSON CREEK # 4	1997	TN	earth	overtopping	hydrologic event		unknown	0		http://npdp.stanford.edu/dam_incidents
LAKE VENITA DAM	1997	MO	earth	piping	breach		unknown	0	The breach grew in size over the next hour and the majority of the water in the lake had drained out by the end of the day.	http://npdp.stanford.edu/dam_incidents
Lava Cap Mine tailings dam	1997	CA	unknown	overtopping	spillway, debris		Failure released 10,000 y3 of arsenic-tainted tailings into Little Clipper Creek & Lost Lake	0	Failure released 10,000 y3 of arsenic-tainted tailings into Little Clipper Creek & Lost Lake	Association of State Dam Safety Officials (www.damsafety.org)
Moss Mill Lake Dam	1997	NJ	earth gravity	overtopping	hydrologic event		unknown	0	Significant rain fell over parts of Cape May and Atlantic Counties with a maximum recorded rainfall of 13.52 inches at the Atlantic City Airport.	http://npdp.stanford.edu/dam_incidents
SCNONAME 02021	1997	SC	earth	overtopping	hydrologic event, upstream dam failure		unknown	0	The riser on a dam upstream (Edisto Lake Dam; SC00361) unexpectedly failed and released all of its impounded water through the barrel. The released water caused the overtopping and breaching of another dam (Brown's Pond Dam; SC00377). Water from both dams then traveled downstream and caused overtopping and breaching of dam this dam.	http://npdp.stanford.edu/dam_incidents
SCNONAME 02109	1997	SC	earth	overtopping	hydrologic event, upstream dam failure		unknown	0	The riser on a dam immediately upstream (Edisto Lake Dam; SC00361) unexpectedly collapsed and released all its impounded water through the barrel. The released water caused the overtopping and breaching of this dam.	http://npdp.stanford.edu/dam_incidents
Udall	1997	AZ	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Wishkah Reservoir No. 2 Dam	1997	WA	timber crib	overtopping	hydrologic event, piping		unknown	0	Failed during a record rainfall event.	http://npdp.stanford.edu/dam_incidents

WOODRUFF (BREACHED 1997)	1997	SD	earth	breach	hydrologic event, spillway		unknown	0	Spring flooding due to record snowfall resulted in the breach of the dam through the primary spillway.	http://npdp.stanford.edu/dam_incidents
Mulberry Phosphate	1997	FL	earth	unknown	unknown		200,000 m3 of phosphogypsum process water released, biota in the Alafia River eliminated.	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Pinto Valley	1997	AZ	earth	unknown	unknown		230,000 m3 of tailings and mine rock released.	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
California Jim’s Pond dam	1998	RI	unknown	unknown	unknown	650,000	Roads washed away, village flooded; ~ $250,000 to rebuild dam; ~ $400,000 damages – incl. $325,000 to town property	0	Failure prompted development of the statewide regulations effected 12/07.	Association of State Dam Safety Officials (www.damsafety.org)
ARCHUSA CREEK WATER PARK LAKE DAM	1998	MS	earth	breach	hydrologic event, spillway		unknown	0	Flows through the emergency spillway during a heavy rain event caused the spillway to erode. Headcutting in the emergency spillway eroded back through the spillway and the dam, resulting in a dam breach and complete draining of the lake.	http://npdp.stanford.edu/dam_incidents
BIG SANDY PLANTATION, INC. LAKE DAM	1998	GA	earth	overtopping	hydrologic event, poor maintenance		unknown	0	A heavy micro rain event coupled with the lack of maintenance (deteriorated condition of the dam) led to the failure of the dam.	http://npdp.stanford.edu/dam_incidents
CAMP WEONA DAM	1998	NY	earth	breach	hydrologic event		unknown	0	A short duration, high intensity storm caused the dam to be overtopped, resulting in a full depth breach.	http://npdp.stanford.edu/dam_incidents
CARL SMITH	1998	CO	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Gouldtown Mill 5 West Channel	1998	NY	concrete gravity	overtopping	hydrologic event		unknown	0	Built-up ice was released and went over a retaining wall at the West Dam and through the concrete block east and west walls of the powerhouse. Heavy, state wide rains occurred.	http://npdp.stanford.edu/dam_incidents

HEMATITE LAKE DAM	1998	KY	earth	piping	breach		unknown	0	The failure is believed to be due to piping. The dam was breached, with damage only to the earthen dam itself.	http://npdp.stanford.edu /dam_incidents
JAN LAND COMPANY LAKE NO 1 DAM	1998	TX	earth	breach	hydrologic event		unknown	0	Reportedly, the dam breached during an October 1998 regional flood event.	http://npdp.stanford.edu /dam_incidents
Lake Runnemede	1998	VT	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
LITTLE OCMULGEE LAKE DAM	1998	GA	concrete	overtopping	foundation		unknown	0	The dam overtopped over its entire length. It failed at the left abutment.	http://npdp.stanford.edu /dam_incidents
NEW SHOAL CREEK	1998	TN	earth	overtopping	hydrologic event		unknown	0	The dam was overtopped and subsequently failed due to heavy rains on July 13, 1998.	http://npdp.stanford.edu /dam_incidents
PEACE DALE POND	1998	RI	earth rockfill	overtopping	hydrologic event		unknown	0	This earthen dam failed as a result of heavy rains (three inches in three hours).	http://npdp.stanford.edu /dam_incidents
Ramseur	1998	NC	masonry	overtopping	hydrologic event		unknown	0	The owner of the dam indicated that the dam was overtopped with about 6 feet of flood water prior to the failure of about 60 feet of the left end of the dam.	http://npdp.stanford.edu /dam_incidents
Sunset Lake	1998	VT	earth masonry	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
Talcville	1998	NY	concrete gravity	overtopping	hydrologic event		none	0	A combined ice storm and high flood event on the Oswegatchie River after heavy continuous rainfall with mild temperatures resulted in river flows washing out the left and right dam abutments of this project. Reservoir status: Overtopped riverbank elevation above 633.0 feet. Ice laden high river flows caused erosion of the immediate left and right dam abutments.	http://npdp.stanford.edu /dam_incidents
Allens Mill Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu /dam_incidents
Bostwicks Pond Dam	1999	NJ	earth gravity	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu /dam_incidents
Cabin Creek Mill Dam	1999	MD	unknown	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu /dam_incidents

CHRISTIANSEN LAKE DAM	1999	MO	earth	poor maintenance	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
COVEY DAM (BREACHED 05/09/99)	1999	SD	earth	overtopping	hydrologic event		unknown	0	Covey dam overtopped and failed during a thunderstorm on May 9, 1999. The reports vary, but up to 7 inches of rain was reported in the immediate area.	http://npdp.stanford.edu/dam_incidents
Cow Creek Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Dubose Lake Dam	1999	NC	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Essex Mill Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Foreman Branch Dam	1999	MD	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Frazers Dam	1999	MD	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Haines Pond Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Hall Lake Dam	1999	NC	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
High Falls	1999	NY	concrete gravity	overtopping	hydrologic event, spillway		unknown	0	It was reported that the Deer River area sustained a heavy rainstorm over the weekend of November 27 and 28, 1999, resulting in a flash flood at the project site. Flows were passing over the top of the spillway during the Thanksgiving weekend.	http://npdp.stanford.edu/dam_incidents
Jones Lake Dam	1999	MD	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Kellys Pond Dam	1999	NC	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Lake Bray Dam	1999	MA	earth gravity	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Lake Lanahan	1999	MD	earth	overtopping	hydrologic event, erosion		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Lake Powell Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Lookover Lake Dam	1999	NJ	earth gravity	unknown	unknown		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents

Lower Rosegill Lake Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Murphy Family Farms Hog Waste Lagoon	1999	NC	unknown	piping	seepage, poor maintenance		1.5 million gallons of hog waste spilled into wetlands and a tributary to the Cape Fear River.	0	Owner fined $40,650 for breach. Excessive seepage, site left unattended while transfer pumps running	Association of State Dam Safety Officials (www.damsafety.org)
Nagels Mill Pond	1999	MD	earth	overtopping	hydrologic event, piping		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Old Forge Pond Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
PITTSFIELD DREDGE DISPOSAL POND DAM	1999	IL	earth	piping	seepage		unknown	0	The dam failed along a conduit placed in a foundation trench. The failure and dewatering apparently occurred in less than two hours. The failure was due to seepage/piping.	http://npdp.stanford.edu/dam_incidents
POST LAKE DAM	1999	SD	earth	overtopping	hydrologic event		unknown	0	Post Lake Dam overtopped and failed on September 3, 1999, when the area received 7 to 10 inches of rain.	http://npdp.stanford.edu/dam_incidents
Quaker Mills dam	1999	IA	unknown	unknown	unknown		About 200 people evacuated from Manchester	0	Private dam impounding 62-acre lake did not fail.	Association of State Dam Safety Officials (www.damsafety.org)
Riley Mill Pond	1999	MD	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Rolling Green Community Pond	1999	MD	unknown	overtopping	spillway		unknown	0	Corrugated metal pipe spillway collapsed and caused partial release of reservoir.	http://npdp.stanford.edu/dam_incidents
Rosegill Upper Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Sassafras Mill Dam	1999	MD	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Sydnors Millpond Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
TIMPERLEY WILDLIFE DAM	1999	NE	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Town Bridge Pond Dam	1999	VA	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Tuckahoe State Park Dam	1999	MD	earth	overtopping	hydrologic event		unknown	0	Hurricane Floyd	http://npdp.stanford.edu/dam_incidents
Volga dam	1999	IA	unknown	overtopping	hydrologic event		Littleport, Iowa inundated when	0	Source: “Residents of town destroyed by flood three years ago revisit” AP 5/20/2002	Association of State Dam Safety Officials (www.damsafety.org)

							upstream dam at Volga broke during the night.			
Winkler Lake Dam Lower	1999	NC	earth	seepage	spillway		unknown	0	The dam failed at 3:00am on April 20, 1999 due to seepage along the outlet pipe.	http://npdp.stanford.edu/dam_incidents
GRAND FORKS CO. COM. #1	2000	ND	earth	overtopping	hydrologic event		unknown	2	A large rainfall event started on June 12, 2000 in northeast North Dakota. Some areas of Grand Forks County received over 12 inches of rain in 24 hours. The flood upstream of this dam was likely greater than a 100-year flood.	http://npdp.stanford.edu/dam_incidents
ASCALMORE STRUCTURE Y17A11 DAM	2000	MS	earth	unknown	unknown		unknown	0	Beavers	http://npdp.stanford.edu/dam_incidents
CAMP LA JUNTA DAM	2000	TX	concrete gravity	breach	hydrologic event		unknown	0	The dam breached due to the heavy rains on October 23, 2000. The middle third was washed out completely.	http://npdp.stanford.edu/dam_incidents
LAKE PARK DAM	2000	MS	earth	piping	biological growth		unknown	0	The dam was in an overall poor condition due to vegetation and animal activity.	http://npdp.stanford.edu/dam_incidents
Massey Energy coal waste impoundmentt	2000	KY	unknown	unknown	unknown		>300 M gals of slurry released into the Big Sandy and Ohio rivers.	0	collapsed into mineshaft	Association of State Dam Safety Officials (www.damsafety.org)
MOSS CREEK LAKE DAM	2000	TX	earth	breach	hydrologic event, spillway		unknown	0	Spillway and levee damage due to the March 22-23, 2000 flood event. Not sure if the dam breached. Deterioration and seepage/piping also involved. Area rainfall on March 22 and 23, 2000: 5 to 6+ inches.	http://npdp.stanford.edu/dam_incidents
MOUNTAIN LAKE DAM	2000	NH	earth	poor construction	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
POWELL LAKE DAM	2000	TX	earth	breach	hydrologic event, piping		unknown	0	The dam breached due to the March 22-23 flood event. Deterioration and seepage/piping also involved. Area rainfall on March 22 and 23, 2000: 5 to 6+ inches.	http://npdp.stanford.edu/dam_incidents

Seneca Lake Dam	2000	NJ	earth gravity	breach	hydrologic event		unknown	0	A total of four dams completely failed as a result of the ensuing floods. The dam was inspected on August 14, 2000, following the flood event. A complete failure of the earthen embankment. There was a 50 foot wide breach directly over the location of the low level outlet.	http://npdp.stanford.edu/dam_incidents
Tomahawk Lake Dam	2000	NJ	earth gravity	breach	hydrologic event, erosion		unknown	0	A total of four dams completely failed as a result of the ensuing floods. The dam was inspected on August 14, 2000, following the flood event. A complete failure of the earthen dam's embankment. There was an approximate 30 foot wide breach adjacent to the low level outlet pipe.	http://npdp.stanford.edu/dam_incidents
Inez	2000	KY	earth	unknown	unknown		250 million gallons (950,000 m3) of coal waste slurry released into local streams, About 75 miles (120 km) of rivers and streams turned an iridescent black, causing a fish kill along the Tug Fork of the Big Sandy River and some of its tributaries. Towns along the Tug were forced to turn off their drinking water intakes.	0	tailings dam failure from collapse of an underground mine beneath the slurry impoundment	http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Hearns Pond Dam	2001	DE	unknown	overtopping	hydrologic event	500,000	$500,000. 60-acre impoundment drained, washout of U.S. 13A near Seaford, Delaware.	0		Association of State Dam Safety Officials (www.damsafety.org)

MARSH LAKE DAM	2001	MN	concrete earth	overtopping	hydrologic event, ice	400,000	emergency repair estimated at $400,000 plus costs of contingency actions at two urban locations downstream (amount unknown)	0	Winds estimated at 50 mph pushed reservoir ice sheets into dam during high water event, causing loss of embankment material. Ice push followed by erosion from large waves overtopping the embankment. Short terms costs consisted of emergency repair estimated at $400,000 plus costs of contingency actions at two urban locations downstream (amount unknown).	http://npdp.stanford.edu/dam_incidents
FRANCIS GALLOWAY LAKE DAM	2001	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Mill Pond Dam	2001	MA	earth	overtopping	hydrologic event, ice		none	0	Winds estimated at 50 mph pushed reservoir ice sheets into dam during high water event, causing loss of embankment material. Ice push followed by erosion from large waves overtopping the embankment. The earthen embankment eroded sufficiently for the reservoir to overtop the embankment in several locations.	http://npdp.stanford.edu/dam_incidents
PRITCHARD LAKE DAM	2001	GA	earth	overtopping	spillway		unknown	0	The principal spillway pipe separated at a joint, causing the pipe and a large chunk of the center downstream slope and crest to slide, fall, and wash away.	http://npdp.stanford.edu/dam_incidents
Windy Hills Lake dam	2002	MS	unknown	overtopping	hydrologic event		unknown	1	*3/03: Man died after driving around a barricade placed around a washout from the failure.	Association of State Dam Safety Officials (www.damsafety.org)
Chatmoss Country Club dam	2002	VA	unknown	overtopping	hydrologic event	10,000	$10,000 spent on emergency repairs	0	Notch cut in dam to prevent failure.	Association of State Dam Safety Officials (www.damsafety.org)
BIG SAND WATERSHED STRUCTURE Y3232 DAM	2002	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
DIXIE SPRINGS	2002	MS	earth	overtopping	hydrologic event		unknown	0	The dam failed due to overtopping during a major storm event.	http://npdp.stanford.edu/dam_incidents

REFUGE LAKE DAM										
EAST MISSISSIPPI STATE HOSPITAL LAKE DAM	2002	MS	earth	poor maintenance	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Pine Lake Dam	2002	GA	unknown	unknown	unknown		1 family evacuated; 8 other homeowners put on evacuation alert	0	Near failure of 35-foot earthen dam impounding 15-acre Pine Lake. Dam's ownership unclear, county sought repair estimate in 2001; balked at $885,000 quote.	Association of State Dam Safety Officials (www.damsafety.org)
ROYAL OAKS DAM	2002	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Smith River Log Pond #2	2002	OR	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Tomkins Lake	2002	TN	unknown	overtopping	spillway		unknown	0	The cause of the overtopping was due to inadequate spillway capacity after a timber company constructed a logging road over the spillway channel to have access to the area.	http://npdp.stanford.edu/dam_incidents
WINDY HILL LOWER LAKE DAM	2002	MS	earth	spillway	hydrologic event, poor maintenance		unknown	0	Concrete chute emergency spillway with riser & conduit primary. Conduit was located under the concrete chute of the emergency spillway. Both failed during a major rain event. Both were in poor condition prior to failure.	http://npdp.stanford.edu/dam_incidents
Silver Lake Dike 1	2003	MI	earth gravity	overtopping	hydrologic event	102,000,000	$102 M, incl $127,000 in emergency/ public safety, $3 M in roads/ bridges, $10.4 M in utilities, $4 M fisheries, soils & trees & $84 M in economic loss	0		http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
Hope Mills Dam #1	2003	NC	concrete gravity	cracking	hydrologic event, erosion	2,100,000	est. $2.1 M damages; 1600 evacuated; estimated cost of rebuilding dam: $6M	0	The dam failed following a rainfall of 6 to 8 inches in the area. Much of the rain fell within a 3 hour period. Prior to its failure, the dam was scheduled to have minor repair work done on cracks and areas of erosion.	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)

Lake Upchurch and McLaughlin Lake Dams	2003	NC	unknown	unknown	unknown	350,000	Lake Upchurch dam reconstruction costs estimated at more than $350,000.	0	4 additional dams damaged; another 16 overtopped during rainfall event (4-6” in less than 24 hrs)	Association of State Dam Safety Officials (www.damsafety.org)
Rumph's Pond dam	2003	SC	unknown	unknown	unknown	144,000	Minimal: $400-$500 estimated damage to Norfolk Southern Railway property; about $144,000 in damages to the dam and a nearby cornfield (unofficial est.)	0		Association of State Dam Safety Officials (www.damsafety.org)
LAKE FOREST DAM	2003	MS	earth	breach	unknown		unknown	0	The riser section separated from the conduit, leading to the loss of the reservoir.	http://npdp.stanford.edu/dam_incidents
Lake Manatee gate failure	2003	FL	unknown	overtopping	gate		2 upstream homes destroyed; 600 homes evacuated	0	Dam did not fail; gate stuck in closed position, causing lake to swell beyond its banks. Diver finally opened gate after numerous unsuccessful attempts.	Association of State Dam Safety Officials (www.damsafety.org)
Marquette No. 3 (Tourist Park)	2003	MI	concrete gravity	overtopping	hydrologic event, upstream dam failure		unknown	0		http://npdp.stanford.edu/dam_incidents
Polk Township dam	2003	PA	unknown	overtopping	hydrologic event		20 homes evacuated	0	Officials also concerned about Twin Lakes Dam in Smithfield Township; nursing home put on alert while the dam was stabilized.	Association of State Dam Safety Officials (www.damsafety.org)
unknown	2003	GA	unknown	overtopping	hydrologic event		No injuries, 6 houses evacuated, 3 trailers damaged.	0		Association of State Dam Safety Officials (www.damsafety.org)
unknown	2003	PA	unknown	overtopping	hydrologic event, upstream dam failure		unknown	0	Up to 200 campers left Yellow Creek Camp Ground after a private dam about three miles upstream overtopped.	Association of State Dam Safety Officials (www.damsafety.org)
Birchwood Lake Dam	2004	NJ	earth gravity	overtopping	hydrologic event	30,000,000	Extensive, >$30 million estimate, 350 homes flooded (see other NJ dams)	0	The dam failed during heavy rains July 13, 2004 several dams failed in NJ	http://npdp.stanford.edu/dam_incidents; Association of State Dam Safety Officials (www.damsafety.org)
Big Bay Lake dam	2004	MS	unknown	unknown	unknown	4,750,000	98 homes, 2 churches, fire station, bridge damaged or destroyed; livestock, pets. SBA estimate: >$2.2 million. $2.5	0	900 -1,100 acre lake; 3.5 billion gallons; quarter-mile-wide flood path extending at least 17 miles downstream	Association of State Dam Safety Officials (www.damsafety.org)

							million dam, > $50K Red Cross			
Lake Powell dam	2004	VA	unknown	unknown	unknown	5,000	$5,000 for emergency repairs	0	Dam had suffered extensive damage from Hurricane Floyd; $55,000 spent on repairs.	Association of State Dam Safety Officials (www.damsafety.org)
2 dams in Powhatan Wildlife Mgmt Area	2004	VA	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Adel Island Park Dam	2004	IA	unknown	overtopping	hydrologic event		unknown	0	“Adel dam weakens after heavy rains” Dallas County News, 5/26/04 Iowa Whitewater Coalition: www.iowawhitewater.org	Association of State Dam Safety Officials (www.damsafety.org)
Backbone State Park dam	2004	IA	unknown	overtopping	hydrologic event		unknown	0	Source: “Campers rescued from flash flooding at Backbone State Park” KCRG-TV9 Dubuque, 5/24/2004	Association of State Dam Safety Officials (www.damsafety.org)
BENNETT YORK LAKE NUMBER 2 DAM	2004	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
BIG BAY LAKE DAM	2004	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
BLUE SPGS PWR PLANT DAM	2004	NE	concrete	overtopping	unknown		unknown	0	A section of the overflow weir, about 40 feet wide, washed out in the middle of the dam.	http://npdp.stanford.edu /dam_incidents
Bohemia Mill Dam/Bridge	2004	MD	unknown	unknown	unknown		unknown	0	Low hazard dam	Association of State Dam Safety Officials (www.damsafety.org)
Callaway Dam	2004	TX	unknown	overtopping	hydrologic event		Unknown	0	Callaway Dam was overtopped by about 1.5’ before it failed. (See next entry.)	Association of State Dam Safety Officials (www.damsafety.org)
CALLAWAY DAM	2004	TX	earth	overtopping	hydrologic event		unknown	0	A rainfall event of approximately 50% of the probable maximum precipitation (PMP) (15 inches in 6 hours) fell in the area. The dam was overtopped by at least 1.3 feet before failing.	http://npdp.stanford.edu /dam_incidents
CARTER POND, UPPER (FERGUS)	2004	MT	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents

Concrete dam on Big Blue River	2004	NE	concrete	overtopping	hydrologic event		unknown	0	Source: “Old dam breaks on Big Blue River” (AP)	Association of State Dam Safety Officials (www.damsafety.org)
East Lake Dam	2004	AL	unknown	overtopping	hydrologic event		unknown	0	270 evacuated due to potential for dam break. Tropical Storm Gaston	Association of State Dam Safety Officials (www.damsafety.org)
Essex Mill Dam	2004	VA	unknown	unknown	unknown		Drained small recreational lake	0		Association of State Dam Safety Officials (www.damsafety.org)
HOOVER CREEK DAM	2004	MT	earth	overtopping	poor maintenance		unknown	0	Complete failure due to clogged fish screen and lack of maintenance. Dam overtopped and eventually breached.	http://npdp.stanford.edu /dam_incidents
Keith Lake dam	2004	AL	earth	overtopping	hydrologic event		Decreased property values, environmental damages, driveways covered with mud, ~20% damage to downstream dam, downstream homes evacuated.	0	Lake ~1200 yards long, 450 yds wide, 40’ deep. 60-70’ earth dam. Downstream homes evacuated. Earth dam. Failure not covered by media.	Association of State Dam Safety Officials (www.damsafety.org)
LAKE DOCKERY DAM	2004	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
Lake Idylwild Dam	2004	VA	unknown	overtopping	hydrologic event, spillway		Minor damage to SR 628.	0	Tropical Storm Gaston dumped 12” rain in 8 hours in watershed. Rainfall from storm exceeded the dam’s spillway capacity.	Association of State Dam Safety Officials (www.damsafety.org)
Lake Stockwell Dam	2004	NJ	earth gravity	overtopping	hydrologic event		Extensive, >$30 million estimate, 350 homes flooded (see other NJ dams)	0	several dams failed in NJ	http://npdp.stanford.edu /dam_incidents
Lake Susan dam	2004	NC	unknown	unknown	unknown		Several homes evacuated	0	Near failure: Collapse of a 35' section of the dam's upstream wall. Residents were allowed to return to their homes after the lake was drawn down to a safe level. The Montreat Conference Center, which owns the 79-year-old dam, had already planned to repair the dam starting in mid-August, and has raised $900,000 toward the effort.	Association of State Dam Safety Officials (www.damsafety.org)
Lebanon Forest #1 Dam	2004	NJ	earth gravity	overtopping	hydrologic event		Extensive, >$30 million estimate, 350 homes flooded (see other NJ dams)	0	several dams failed in NJ	http://npdp.stanford.edu /dam_incidents

Lower Aetna Lake Dam	2004	NJ	earth gravity	overtopping	hydrologic event		Extensive, >$30 million estimate, 350 homes flooded (see other NJ dams)	0	several dams failed in NJ	http://npdp.stanford.edu/dam_incidents
McGuire Dam	2004	TX	unknown	overtopping	hydrologic event		Unknown	0	McGuire Dam is located downstream of Callaway Dam. It was overtopped by at least 3' before failure. The sequence of failure is not known. The stream does not go through Hearne so the flooding in Hearne was not from the failures.	Association of State Dam Safety Officials (www.damsafety.org)
Piedmont Driving Club Dam	2004	GA	unknown	unknown	unknown		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
SHALE CREEK	2004	MT	earth	piping	corrosion		unknown	0	CMP pipe Corroded caused piping which caused the dam to fail.	http://npdp.stanford.edu/dam_incidents
Simmons Dam	2004	PA	unknown	overtopping	hydrologic event		No significant damages, no mandatory evacuations (but some voluntary)	0	No failure, dam overtopped. NWS issued warning that the dam had failed, but later retracted the warning. DEP ordered owner to drain lake & obtain permit for dam improvements; dam meets regulatory criteria, but had not been on state inventory.	Association of State Dam Safety Officials (www.damsafety.org)
Smiths Pond Dam	2004	MA	unknown	overtopping	hydrologic event, spillway		unknown	0	Dam overtopped; spillway clogged by debris. Divers from the Leominster EMA and crane operators worked to clear the spillway.	Association of State Dam Safety Officials (www.damsafety.org)
Timber (York) Lake dam	2004	MS	unknown	poor maintenance	biological growth		unknown	0	improper repair	Association of State Dam Safety Officials (www.damsafety.org)
Timber Lake Dam	2004	NJ	earth gravity	overtopping	hydrologic event		Extensive, >$30 million estimate, 350 homes flooded (see other NJ dams)	0	several dams failed in NJ	http://npdp.stanford.edu/dam_incidents
unknown	2004	AR	earth	overtopping	hydrologic event		At least 5 businesses damaged	0		Association of State Dam Safety Officials (www.damsafety.org)
unknown	2004	TX	unknown	overtopping	hydrologic event		unknown	0	Near failure	Association of State Dam Safety Officials (www.damsafety.org)

unknown	2004	MS	unknown	overtopping	hydrologic event		2 homes flooded, 1 car swept off road	0	Near Anchor Lake subdivision, between Picayune and Poplarville	Association of State Dam Safety Officials (www.damsafety.org)
unknown	2004	VA	unknown	foundation	erosion		none	0	State drains dam after unsuccessful attempt by owner, who had been ordered to do so in January	Association of State Dam Safety Officials (www.damsafety.org)
unknown	2004	VA	unknown	unknown	unknown		Minor damage to SR 301, car swept away	0	Tropical Storm Gaston	Association of State Dam Safety Officials (www.damsafety.org)
Upper Aetna Lake Dam	2004	NJ	earth gravity	overtopping	hydrologic event		Extensive, >$30 million estimate, 350 homes flooded (see other NJ dams)	0	several dams failed in NJ	http://npdp.stanford.edu/dam_incidents
Victor Lake (aka Upper Stinchomb)	2004	GA	unknown	poor maintenance	unknown		approximately 20 trailers received damage; around 20 people rescued by emergency personnel	0	Unregulated dam impounding 15 acre lake failed suddenly and flooded part of a trailer park. Approximately 20 trailers received damage; around 20 people rescued by emergency personnel; Unregulated dam, lack of maintenance, vegetation on embankment	Association of State Dam Safety Officials (www.damsafety.org)
Riverview	2004	FL	earth	overtopping	hydrologic event		60 million gallons (227,000 m3) of acidic liquid released	0	A dike at the top of a 100-foot-high gypsum stack holding 150-million gallons of polluted water broke after waves driven by Hurricane Frances bashed the dike's southwest corner	http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Hadlock Pond dam	2005	NY	unknown	overtopping	hydrologic event, piping	1,000,000	At least 4 homes destroyed, ~12 w/ moderate to severe damage, roads washed out, power outages. > $1M damages.	0	Embk. dam completed 5/2005. 220-acre lake, 12-15’ deep. state Rte 149 closed, major link between upstate NY & VT, Heavy rain, first filling, piping, suspected const. flaw	Association of State Dam Safety Officials (www.damsafety.org)
ALLEN SUBDIVISION LAKE DAM	2005	MS	earth	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
DENNERY LAKE DAM	2005	MS	earth	breach	erosion		unknown	0	Section near center of dam eroded away.	http://npdp.stanford.edu/dam_incidents

Lower Robertson	2005	NH	concrete rockfill	overtopping	hydrologic event		unknown	0	Left abutment had been washed out and high flows were still being experienced at the site. The Exemptee's representative reported that there was no downstream impact as a result of the abutment being washed out.	http://npdp.stanford.edu/dam_incidents
Simplot Wastewater Lagoon #1	2005	OR	unknown	unknown	unknown		Breach of off-channel reservoir resulted in breach of canal, loss of irrigation water, agricultural lands, water/mud damage to farm houses & outbuildings.	0		Association of State Dam Safety Officials (www.damsafety.org)
Taum Sauk	2005	MO	unknown	poor maintenance	unknown		Toops family home demolished; state highway washed out; at least 3 trucks swept from road. Extensive damage to Johnson's Shut-Ins, the East Fork of the Black River and the mountainside.	0	In Nov. 2007 the state reached a $180 million settlement with the utility that owned the reservoir. Suspected instrumentation failure caused water to be pumped into reservoir.	Association of State Dam Safety Officials (www.damsafety.org)
Whittenton Pond Dam	2005	MA	other wooden	unknown	unknown		~2,000 evacuated, including a housing development for the elderly	0	173-year-old wooden dam , ~100’ across, ~12’ high,	Association of State Dam Safety Officials (www.damsafety.org)
Bangs Lake	2005	MS	earth	unknown	unknown		approx. 17 million gallons of acidic liquid (64,350 m3) released. liquid poured into adjacent marsh lands, causing vegetation to die.	0	Phosphogypsum stack failure, because the company was trying to increase the capacity of the pond at a faster rate than normal, according to Officials with the Mississippi Department of Environmental Quality	http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;

Kaloko Reservoir	2006	HI	earth	poor maintenance	hydrologic event, spillway		Destroyed an ocean reef.	7	Poor inspection/maintenance. Privately owned. May have been improper maintenance.	NRC, 2012; Godbey, 2007; http://www.oregon.gov/owrd/SW/docs/dam_safety/M2_Mills_%20Historical_Dam_Failures_and_Modes.pdf; Association of State Dam Safety Officials (www.damsafety.org); http://www.croninfried.com/Articles/Dam-Probe-Faults-Covered-Spillway.shtml; http://the.honoluluadvertiser.com/pdf/kaloko/Kaloko-Report.pdf
Galestown Dam	2006	MD	unknown	unknown	unknown		Roads washed out; dam replacement cost $2.5M	0		Association of State Dam Safety Officials (www.damsafety.org)
Needwood Dam	2006	MD	earth	foundation	hydrologic event, seepage		2200 evacuated for 3 days	0	65’ high, 40-year-old earth dam sprang 7 leaks at toe; lake reached 23’ above flood stage	Association of State Dam Safety Officials (www.damsafety.org)
Raeford Dam and Fuseplug	2006	NC	concrete gravity	breach	hydrologic event, spillway		unknown	0	Rainfall backed up water in the reservoir, causing a breach of the cofferdam protecting the labyrinth spillway.	http://npdp.stanford.edu/dam_incidents
Cole Marsh dam NH01042	2007	NH	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Disrow Pond dam (Inv#810)	2007	CT	unknown	unknown	unknown		unknown	0	Embankment failed near inlet structure. The breach was approximately 12 ft high and 15 ft wide. The dam was designed by NRCS.	Association of State Dam Safety Officials (www.damsafety.org)
Hansonville Pond dam NH01091	2007	NH	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Hayden's Mill Pond Dam NH00504	2007	NH	unknown	controlled breach	hydrologic event		Dam severely damaged. 12 families evacuated. Pond supplied water for fighting fires; replacement will cost 100s of thousands of dollars.	0	Sudden structural failure averted by controlled breach.	Association of State Dam Safety Officials (www.damsafety.org)

Lee's Fishing Lake Dam	2007	WV	unknown	overtopping	hydrologic event		Nearly 1000 evacuated	0	Pond had been drained, then refilled by new owner. 22' high HH dam	Association of State Dam Safety Officials (www.damsafety.org)
McClure	2007	WI	earth gravity	unknown	unknown		none	0		http://npdp.stanford.edu /dam_incidents
Millers Pond dam Inv#15205	2007	CT	unknown	unknown	unknown		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Mossman Dam	2007	NH	unknown	unknown	unknown		Property owners spent ~ $500,000 on cleanup & repairs	0		Association of State Dam Safety Officials (www.damsafety.org)
Nottingham Dam NH00522	2007	NH	unknown	unknown	unknown		"upwards of 1000 evacuated"	0		Association of State Dam Safety Officials (www.damsafety.org)
Oakland	2007	PA	other	unknown	unknown		unknown	0		http://npdp.stanford.edu /dam_incidents
Rainbow Lake Dam	2007	NJ	earth	overtopping	hydrologic event		County roadway washed out; repair will cost "several million" – gas main broken.	0	From NJ Dam Safety: Sun-Mon, 4/15-16, "nor'easter" dumped up to 10" of rain in parts of NJ. Muddy Run watershed. Salem Co, particularly hard hit w/ high flood flows that overflowed and failed Rainbow Lake Dam on SR 56 in Pittsgrove Township. The 20' high earth embankment dam w/ state highway atop impounded an 80 acre lake. Dam owner: NJ DOT.	Association of State Dam Safety Officials (www.damsafety.org)
Rogers Pond Inv# 12702	2007	CT	unknown	foundation	hydrologic event, erosion		unknown	0	Part of the embankment failed; breach area ~ 15 ft deep and 30ft wide.	Association of State Dam Safety Officials (www.damsafety.org)
Spit Brook dam 165.10	2007	NH	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Station 26	2007	NY	concrete gravity	unknown	unknown		none	0		http://npdp.stanford.edu /dam_incidents
Whittle Brook dam 097.03	2007	NH	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)

Truckee Canal	2008	NV	unknown	piping	animal	28,000,000	~600 homes flooded; 2- month loss of agriculture water supply to ~3,000 users; Dozens evacuated by boat & helicopter. Up to 3500 people stranded; at least 165 in shelters. Est. repair/replacement costs: $28 - $390M million	0	Break occurred just after 4am. Dozens evacuated by boat & helicopter. Up to 3500 people stranded; at least 165 in shelters. Est. repair/replacement costs: $28 - $390M million	Association of State Dam Safety Officials (www.damsafety.org)
Breedsville Dam	2008	MI	unknown	overtopping	hydrologic event		Flooded park	0	Break in earthen part of Black River dam built in 1837; dam impounded 8-acre pond.	Association of State Dam Safety Officials (www.damsafety.org)
Earlham Lake Dam	2008	IN	unknown	overtopping	hydrologic event, spillway		Callon Road washed out, eliminating road access to 78 homes for 5 days.	0	Three others were damaged by June floods, >10" rain overwhelmed spillways previously termed inadequate by the state. (3) East Lake Dam in Johnson County	Association of State Dam Safety Officials (www.damsafety.org)
East Lake Dam	2008	IN	unknown	overtopping	hydrologic event		100 homes damaged, road access to ~120 homes cut off; dam severely damaged	0		Association of State Dam Safety Officials (www.damsafety.org)
Graybrook Dam	2008	IN	unknown	overtopping	hydrologic event		Dam severely damaged; ~40-acre lake emptied	0	Owned by the Graybrook Conservation Association	Association of State Dam Safety Officials (www.damsafety.org)
Hebgen Dam	2008	ID	unknown	unknown	unknown		none	0	Failure of two hydraulic gates released 3,400 cu ft (normal discharge: 900 cu ft) water, causing 1' rise in Madison R. No evacuations.	Association of State Dam Safety Officials (www.damsafety.org)
Kingston Plant coal waste dam	2008	TN	unknown	unknown	unknown		5.4 million cubic yards (> 1 billion gal) of sludge damaged 12 homes and covered hundreds of acres. Cleanup costing ~$1 million per day.	0	40-acre pond used by the Tennessee Valley Authority to hold slurry of ash generated by the coal-burning Kingston Steam Plant. The dam gave way just before 1 a.m, burying a road and railroad tracks leading to the plant. No one was seriously injured or hospitalized.	Association of State Dam Safety Officials (www.damsafety.org)
Lake Bella Vista Dam	2008	AR	unknown	unknown	unknown		Washed out road across the dam.	0	FEMA may grant $ 700,000 for repairs; reconstruction could cost approximately $2.2 million.	Association of State Dam Safety Officials (www.damsafety.org)

Lake Delton	2008	WI	unknown	unknown	unknown		245-acre lake emptied; 5 homes destroyed; highway washed out. 20 lakeside resorts affected. $Millions	0	Lake embankment (a peninsula, not the dam) washed out.	Association of State Dam Safety Officials (www.damsafety.org)
Locklin Lake Dam	2008	FL	other wooden	unknown	unknown		Minor damages to residential area	0	Locklin Lake Committee had been in process of replacing old wooden dam; awaiting approval to finish construction.	Association of State Dam Safety Officials (www.damsafety.org)
Mill Creek Dam	2008	WA	unknown	unknown	unknown		Pedestrian bridge washed out; residential areas flooded; ~12 homes received flood damages	0	"…serious situation was narrowly averted as a pedestrian bridge was washed out with children on their way to school…"	Association of State Dam Safety Officials (www.damsafety.org)
Moon Valley Lake	2008	MO	unknown	unknown	unknown		Emptied 17-acre lake; probable decrease in property values	0	Unregulated dam	Association of State Dam Safety Officials (www.damsafety.org)
Oakland Dam	2008	PA	timber crib	unknown	unknown		none	0		http://npdp.stanford.edu/dam_incidents
Pure Oil (aka Rhine) Lake Dam	2008	TX	unknown	overtopping	hydrologic event, spillway		County road closed	0	350-acre lake. Dam failed at spillway. Both drought & flooding suspected	Association of State Dam Safety Officials (www.damsafety.org)
Redlands Ranch Dam	2008	AZ	unknown	poor maintenance	unknown		Damaged waterfalls, pools & trails, repairs will take at least 6 months.	0	~ 426 people evacuated by helicopter. Previous dam (Cataract) failed in 1993,	Association of State Dam Safety Officials (www.damsafety.org)
Victor Conservation Club dam	2008	IN	unknown	overtopping	hydrologic event		Dam severely damaged	0		Association of State Dam Safety Officials (www.damsafety.org)
Kingston fossil plant	2008	TN	earth	unknown	unknown		Release of 5.4 million cubic yards [4.1 million m3] of ashy slurry. The ash slide covered 400 acres [1.6 square kilometres] as deep as 6 feet [1.83 metres]. The wave of ash and mud toppled power lines, covered Swan Pond Road and ruptured a gas line. It damaged 12 homes, and one person had to be rescued, though no one was seriously hurt.	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;

Etowah County, near the Gallant Community	2009	AL	unknown	overtopping	hydrologic event	103,000	Floodwaters washed away a culvert and a private dam broke producing up to 12 ft. of flooding in the area causing residences to be evacuated. A dozen roads were also closed due to the floodwaters and property damage was reported to be $100,000 ($103,000 in 2010 dollars).	0		Association of State Dam Safety Officials (www.damsafety.org)
Apple River	2010	WI	concrete masonry	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Atkinson Dam	2010	NE	unknown	overtopping	hydrologic event		unknown	0	Sources: “Dams monitored after failures” Omaha World Herals, 6/13/2010 “Heavy rains cause Ericson Dam to fail” Grand Island Independent, 6/14/2010 “NEMA says 10 Neb. dams failed during heavy rains” Sioux City Journal, 6/20/2010 Wikipedia	Association of State Dam Safety Officials (www.damsafety.org)
Burwell Sumter Diversion Dam	2010	NE	unknown	overtopping	hydrologic event		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Hydro-Kennebec	2010	ME	concrete gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Lake Delhi Dam	2010	IA	unknown	overtopping	hydrologic event, spillway		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Lake Ponderosa Dam	2010	IA	unknown	cracking	hydrologic event, overtopping		unknown	0		Association of State Dam Safety Officials (www.damsafety.org)
Madison	2010	MT	timber crib	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Tallulah Falls	2010	GA	gravity	unknown	unknown		unknown	0		http://npdp.stanford.edu/dam_incidents
Taylor Ord Diversion Dam	2010	NE	unknown	overtopping	hydrologic event		unknown	0	Heavy rains led to dam failures in Atkinson, Burwell, North Loup, Sargent, Scotia, Spalding and Taylor. Village of North Loupe evacuated due to Bredthauer failure	Association of State Dam Safety Officials (www.damsafety.org)

Ericson Dam	2010	NE	earth	overtopping	hydrologic event, spillway		significant flooding, roads and bridges washed out	0		https://www.weather.gov/gid/53617
Spalding Dam	2010	NE	earth	overtopping	hydrologic event, upstream dam failure		significant flooding, roads and bridges washed out	0		https://www.weather.gov/gid/53618
Brown Bridge Dam	2012	MI	earth	foundation	erosion		66 properties damaged	0		https://www.michigan.gov/deq/0,4561,7-135-3313_3684_3723-331769--,00.html
Dan River Steam Station	2014	NC	earth	unknown	unknown		collapse of an old drainage pipe under a 27-acre ash waste pond, ash flowing through drainage pipe into Dan River, about 82,000 short tons [74,400 t] of toxic coal ash and 27 million gallons [100,000 m3] of contaminated water	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Corbett Lake SCNONAME 02027	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
SC NONAME 02019 (Bailey Pond)	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures

Able/Cobett Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Cook Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Clyburn	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Old Mill Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures

Barr Lake Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Gibson's Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
JW Smoaks Pond	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Cary's Lake Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures

Lake Elizabeth	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Lower Rocky Ford Dam /Rocky Ford Lake	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Ulmers Pond	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Upper Rocky Creek/ North Lake/Overcreek Rd.	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures

Walden Place Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Beaver Dam/Wildewood Pond #2/Boyd Pond Two (Controlled release)	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Covington Lake Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Murray Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures

Pinewood Lake Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Sunview Lake Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Wilson Millpond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Semmes Lake Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures

Weston Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Clarkson Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Duffies Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
O E Rose Dam (SCNONAME 14001)	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures

Lakewood Pond	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Chapman's Pond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Culler Pond (SCNONAME 38070)	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Busbees Pond (Hutto's Millpond Dam)	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures

SCNONAME 38036 (Cleveland Street)	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
Ellerbees Millpond Dam	2015	SC	earth	overtopping	hydrologic event, erosion			0	In October 2015, South Carolina received record amounts of rainfall which caused a 1000-year flood throughout much of the state. During this flood event, emergency orders were issued too many dams throughout the state, and 36 dams have been reported to have failed, 4 of which were unregulated.	http://npdp.stanford.edu/2015_SC_Flood_Failures
New Wales Plant	2016	FL	earth	unknown	unknown		a 14 metre-wide sinkhole appeared in a phosphogypsum stack, opening a pathway for contained liquid into the underground; the liquid reached the Floridan Aquifer, a major drinking water resource. 840,000 m3 of contaminated liquid released.	0		http://www.wise-uranium.org/mdaf.html; U.S. Committee on Large Dams;
Oroville Dam	2017	CA	earth fill	overtopping	hydrologic event, spillway		damage to spillway and emergency spillway, sedimentation and debris	0	Prolonged drought followed by heavy rain.	Vahedifard et al., 2017
Hatfield	1987	WI	earth gravity	overtopping	gate			0	Collapse of sections of trip gates.	http://npdp.stanford.edu/dam_incidents

Appendix G: Levee Failures

(see following pages)

Also available in filterable/searchable format at: https://blindreview1.shinyapps.io/levees/

Year	State Region	District Location	Total Incidents	Primary Cause	Secondary Cause	Other Factor	Cost	Fatalities	Description of Damages and Comments	Lessons Learned and Comments	References
Total 1993	Midwest (IL, IA, KS, MN, MO, NE, ND, WI)	Multiple	1083				15,700,000,000	52	Regional impacts due to extended rainfall and saturated upland areas. Record summer rainfalls exceeding 300-year events. Over 1000 levees failed; 75 towns and 15 million acres of farmland inundated; barge traffic on Missouri and Mississippi stopped for 2 months; highways 35, 70, 29 closed; 10 commercial airports closed; all rail traffic in midwest halted; 200-400% normal rainfall across region for 20 days or more; estimated 500-year event; soil moisture at field capacity; locations above flood stage for 150-200 days; 30,000 jobs and 149,000 households disrupted for 2 months; 200 water treatment plants impacted; Over 800 miles rail track damaged; High nitrogen levels contributed to plankton bloom with 7000 square mile dead zone in Gulf of Mexico; Significant erosion and sediment transport; [NWS damage estimates by state in billions: IL-2.64, IA-5.74, KS-0.55, MN-0.96, MO-3.4, NE-0.30, ND-0.41, WI-0.90]. Red Cross responded rapidly providing shelter for 14,500 people; served 2.5 million meals; National Guard and Coast Guard provided rescue and security; broad community response (sandbagging, volunteering, etc.); 6.2 billion in property damage reimbursed by federal gov; FEMA provided 650 million; SBA l loans 334 million; 2.85 billion in USDA flood disaster payments; Over 12,000 properties mitigated by FEMA.	Need better models for failure regarding long-term flooding; need more reliable real-time data on long-term stream flow gaging stations and soil moisture; need improved forecasting models for precipitation and river levels; need real-time streamflow data to generate and communicate better forecasts; need better streamflow monitoring network.	Johnson et al., 2004; Parrett & James, 1993; Southard, 1995; Perry & Combs, 1999; Josephson, 1994; Galloway, 1994; Galloway, 1995; Stallings, 1994; Interagency Floodplain Management Task Force, 1994; Changnon, 1996; NRC, 2012; Larson, 1997; Theiling, 1998
1993	Midwest (IL, IA, KS, MN, MO, NE, ND, WI)	St. Paul	3	overtopping	hydrologic event, breach	soil saturation and persistent nature of heavy rainfall					

1993	Midwest (IL, IA, KS, MN, MO, NE, ND, WI)	Rock Island	31	overtopping	hydrologic event, breach	soil saturation					
1993	Midwest (IL, IA, KS, MN, MO, NE, ND, WI)	St. Louis	51	overtopping	hydrologic event, breach	soil saturation					
1993	Midwest (IL, IA, KS, MN, MO, NE, ND, WI)	Kansas City	816	overtopping	hydrologic event, breach	soil saturation					
1993	Midwest (IL, IA, KS, MN, MO, NE, ND, WI)	Omaha	182	overtopping	hydrologic event, breach	soil saturation					
Total 1997	Sacramento/ San Joaquin Central Valley, CA		38				2,000,000,000		30,000 homes damaged or destroyed, 2000 businesses damaged or destroyed; $690,000 disaster unemployment payments; 80,00 acres of flooded area had to be pumped; Only 6% home owners covered by NFIP; $25.5 million in FEMA and state relief for shelter; SBA approved $24.7 million in loans.	Need better coordination of flood releases across delta; need comprehensive approach to managing runoff; need removal of vegetation encroaching into floodways; need sediment control management; need information dissemination to communities to better prepare and respond to flood; needs integration of seismic susceptibility; needs channel maintenance management; land use planning, setbacks, levee elevation; better maintenance practices; Public notifications of impending danger or flooding were not clearly understood by the public or the media. Terms	FEAT, 1997; Burton & Cutter, 2008

										such as "voluntary" and "mandatory" evacuations were not clearly defined. Evacuations ranged from very smooth, timely operations to panic; need to increase the number of telemetered gaging stations for streamflow and precipitation in the Sacramento-San Joaquin River system and otl1er streams.	
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento	2	overtopping	hydrologic event, erosion	damaged trying to make cuts for pump out lines, landside wavewash erosion					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento	1	overtopping	hydrologic event, wavewash	landside wavewash erosion					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, East levee Feather River	1	sloughing	hydrologic event, relief cuts	damaged trying to make relief cuts, landside and wavewash					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, West levee of Sutter Bypass	1	sloughing	hydrologic event, seepage	sloughing, landside wavewash					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, Steamboat Slough East Levee, Sacramento River West Levee, Butte Slough Levee, Colusa Basin Drain Levee	4	sloughing	hydrologic event, waterside erosion	waterside					
1997	Sacramento/ San Joaquin	Sacramento, Butte	1	sloughing	hydrologic event, piping	at waterside toe, boils and sinkhole					

	Central Valley, CA	Slough Levee									
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, West levee of Sutter Bypass	1	sloughing	hydrologic event, wavewash	wavewash erosion, scour hole near levee					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, West levee Sacramento River, South Levee Bear River, North levee of the Natomas Cross Canal	3	overtopping	hydrologic event, waterside erosion	waterside					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, East levee Three Mile Slough	1	overtopping	hydrologic event, subsidence	levee crown					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, West levee of Georgiana Slough	1	sloughing	hydrologic event, subsidence	landside subsidence					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, Sacramento Bypass	1	sloughing	hydrologic event, landside erosion	landside slope erosion, boils					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, West levee Middle Creek	1	overtopping	hydrologic event, seepage	seepage, wavewash erosion					
1997	Sacramento/ San Joaquin Central Valley, CA	Sacramento, West levee Deer Creek, South levee Elder Creek	2	breach	hydrologic event, erosion	erosion, 4 breaks					
1997	Sacramento/ San Joaquin Central Valley, CA	San Joaquin, Lower San Joaquin North Levee (Madera), Lower San Joaquin South levee (Fresno)	2	overtopping	hydrologic event	failed in 4 places					
1997	Sacramento/ San Joaquin Central Valley, CA	San Joaquin, East levee San Joaquin River (Elliott), East levee San Joaquin	2	overtopping	hydrologic event, relief cuts	relief cut, landside and waterside slope erosion, wavewash erosion, failed in 5 places					

		River (River Junction)									
1997	Sacramento/ San Joaquin Central Valley, CA	San Joaquin, West levee San Joaquin River (Blewett)), West levee San Joaquin River (White Lake Ranch), East levee San Joaquin River (Wetherbee Lake), East levee San Joaquin River (River Junction)	4	overtopping	hydrologic event, landside wavewash	landside wavewash, relief cut, failed 2 places					
1997	Sacramento/ San Joaquin Central Valley, CA	San Joaquin, Paradise Cut East levee (Paradise Junction), East levee San Joaquin River {McMullin Ranch)	2	overtopping	hydrologic event, waterside erosion	waterside erosion, cracks and holes in levee					
1997	Sacramento/ San Joaquin Central Valley, CA	San Joaquin, Fresno River South levee, West levee San Joaquin River (Upper Roberts Island), East levee San Joaquin River (Boggs)	3	overtopping	hydrologic event, erosion	slope					
1997	Sacramento/ San Joaquin Central Valley, CA	San Joaquin, North levee Old River	1	sloughing	hydrologic event, piping	erosion, boils, seepage, shallow inundation, 4 places					
1997	Sacramento/ San Joaquin Central Valley, CA	Islands, Upper Roberts Island	1	seepage	hydrologic event, culvert	excessive water in adjacent channels					

1997	Sacramento/ San Joaquin Central Valley, CA	Islands, Quimby Island, Bouldin Island, Twitchell Island	3	cracking	hydrologic event, slumping	movement of landside slope, excessive water in adjacent channels					

Total 2005	New Orleans, LA	New Orleans	13 (of suspected 50)				100,000,000,000	1500	400,000 cars inundated; 25,000 barrels of crude spilled contaminating 1700 homes; 118 million cubic yards of debris; estimated uninsured losses at $215 billion, and insured losses at $25 billion; damaged 19 percent of U.S. oil production; of those who died, 71 percent were 60 years or older; half were 75 years or more; 124,000 jobs lost.	Levees constructed using hydraulic fill with high silt and sand content were severely damaged; rolled fill levees survived overtopping without breaching; I-Type floodwalls caused catastrophic flooding in Ninth Ward; water flowing over top of I-Type wall eroded soils and stability, also issues with foundation soils; overtopping alone would have resulted in far less flooding; breaches due soils and fill contributed significantly to damage; worst flooding caused by levees and walls in ninth ward area built on marsh and sand causing pressure, seepage, sliding, and gaps formed between sheet pile wall and canal side portion of levee, many I-Type floodwalls built atop levees - Earthen levees without I-walls all around New Orleans— including the levee at the Industrial Canal West Bank South breach —	Reible et al., 2006; Sills et al., 2008; Wolshon, 2006; Knabb et al., 2005; Mlakar, 2006; Brunkard et al., 2008; ASCE, 2007; USACE, 2007; Cutter & Gall, 2007; USACE, 2009

										were overtopped by Hurricane Katrina’s storm surge. Out of the 50 total estimated levee breaches system-wide, the majority can be attributed to overtopping and erosion. Levees constructed with properly compacted clay with a good grass cover appeared to have withstood the storm the best. Levees with higher silt and sand content in the embankment material —or levees built with hydraulic fill (in which the levee material was mixed with water to create a slurry, then pumped or flowed into place)— sustained the worst erosion damage, and in some cases were completely washed away.	
2005	New Orleans, LA	New Orleans	2	sliding	hydrologic event	I-Type floodwalls built atop levees failed due to load exceedance, weak					

						foundational soils, breached occurred with water below top of floodwall, gap formed between sheet pile wall and canal side portion of levee					
2005	New Orleans, LA	New Orleans	1	breach	hydrologic event, piping	breached occurred with water below top of floodwall, constructed over marsh layer with beach and sand layer, heaving and sand boils, seepage and piping, gap formed between sheet pile wall and canal side portion of levee					
2005	New Orleans, LA	New Orleans	1	piping	hydrologic event, seepage	constructed over marsh layer with beach and sand layer, gap formed between sheet pile wall and canal side portion of levee					
2005	New Orleans, LA	New Orleans	2	overtopping	hydrologic event, storm surge	overwhelmed by surge					
2005	New Orleans, LA	New Orleans	4	overtopping	hydrologic event, breach	I-Type floodwalls built atop levees failed due to load exceedance					
2005	New Orleans, LA	New Orleans	1	breach	hydrologic event, floodwall	small section failed, I-Type floodwalls built atop levees failed due to load exceedance					
2005	New Orleans, LA	New Orleans	1	breach	hydrologic event, sliding	break in wall, constructed over marsh layer with					

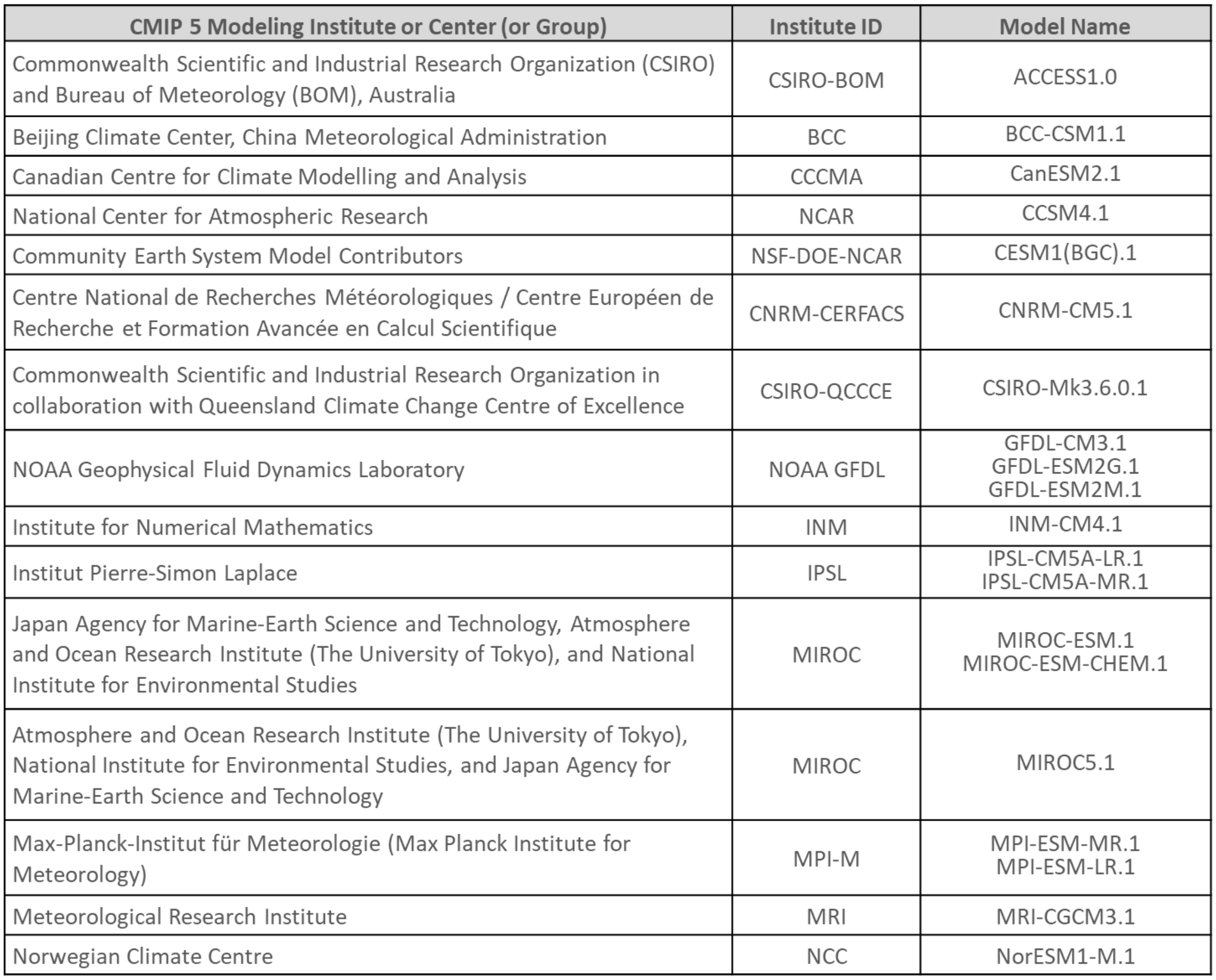
						beach and sand layer					
2005	New Orleans, LA	New Orleans	1	breach	hydrologic event, piping	constructed of hydraulic fill with sand and silt, numerous breaches and total loss of levee wall					
Total 2008	Midwest	Multiple	25	overtopping	hydrologic event	extended period of heavy rain, snowpack	15,000,000,000	24	The 2008 flood brought similar, and even higher, river stages to many areas that were devastated in 1993. Damage more localized around rivers and tributaries as opposed to 1993. Multiple rain events and higher than average snowpack Jan-Sep 2008. Levees breached along Mississippi were mainly lower agricultural levees. Overtopping occurred in Cedar Rapid IA, causing severe damage to populated areas. (IA - 85 of 99 counties were declared a Federal Disaster Area. IA damage alone $10 billion with over 40,000 people were affected. 2.5 to 3 million acres of corn and soybeans were underwater. 10-square miles cedar rapids and Iowa city inundated including downtown areas.)	See 1993 flood; limited river gauging information constrained the National Weather Service and others in developing timely and accurate river stage forecasts during this year’s flooding. This experience underscores the need to reverse the trend of recent years, during which federal support for the USGS-operated system of river gauges has eroded and non-federal partners have not been able to fill the gaps completely; every record breaking flood event presents a need to review the accuracy of the stage-discharge, discharge-frequency, and stage-frequency relations that	Bernhardt et al., 2011; Holmes et al.,2010; Gleason, 2008; Coleman & Budikova, 2010; Budikova et al., 2010; Patricola et al., 2015; Carter, 2009

										underpin flood control planning, floodplain regulation, and flood insurance ratings. Considerable work was done in these areas following 1993. However, this work should be assessed against our experience in 2008, with particular attention to whether changes in land use patterns and, potentially, climate are fundamentally altering any of these relationships; human and financial costs associated with repetitive loss structures, which again accounted for a significant share of damages. Continued investment in flood damage reduction and enforcement of building restrictions are critical to making progress with these repetitive loss structures.	
2008	WI	Lake Delton/Wisconsin River	1								
2008	IA	Two Rivers Upper	1	overtopping	hydrologic event						
2008	IL	Keithsburg	1	overtopping	hydrologic event						

2008	IL	Henderson #3	1	overtopping	hydrologic event						
2008	IL	Henderson #2	1	overtopping	hydrologic event						
2008	IL	Henderson #1	1	overtopping	hydrologic event						
2008	MO	Mississippi-Fox 1	1	overtopping	hydrologic event						
2008	MO	Mississippi-Fox 2	1	overtopping	hydrologic event						
2008	MO	Mississippi-Fox 3	1	overtopping	hydrologic event						
2008	MO	Gregory	1	overtopping	hydrologic event						
2008	IL	Hunt-Lima	1	overtopping	hydrologic event						
2008	MO	Union Township	1	overtopping	hydrologic event						
2008	IL	Indian Grave Lower	1	overtopping	hydrologic event						
2008	MO	John Reiff	1	overtopping	hydrologic event						
2008	MO	Pike Grain #3	1	overtopping	hydrologic event						
2008	MO	Pike Grain #4	1	overtopping	hydrologic event						
2008	MO	Kissinger	1	overtopping	hydrologic event						
2008	MO	Elsberry	1	overtopping	hydrologic event						
2008	MO	Kings Lake	1	overtopping	hydrologic event						
2008	MO	Sandy Creek	1	overtopping	hydrologic event						
2008	MO	Foley	1	overtopping	hydrologic event						
2008	MO	Cap Au Gris	1	overtopping	hydrologic event						
2008	MO	Brevator	1	overtopping	hydrologic event						
2008	MO	Kuhs	1	overtopping	hydrologic event						
2008	MO	Columbia Bottom	1	overtopping	hydrologic event						

Total 2011	MO	Memphis	1	induced breach	hydrologic event	extended period of heavy rain, snowpack	2,800,000,000		For first time, the Birds Point–New Madrid and morganza floodways and the Bonnet Carré Spillway were placed into operation during a single flood event. Cost estimated as damage/repair costs by USACE actions to activate all 3 floodways. (Actions prevented $234 billion in total flood damages during the 2011 flood event. Cumulative damages prevented are estimated at $612 billion, a $44 return on every $1 invested, based on $14 billion invested to date. An estimated 3.6 million people may have been impacted by the 2011 flood event without actions taken. A total of 43,358 people were actually impacted.) Estimated between 3,500 and 22,500 evacuated from all 3 floodway areas.	Most promising technologies was developed by the U.S. Army Corps Engineer Research and Development Center in Vicksburg, Miss. A new smart phone application provided real-time GPS pinpointing of flood-fight progress and related issues in the field, giving trained floodfighters the ability to use a phone to upload images, descriptions of flood damage and other critical data to the Command Center. The experimental technology was employed by the Memphis District in the flood's early stages as one of the first true field tests of this technology. These devices were later transferred to New Orleans and Missouri flood fighters. Enhancements and refinements of this new flood fight tool were made from these field tests, ensuring this tool will be even more useful for the next flood fight.	USACE, 2012

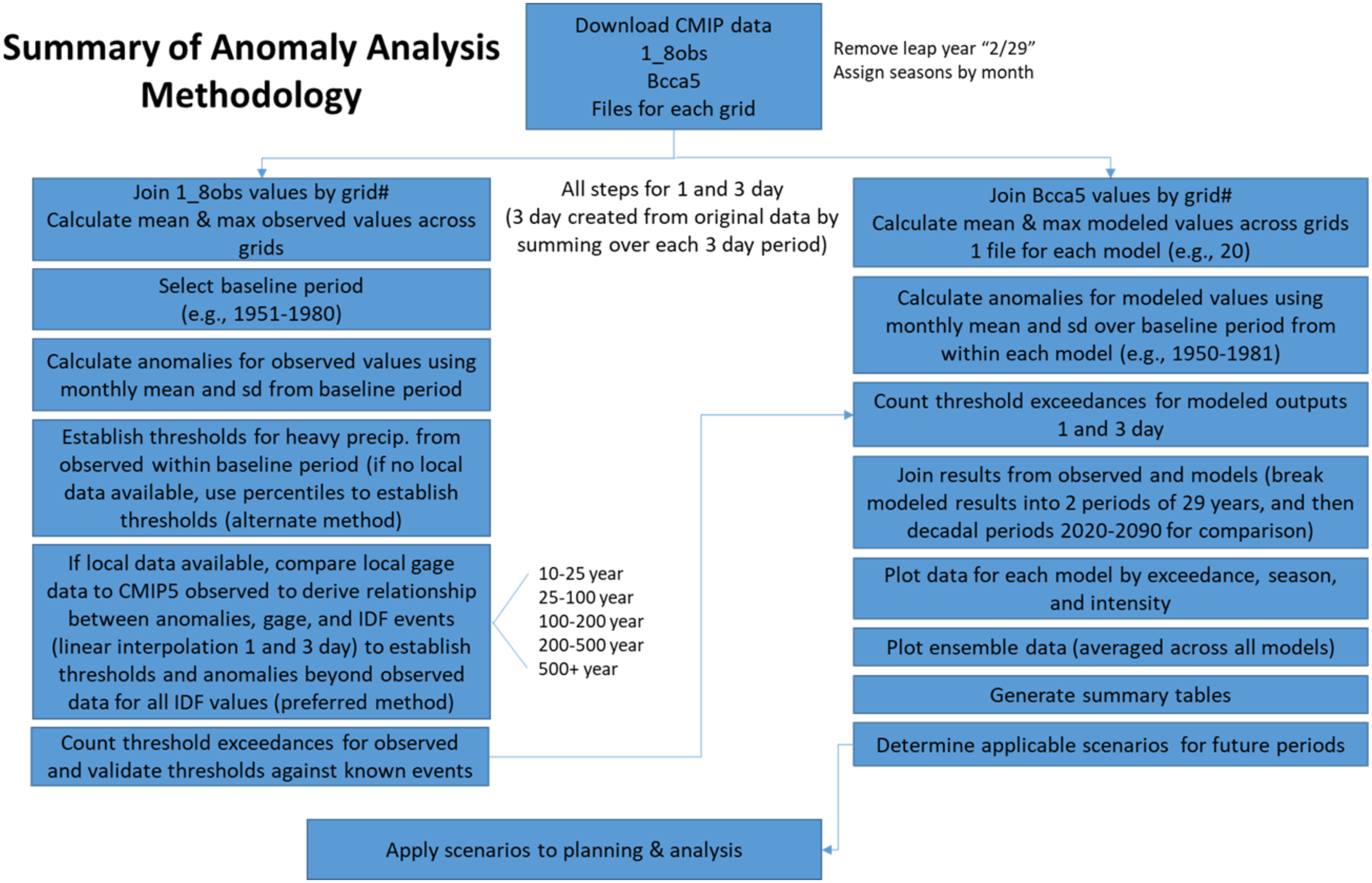
Appendix H: CMIP5 Model Sources and Acknowledgment



CMIP 5 Modeling Institute or Center (or Group)	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2.1
National Center for Atmospheric Research	NCAR	CCSM4.1
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC).1
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5.1
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0.1
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3.1 GFDL-ESM2G.1 GFDL-ESM2M.1
Institute for Numerical Mathematics	INM	INM-CM4.1
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR.1 IPSL-CM5A-MR.1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM.1 MIROC-ESM-CHEM.1
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5.1
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-MR.1 MPI-ESM-LR.1
Meteorological Research Institute	MRI	MRI-CGCM3.1
Norwegian Climate Centre	NCC	NorESM1-M.1

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. We further acknowledge: Maurer et al., 2007; Meehl et al., 2007; Hibbard et al., 2007; Meehl et al., 2009; Reclamation, 2013.

Appendix I: Analysis of Anomalies Methodology



Summary of Anomaly Analysis Methodology

Download CMIP data
1_8obs
Bcca5
Files for each grid

Remove leap year "2/29"
Assign seasons by month

All steps for 1 and 3 day
(3 day created from original data by summing over each 3 day period)

Join 1_8obs values by grid#
Calculate mean & max observed values across grids

Select baseline period
(e.g., 1951-1980)

Calculate anomalies for observed values using monthly mean and sd from baseline period

Establish thresholds for heavy precip. from observed within baseline period (if no local data available, use percentiles to establish thresholds (alternate method)

If local data available, compare local gage data to CMIP5 observed to derive relationship between anomalies, gage, and IDF events (linear interpolation 1 and 3 day) to establish thresholds and anomalies beyond observed data for all IDF values (preferred method)

10-25 year
25-100 year
100-200 year
200-500 year
500+ year

Count threshold exceedances for observed and validate thresholds against known events

Join Bcca5 values by grid#
Calculate mean & max modeled values across grids
1 file for each model (e.g., 20)

Calculate anomalies for modeled values using monthly mean and sd over baseline period from within each model (e.g., 1950-1981)

Count threshold exceedances for modeled outputs
1 and 3 day

Join results from observed and models (break modeled results into 2 periods of 29 years, and then decadal periods 2020-2090 for comparison)

Plot data for each model by exceedance, season, and intensity

Plot ensemble data (averaged across all models)

Generate summary tables

Determine applicable scenarios for future periods

Apply scenarios to planning & analysis

Example Tools & Resources

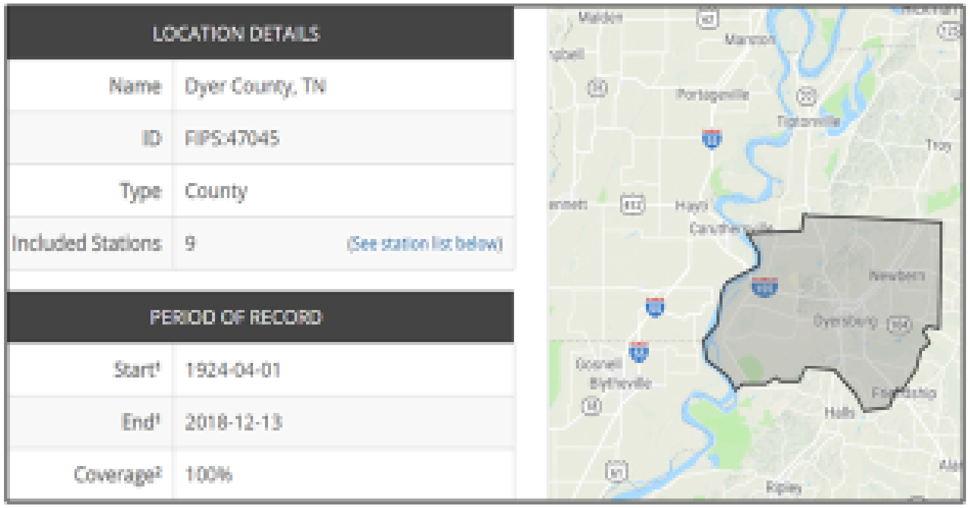
- Rstudio
- Downscaled CMIP5 Climate Projections (https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html)
- NOAA precipitation gage data:

STATION NAME & ID	START¹	END¹	COVERAGE²
DYERSBURG 4.1 NNW, TN US GHCND:US1TNDY0004	5/16/2008	11/24/2008	88%
DYERSBURG 4.5 W, TN US GHCND:US1TNDY0003	12/12/2007	7/2/2014	13%
DYERSBURG 4.9 SSE, TN US GHCND:US1TNDY0002	1/1/2008	5/29/2008	51%
DYERSBURG MUNICIPAL AIRPORT, TN US GHCND:USW00003809	9/1/1948	4/30/2018	94%
DYERSBURG, TN US GHCND:USC00402680	1893-05-01	10/31/2018	25%
FINLEY, TN US GHCND:USC00403125	6/20/1941	1/31/1944	97%
NEWBERN 0.9 SW, TN US GHCND:US1TNDY0006	9/4/2017	11/24/2018	27%
NEWBERN 6.5 SE, TN US GHCND:US1TNDY0001	11/2/2007	12/13/2018	88%
NEWBERN, TN US GHCND:USC00406471	4/1/1924	9/30/1993	94%

- NOAA Intensity-Duration-Frequency Data:

IDF - NOAA Atlas 14, Volume 2, Version 3 DYERSBURG Station ID: 40-2680 Location name: Dyersburg, Tennessee, USA* Latitude: 36.0456°, Longitude: -89.3697°

https://www.ncdc.noaa.gov/cdo-web/



LOCATION DETAILS	
Name	Dyer County, TN
ID	FIPS:47045
Type	County
Included Stations	9 (See station list below)

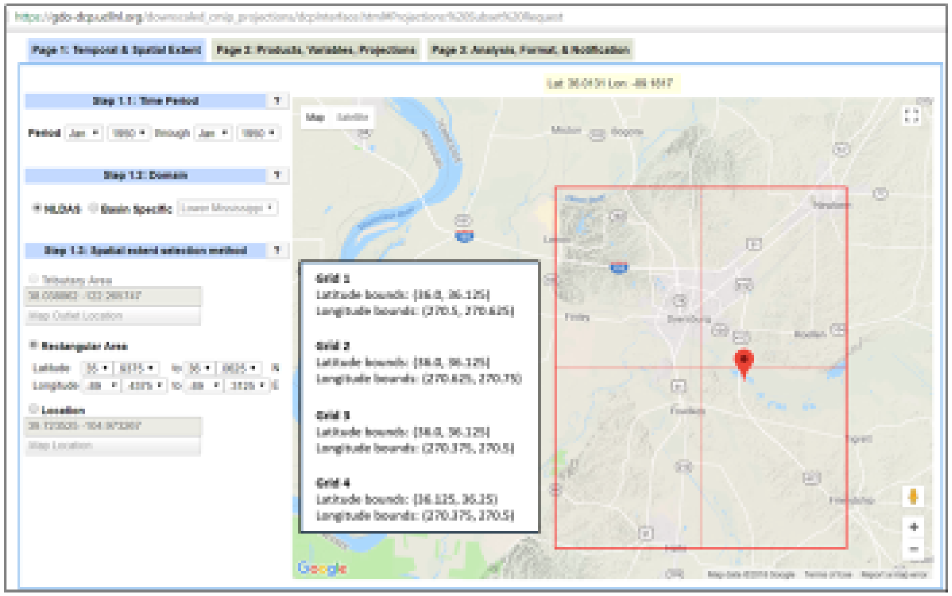
PERIOD OF RECORD	
Start¹	1924-04-01
End¹	2018-12-13
Coverage²	100%

Get CMIP5 Data

RECLAMATION NCAR USGS

SCRIPPS INSTITUTION OF OCEANOGRAPHY

1. Go to the Downscaled CMIP3 and CMIP5 Climate Projections website: https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html#Projections:%20Subset%20Request
2. Select time period: Jan 1, 1950-Dec 31, 2099
3. Select NLDAS
4. Select 1st of 4 rectangular 12x12 km grids over the area of interest (up to 4 can be selected)
5. Select BCCAv2-CMIP5-Climate-daily
6. Select:
    - 1/8 degree BCCA projections
    - 1/8 degree Observed data (1950-1999)
    - Precipitation Rate (mm/day) [BCCAv2]
7. Select emissions scenario (RCP 8.5)
8. Select models to include (all 20 models)
9. Select:
    - No Analysis (Extracting Time Series only)
    - ASCII text, comma-delimited (csv)
10. Enter email and submit requests (4 at a time)



Grid 1
Latitude bounds: [36.0, 36.125]
Longitude bounds: (270.5, 270.625]

Grid 2
Latitude bounds: [36.0, 36.125]
Longitude bounds: (270.625, 270.75]

Grid 3
Latitude bounds: [36.0, 36.125]
Longitude bounds: (270.375, 270.5]

Grid 4
Latitude bounds: [36.125, 36.25]
Longitude bounds: (270.375, 270.5]

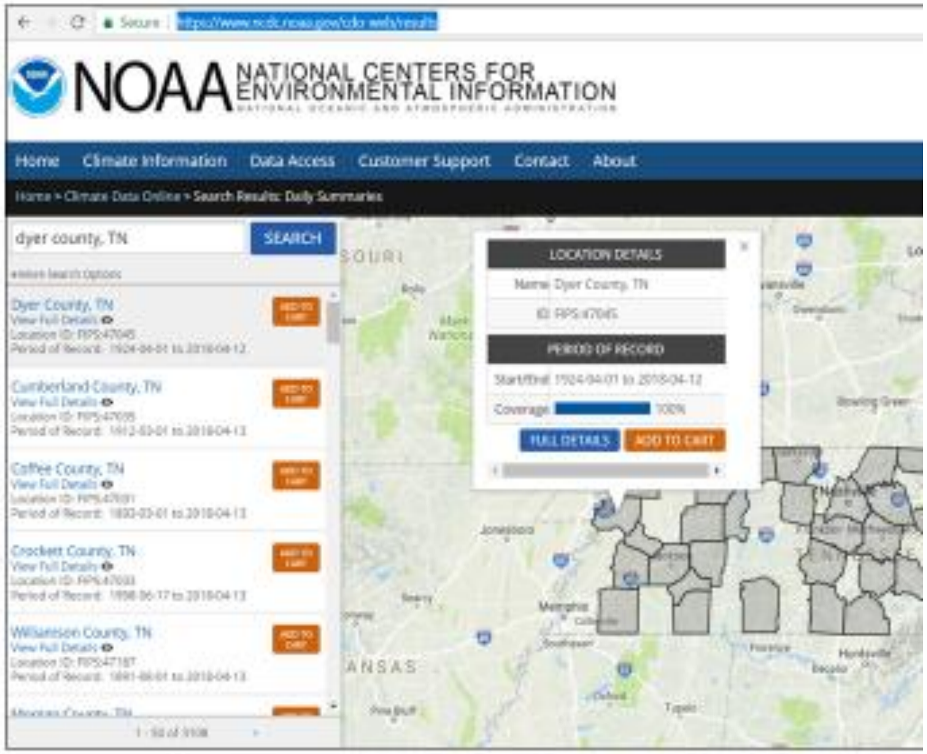
Note: projection selection only lets you select up to 4 grids at a time, but you can select as many as you want and the precip projection tool can be tailored to allow as many grids as you want. It can also be tailored to allow for evaluation of precip and/or temp.

Get Local NOAA Precip. Gage Data if Available

12. Go to the NOAA website: https://www.ncdc.noaa.gov/cdo-web/
13. Select daily summaries and choose dates
14. Search for location
15. Select the appropriate data
16. Submit request
17. Data arrives by gage and must be treated to account for missing days across gages
18. Treat data by taking the max (or ave) value for each day to produce a single set of gage data for the area (this can be done in Rstudio):

```
dups=read.csv('precipdup.csv')
maxnew=dups %>% group_by(DATE) %>% filter(PRCP==max(PRCP))
maxnew1=maxnew[!duplicated(maxnew$DATE), ]
write.csv(maxnew1, file = "maxnew1.csv")
```

19. This allows for an understanding of raw data and associated maximum values needed when setting thresholds later with anomalies and IDF data



Dyer County, TN
View Full Details
Location ID: FIPS:47045
Period of Record: 1924-04-01 to 2018-04-12

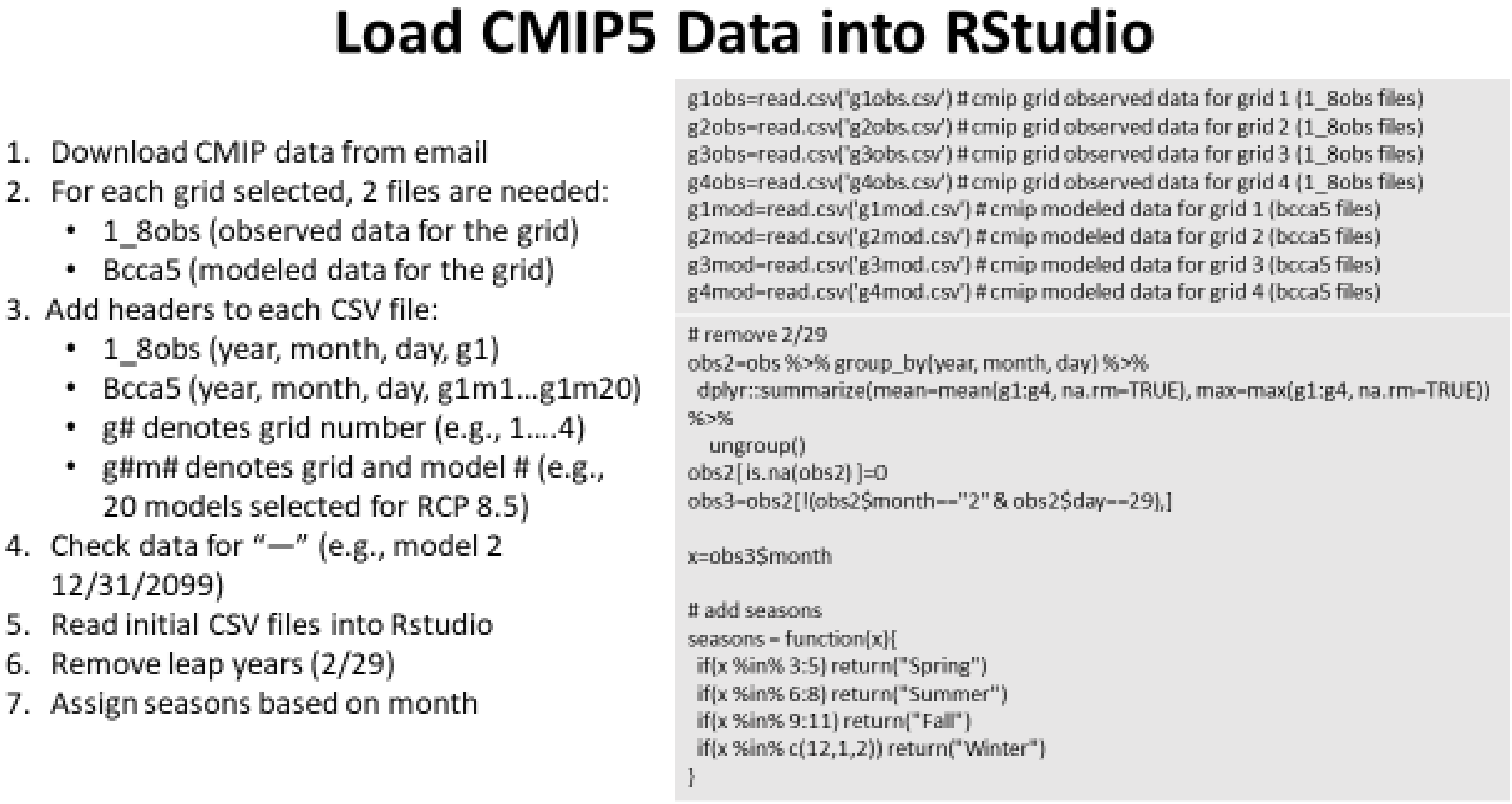
Cumberland County, TN
View Full Details
Location ID: FIPS:47035
Period of Record: 1912-03-01 to 2018-04-13

Coffee County, TN
View Full Details
Location ID: FIPS:47031
Period of Record: 1893-03-01 to 2018-04-13

Crockett County, TN
View Full Details
Location ID: FIPS:47033
Period of Record: 1898-06-17 to 2018-04-13

Williamson County, TN
View Full Details
Location ID: FIPS:47187
Period of Record: 1891-08-01 to 2018-04-13

Name: Dyer County, TN
ID: FIPS:47045
Start/End: 1924-04-01 to 2018-04-12
Coverage: 100%



Load CMIP5 Data into RStudio

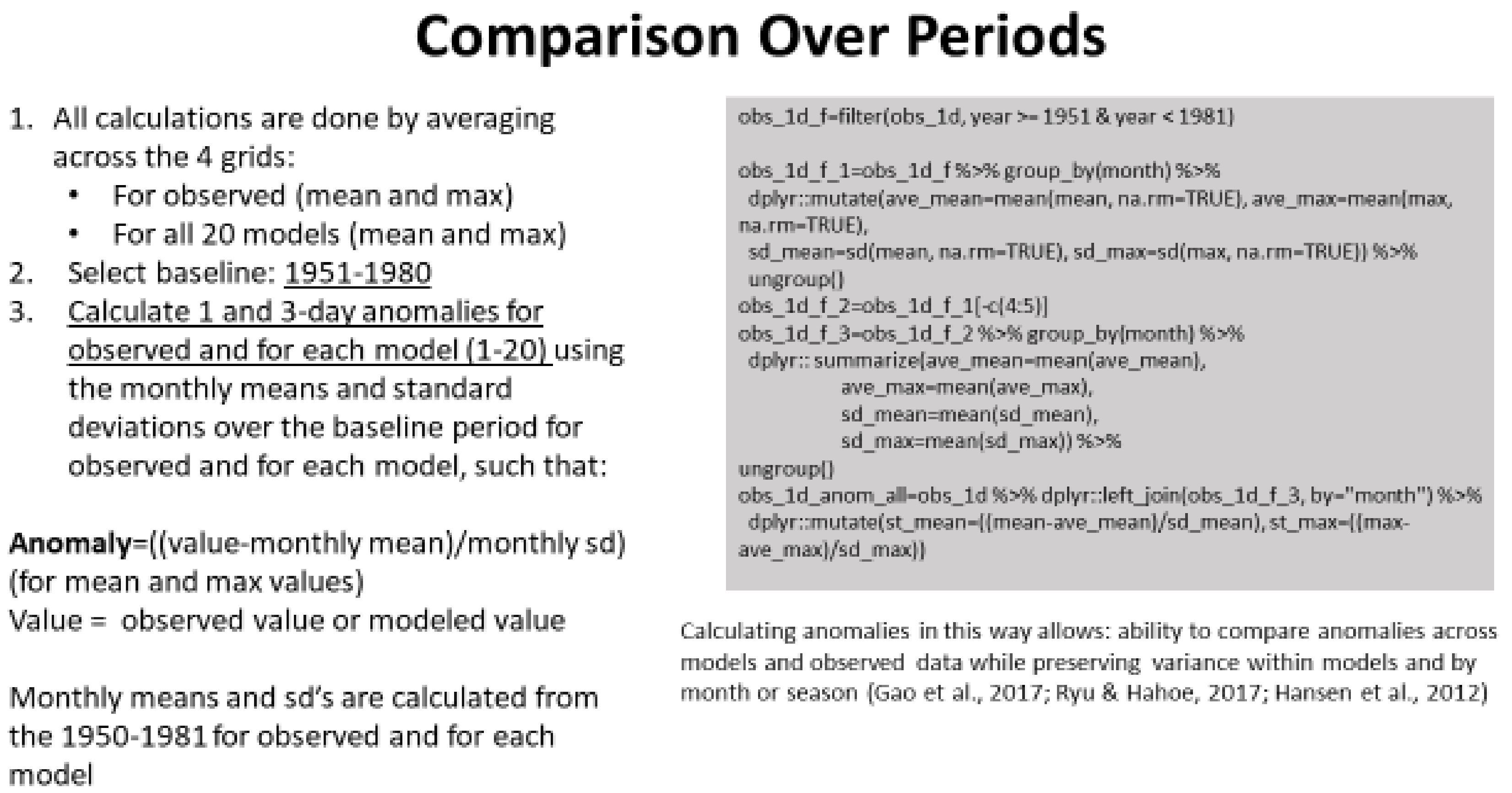
1. Download CMIP data from email
2. For each grid selected, 2 files are needed:
   - 1_8obs (observed data for the grid)
   - Bcca5 (modeled data for the grid)
3. Add headers to each CSV file:
   - 1_8obs (year, month, day, g1)
   - Bcca5 (year, month, day, g1m1…g1m20)
   - g# denotes grid number (e.g., 1….4)
   - g#m# denotes grid and model # (e.g., 20 models selected for RCP 8.5)
4. Check data for "—" (e.g., model 2 12/31/2099)
5. Read initial CSV files into Rstudio
6. Remove leap years (2/29)
7. Assign seasons based on month

```
g1obs=read.csv('g1obs.csv’) # cmip grid observed data for grid 1 (1_8obs files)
g2obs=read.csv('g2obs.csv’) # cmip grid observed data for grid 2 (1_8obs files)
g3obs=read.csv('g3obs.csv’) # cmip grid observed data for grid 3 (1_8obs files)
g4obs=read.csv('g4obs.csv’) # cmip grid observed data for grid 4 (1_8obs files)
g1mod=read.csv('g1mod.csv’) # cmip modeled data for grid 1 (bcca5 files)
g2mod=read.csv('g2mod.csv’) # cmip modeled data for grid 2 (bcca5 files)
g3mod=read.csv('g3mod.csv’) # cmip modeled data for grid 3 (bcca5 files)
g4mod=read.csv('g4mod.csv’) # cmip modeled data for grid 4 (bcca5 files)
```

```
# remove 2/29
obs2=obs %>% group_by(year, month, day) %>%
  dplyr::summarize(mean=mean(g1:g4, na.rm=TRUE), max=max(g1:g4, na.rm=TRUE))
%>%
   ungroup()
obs2[ is.na(obs2) ]=0
obs3=obs2[!(obs2$month=="2" & obs2$day==29),]

x=obs3$month

# add seasons
seasons = function(x){
  if(x %in% 3:5) return("Spring")
  if(x %in% 6:8) return("Summer")
  if(x %in% 9:11) return("Fall")
  if(x %in% c(12,1,2)) return("Winter")
}
```



Comparison Over Periods

1. All calculations are done by averaging across the 4 grids:
    - For observed (mean and max)
    - For all 20 models (mean and max)
2. Select baseline: 1951-1980
3. Calculate 1 and 3-day anomalies for observed and for each model (1-20) using the monthly means and standard deviations over the baseline period for observed and for each model, such that:

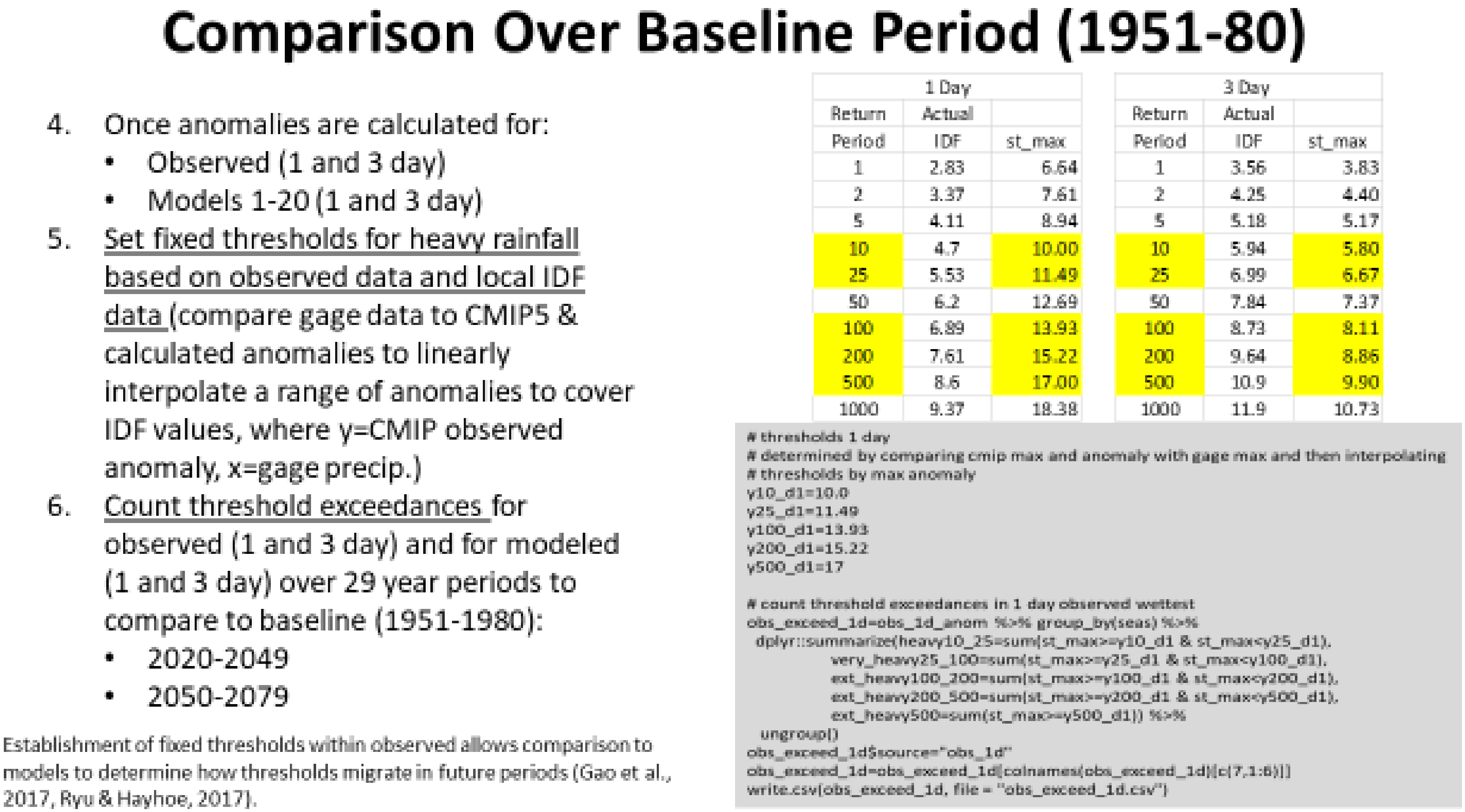
Anomaly=((value-monthly mean)/monthly sd)
(for mean and max values)
Value = observed value or modeled value

Monthly means and sd's are calculated from the 1950-1981 for observed and for each model

```
obs_1d_f=filter(obs_1d, year >= 1951 & year < 1981)

obs_1d_f_1=obs_1d_f %>% group_by(month) %>%
  dplyr::mutate(ave_mean=mean(mean, na.rm=TRUE), ave_max=mean(max,
na.rm=TRUE),
  sd_mean=sd(mean, na.rm=TRUE), sd_max=sd(max, na.rm=TRUE)) %>%
  ungroup()
obs_1d_f_2=obs_1d_f_1[-c(4:5)]
obs_1d_f_3=obs_1d_f_2 %>% group_by(month) %>%
  dplyr:: summarize(ave_mean=mean(ave_mean),
                ave_max=mean(ave_max),
                sd_mean=mean(sd_mean),
                sd_max=mean(sd_max)) %>%
ungroup()
obs_1d_anom_all=obs_1d %>% dplyr::left_join(obs_1d_f_3, by="month") %>%
  dplyr::mutate(st_mean=((mean-ave_mean)/sd_mean), st_max=((max-
ave_max)/sd_max))
```

Calculating anomalies in this way allows: ability to compare anomalies across models and observed data while preserving variance within models and by month or season (Gao et al., 2017; Ryu & Hahoe, 2017; Hansen et al., 2012)



Comparison Over Baseline Period (1951-80)

4. Once anomalies are calculated for:
   - Observed (1 and 3 day)
   - Models 1-20 (1 and 3 day)
5. Set fixed thresholds for heavy rainfall based on observed data and local IDF data (compare gage data to CMIP5 & calculated anomalies to linearly interpolate a range of anomalies to cover IDF values, where y=CMIP observed anomaly, x=gage precip.)
6. Count threshold exceedances for observed (1 and 3 day) and for modeled (1 and 3 day) over 29 year periods to compare to baseline (1951-1980):
   - 2020-2049
   - 2050-2079

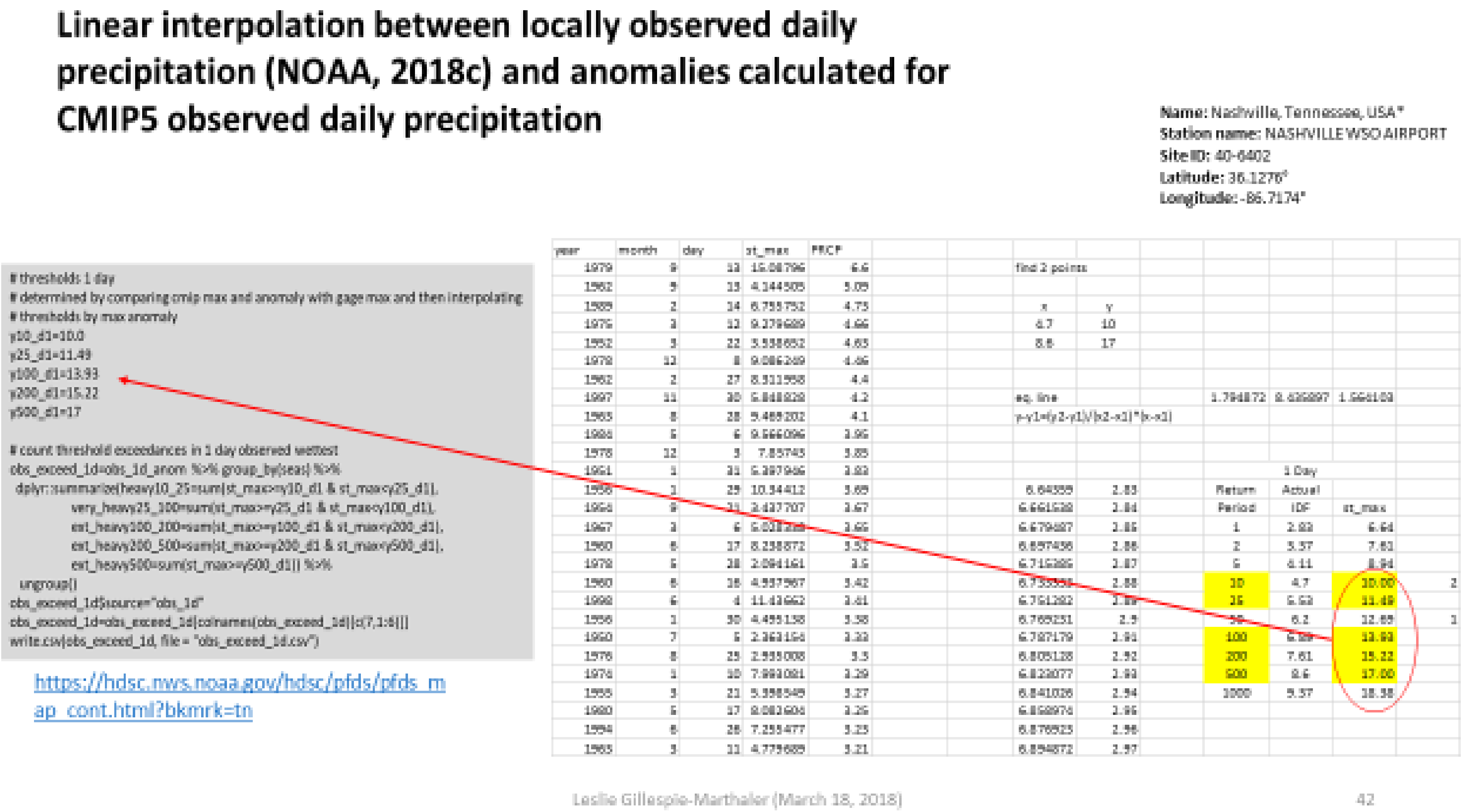
Establishment of fixed thresholds within observed allows comparison to models to determine how thresholds migrate in future periods (Gao et al., 2017, Ryu & Hayhoe, 2017).

1 Day		
Return Period	Actual IDF	st_max
1	2.83	6.64
2	3.37	7.61
5	4.11	8.94
10	4.7	10.00
25	5.53	11.49
50	6.2	12.69
100	6.89	13.93
200	7.61	15.22
500	8.6	17.00
1000	9.37	18.38

3 Day		
Return Period	Actual IDF	st_max
1	3.56	3.83
2	4.25	4.40
5	5.18	5.17
10	5.94	5.80
25	6.99	6.67
50	7.84	7.37
100	8.73	8.11
200	9.64	8.86
500	10.9	9.90
1000	11.9	10.73

```
# thresholds 1 day
# determined by comparing cmip max and anomaly with gage max and then interpolating
# thresholds by max anomaly
y10_d1=10.0
y25_d1=11.49
y100_d1=13.93
y200_d1=15.22
y500_d1=17

# count threshold exceedances in 1 day observed wettest
obs_exceed_1d=obs_1d_anom %>% group_by(seas) %>%
  dplyr::summarize(heavy10_25=sum(st_max>=y10_d1 & st_max<y25_d1),
                   very_heavy25_100=sum(st_max>=y25_d1 & st_max<y100_d1),
                   ext_heavy100_200=sum(st_max>=y100_d1 & st_max<y200_d1),
                   ext_heavy200_500=sum(st_max>=y200_d1 & st_max<y500_d1),
                   ext_heavy500=sum(st_max>=y500_d1)) %>%
   ungroup()
obs_exceed_1d$source="obs_1d"
obs_exceed_1d=obs_exceed_1d[colnames(obs_exceed_1d)[c(7,1:6)]]
write.csv(obs_exceed_1d, file = "obs_exceed_1d.csv")
```



Linear interpolation between locally observed daily precipitation (NOAA, 2018c) and anomalies calculated for CMIP5 observed daily precipitation

Name: Nashville, Tennessee, USA*
Station name: NASHVILLE WSO AIRPORT
Site ID: 40-6402
Latitude: 36.1276°
Longitude: -86.7174°

```
# thresholds 1 day
# determined by comparing cmip max and anomaly with gage max and then interpolating
# thresholds by max anomaly
y10_d1=10.0
y25_d1=11.49
y100_d1=13.93
y200_d1=15.22
y500_d1=17

# count threshold exceedances in 1 day observed wettest
obs_exceed_1d=obs_1d_anom %>% group_by(seas) %>%
  dplyr::summarize(heavy10_25=sum(st_max>=y10_d1 & st_max<y25_d1),
            very_heavy25_100=sum(st_max>=y25_d1 & st_max<y100_d1),
            ext_heavy100_200=sum(st_max>=y100_d1 & st_max<y200_d1),
            ext_heavy200_500=sum(st_max>=y200_d1 & st_max<y500_d1),
            ext_heavy500=sum(st_max>=y500_d1)) %>%
  ungroup()
obs_exceed_1d$source="obs_1d"
obs_exceed_1d=obs_exceed_1d[colnames(obs_exceed_1d)[c(7,1:6)]]
write.csv(obs_exceed_1d, file = "obs_exceed_1d.csv")
```

https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=tn

year	month	day	st_max	PRCP									
1979	9	13	16.08796	6.6			find 2 points						
1982	9	13	4.144505	5.09									
1989	2	14	6.755752	4.73			x	y					
1975	3	12	9.279689	4.66			6.7	10					
1952	3	22	3.538652	4.63			8.8	17					
1979	12	8	9.086249	4.46									
1962	2	27	8.311958	4.4									
1997	11	30	6.848828	4.2			eq. line			1.794872	8.626897	1.566103	
1983	8	28	9.489202	4.1			y-y1=(y2-y1)/(x2-x1)*(x-x1)						
1988	5	6	9.666096	3.96									
1978	12	3	7.85743	3.85									
1961	1	31	6.287946	3.83							1 Day		
1956	1	29	10.34412	3.69			6.64359	2.83		Return	Actual		
1964	9	31	2.427707	3.67			6.661538	2.84		Period	IDF	st_max	
1967	3	6	6.03[illegible]	3.66			6.679487	2.85		1	2.83	6.64	
1980	6	17	8.238872	3.52			6.697436	2.86		2	3.37	7.61	
1979	5	18	2.094161	3.6			6.715385	2.87		5	4.11	8.94	
1980	6	16	4.937987	3.42			6.733333	2.88		10	4.7	10.00	2
1998	6	4	11.43662	3.41			6.751282	2.89		25	5.53	11.49	
1956	1	30	4.495138	3.38			6.769231	2.9		50	6.2	12.69	1
1960	7	5	2.363154	3.33			6.787179	2.91		100	6.89	13.93	
1976	8	25	2.955008	3.3			6.805128	2.92		200	7.61	15.22	
1974	1	10	7.993081	3.29			6.823077	2.93		500	8.6	17.00	
1955	3	21	5.398549	3.27			6.841026	2.94		1000	9.37	18.38	
1980	5	17	8.082606	3.26			6.858974	2.95					
1994	6	28	7.255477	3.23			6.876923	2.96					
1963	3	11	4.779689	3.21			6.894872	2.97					

Leslie Gillespie-Marthaler (March 18, 2018)

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