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

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.

Keywords: Sustainable Resilience, Resilience, Vulnerability, Adaptive Capacity, Sustainability, Integrative Framework, 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., 2018a). 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., 2018a). 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. (2018a) 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. (2018a) 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 A.

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. (2018a) (Figure 1) 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. 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., 2018a). 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 2.

A more detailed representation of the process for assessing changes in sustainable resilience appears in Figure 3. 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 2).

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.

Navigating the Framework

Figure 3 provides a detailed illustration of the sustainable resilience framework. Below, we discuss each step in the framework in detail.

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 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

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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.

system conditions for a future time step whose length is based on the estimated time to reorganize the system.

Assessing Tradeoffs 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 1, 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]

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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.

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

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

extrapolate the magnitude of rainfall events associated with anomalies for future periods as described by Gillespie-Marthaler et al. (2018b). 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 4).

This analysis suggests that more severe flooding is expected 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.

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 5), were present throughout the system. While not completed in the preliminary analyses, a composite indicator could be constructed using the vulnerability

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

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]

[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.

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 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 6 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 6 also indicates that the home-buyout program

[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.

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 increase over time. The trajectories for property damage displayed in Figure 7 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). The trajectory for natural flood attenuation as shown in Figure 8 suggests that the home-buyout program adaptation scenarios slightly increase the environmental capital of the system by expanding riparian buffer zones. 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 6-8) 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.

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Appendix A

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 B

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.

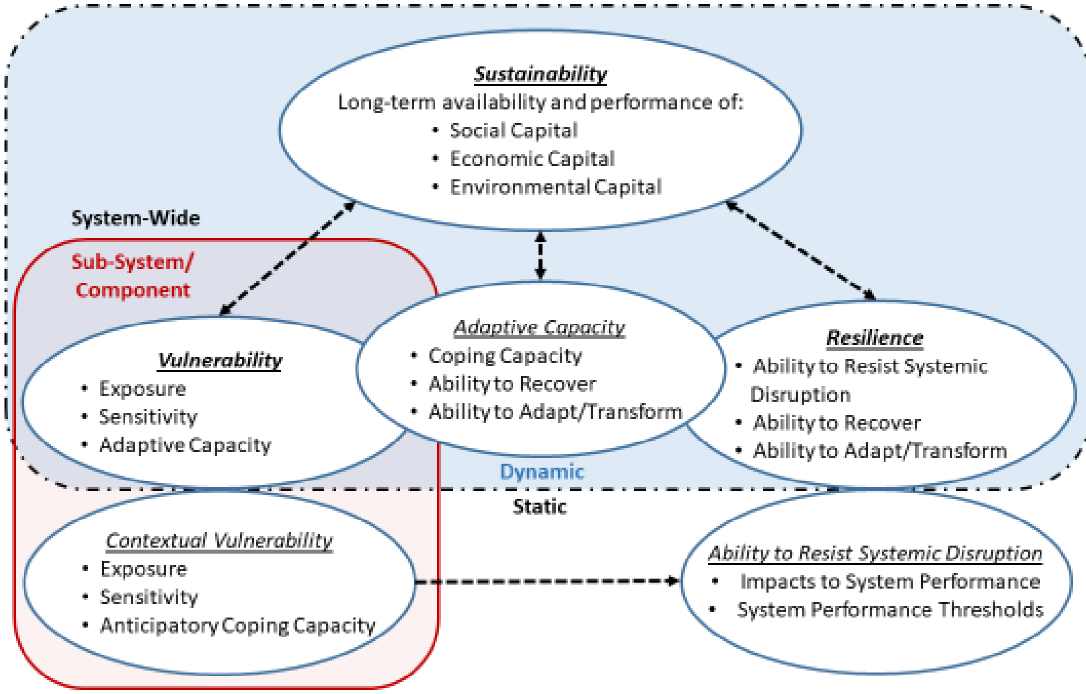

Figure 1: Assessing System Quality - Conceptual Linkages and Interactions (reproduced from: Gillespie-Marthaler et al., 2018a)

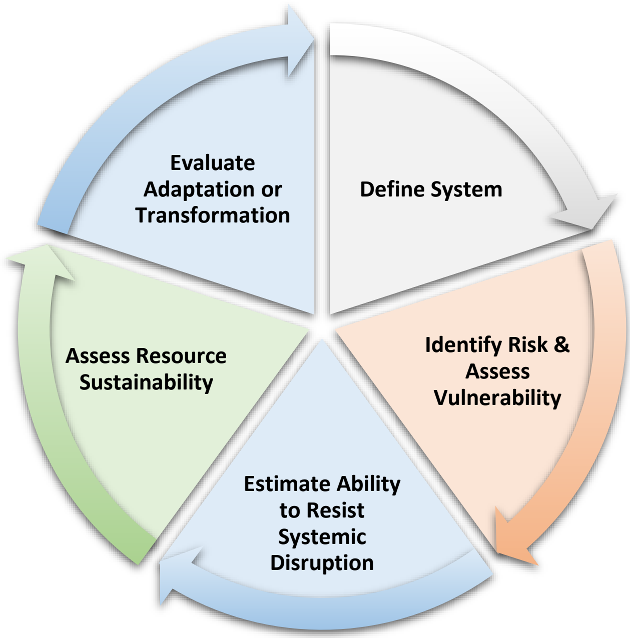

Figure 2: Macro-level Diagram of the Sustainable Resilience Assessment Process

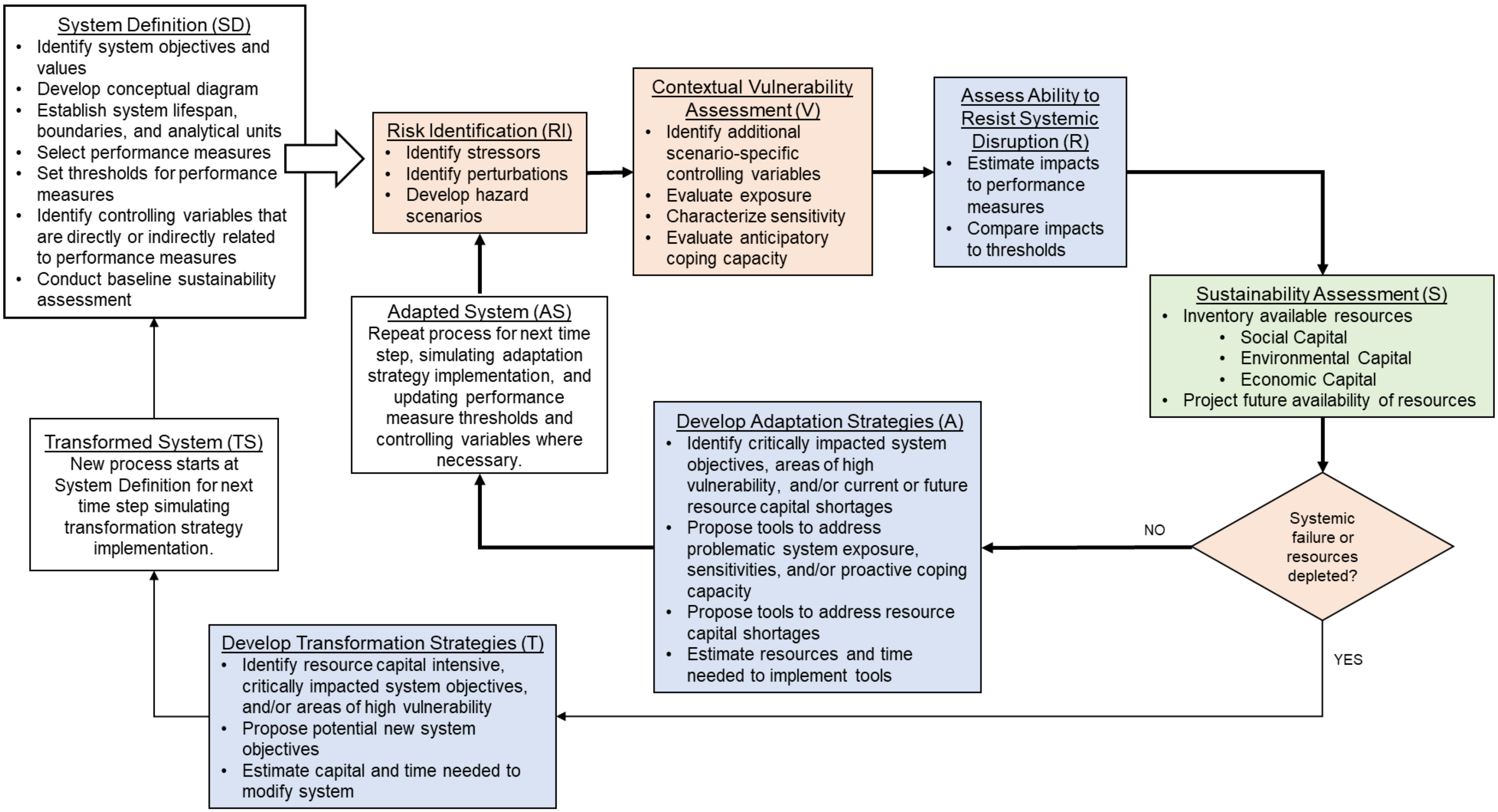

Figure 3: Sustainable Resilience Assessment Framework for Complex Adaptive Systems. [Operations associated with sustainability are shown in green, operations associated with risk and vulnerability are shown in orange, and operations associated with resilience are shown in blue. White indicates operations associated with all three concepts.]

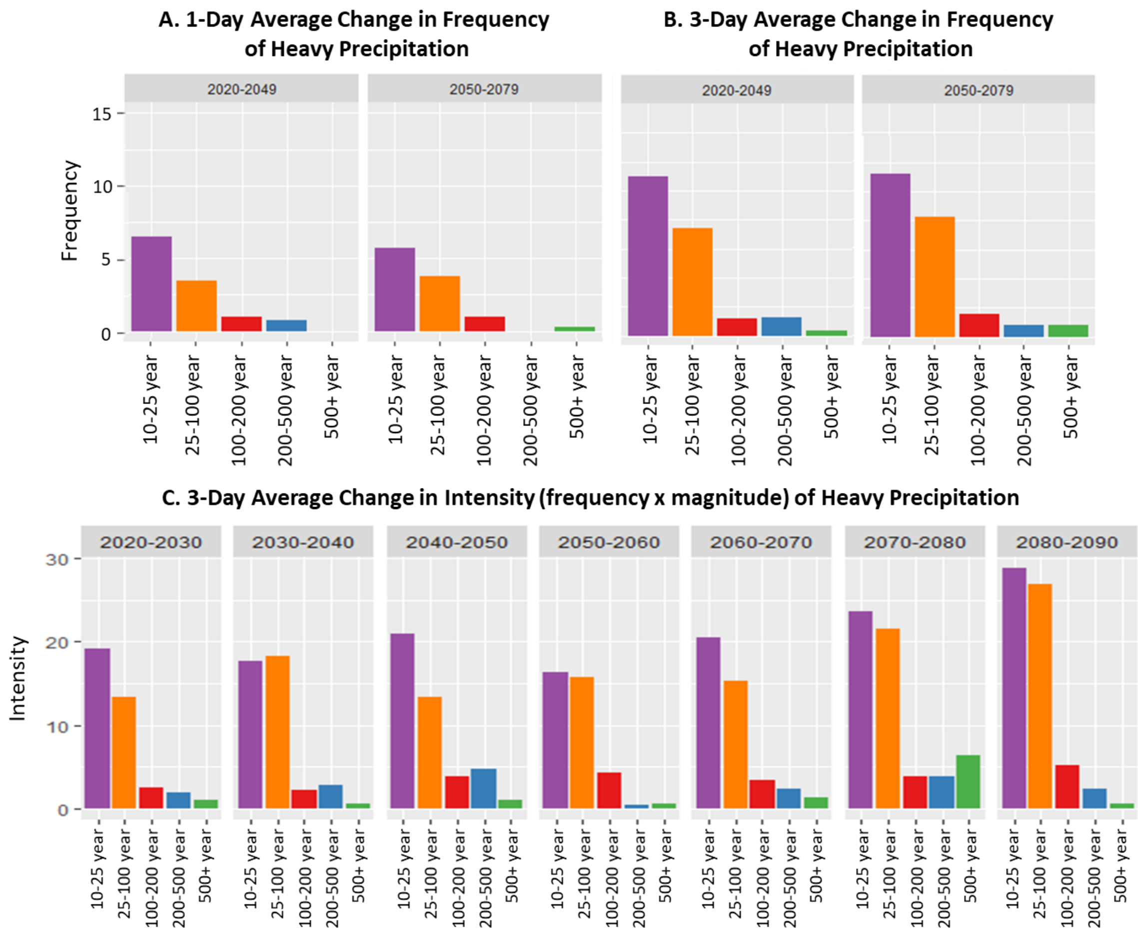

Figure 4: Analysis of Change in Frequency of Heavy Precipitation (modified from Gillespie-Marthaler et al., 2018b)

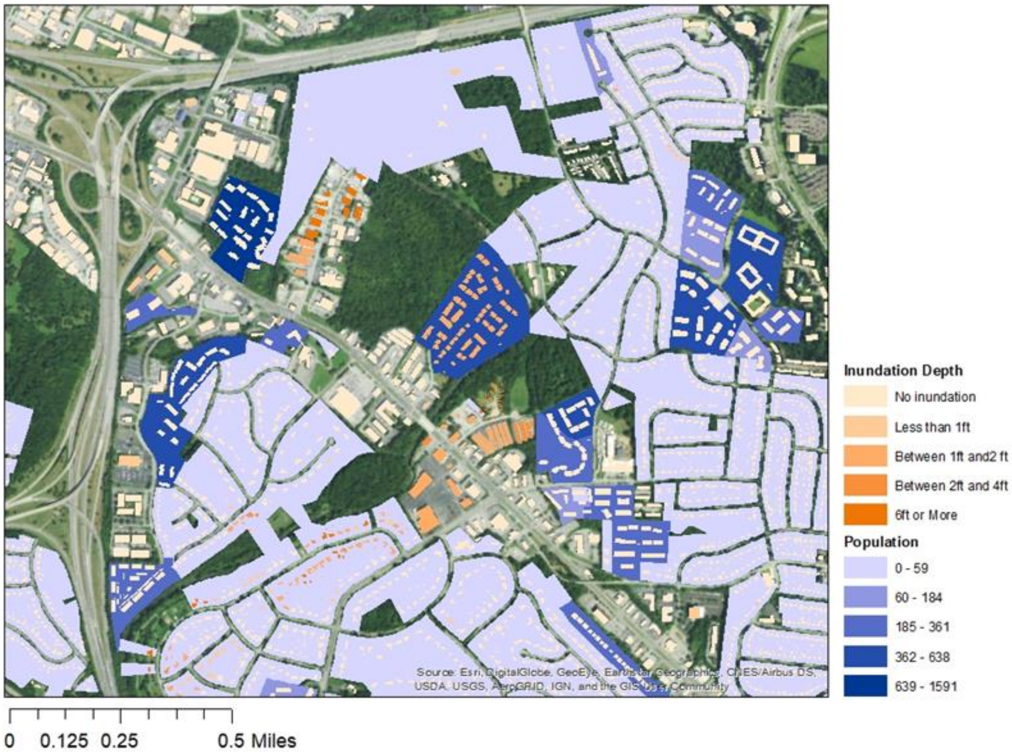

Figure 5: Spatial Distribution of Physical Exposure to Flooding and Resident Population (modified from Nelson, 2018)

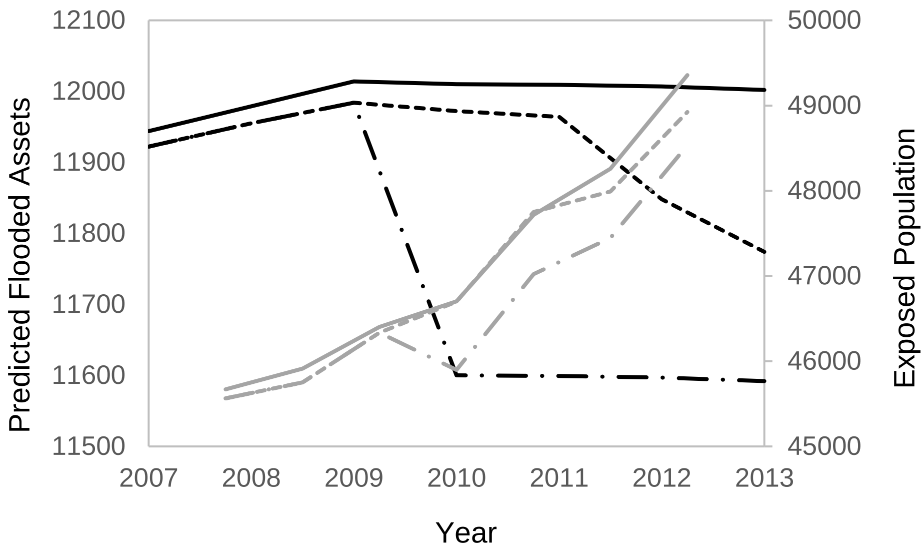

Figure 6: Trajectories for Damaged Property and Exposed Population (modified from Nelson, 2018) [Black lines correspond to flooded assets and grey lines to exposed population. Solid lines refer to a scenario with no home buyouts, dashed lines refer to a scenario with buyouts completed by the community, and dot-dash lines refer to a scenario with a rapidly expanded home buyout program.]

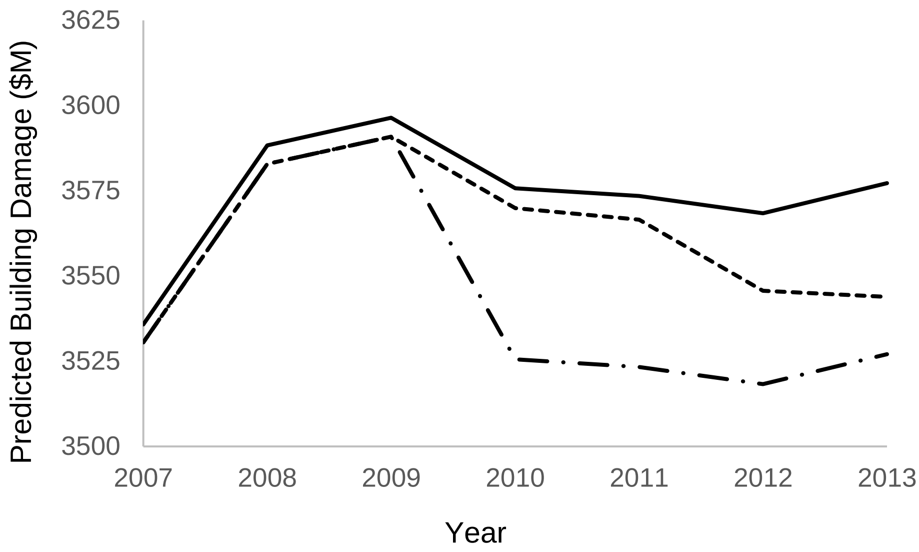

Figure 7: Trajectories for Building Damages (modified from Nelson, 2018) [The solid line refers to a scenario with no home buyouts, the dashed line refers to a scenario with buyouts completed by the community, and the dot-dash line refers to a scenario with a rapidly expanded home buyout program.]

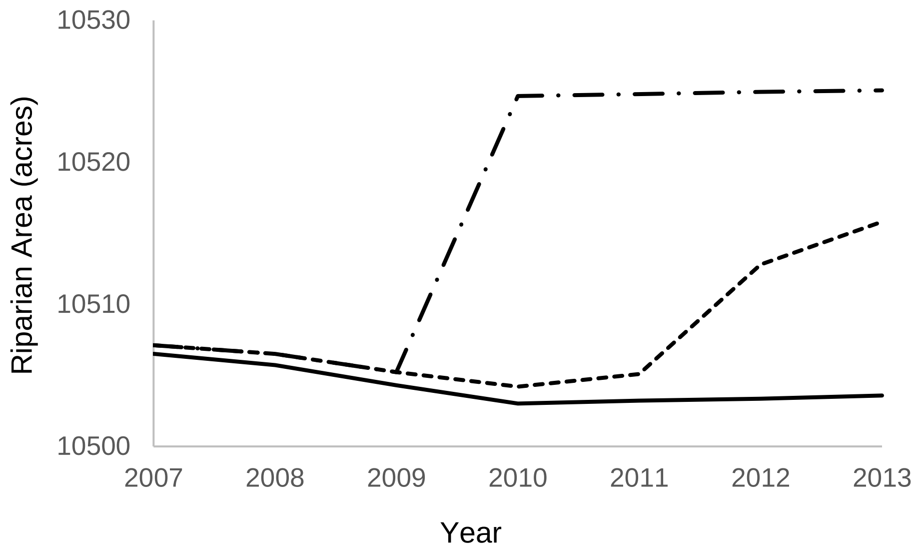

Figure 8: Trajectories for Riparian Area (modified from Nelson, 2018) [The solid line refers to a scenario with no home buyouts, the dashed line refers to a scenario with buyouts completed by the community, and the dot-dash line refers to a scenario with a rapidly expanded home buyout program.]

Figure 1: Assessing System Quality - Conceptual Linkages and Interactions

Figure 2: Macro-level Diagram of the Sustainable Resilience Assessment Process

Figure 3: Sustainable Resilience Assessment Framework for Complex Adaptive Systems

Figure 4: Analysis of Change in Frequency of Heavy Precipitation

Figure 5: Spatial Distribution of Physical Exposure to Flooding and Resident Population

Figure 6: Trajectories for Damaged Property and Exposed Population

Figure 7: Trajectories for Property Damages

Figure 8: Trajectories for Riparian Area