Chapter 2
Resilience Matrix for Comprehensive Urban Resilience Planning

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2.1 Introduction

The US Army Corps of Engineers (USACE) has a long standing mission and tradition of protecting people and property from flood damage for the safety and commercial success of the nation. Although this work began as protection from riverine flooding, it has grown to encompass coastal flooding from both tide and storm surge. Throughout the 18th and 19th centuries, local landowners built levees and dams to hold back flood waters and protect their own investments, but after several destructive floods and intermediate legislation, the Flood Control Act of 1936 (Arnold 1988) made it clear that national flood protection would be a responsibility of the federal government. For several decades the USACE sought to control floods through large-scale structures and centralized governance; though, eventually, the government recognized that these engineering approaches alone had a limitations and that the cost of constructing and maintaining massive projects was enormous. Thus the USACE ushered in an era of decision making based on a combination of probabilistic risk analysis and benefit-cost analysis (Moser 2011). Risk was defined as the "likelihood of occurrence and the magnitude of the consequences of an adverse event", effectively the equation: risk = probability × consequence (Moser 2011). In adopting this practice, the USACE and other federal agencies could now set a risk standard. If it is impossible—physically or financially—to prevent every possible flood threat, what level of risk is acceptable? The Federal Emergency Management Agency (FEMA) has used the 100-year flood as the "base flood", implying that lower probability events are beyond

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the government's responsibility to manage. The events that fall below this threshold are "residual risk." Federal risk management focuses on reducing or mitigating the unacceptable risk and but leaves residual risk largely overlooked. The existence of residual risk is also often poorly communicated to local communities. However recent low-probability high-consequence events—Hurricanes Katrina and Sandy in 2005 and 2012, the South Asian floods of 2007, the Sumatran earthquake of 2004, the Fukushima-Daiichi disaster in 2016—have forced a re-evaluation of this approach to risk management.

2.2 Challenges of Traditional Risk Analysis

In contemporary times we face several major challenges with respect to risk analysis and management for flooding and coastal storm events. The modern risk analysis process—as it is rigidly based in the calculation of hazard × vulnerability × consequence (HVC)—has several limitations. One, the current methodology is threat-specific; it does not include assessment measures for general capacity to respond to unexpected threats or integrated threat scenarios. Two, the risk analysis HVC calculation requires quantification of each of those three components. In an era of climate change and globalization, the data does not always exist to adequately describe the potential precipitation and storm conditions or the potential consequences. Three, the HVC calculation has no temporal component, no flexible way to account for how consequences migrate or compound over time if the recovery period is prolonged. Fourth, the methodology does not include any aspect of human behavior for the population that lives in the affected area. While some general demographics may be included in the calculation of vulnerability and consequence (how many potential lives are at risk), there is no understanding of the risk perception held by a community and their willingness or economic ability to put up temporary protections, to evacuate when notified, or to repair any damage. Thus, while the HVC calculation can and does reliably yield a risk value, it can also lead to a false sense of certainty, when in fact the extent to which the computed value reflects today's reality is increasingly questionable.

The risk management practices that result from risk analysis are equally challenged by these deficiencies. First, the process of risk management is enormously expensive for integrated complex systems. As we have already invested in many of the easy and affordable risk reduction measures, attempting to further reduce the risk of localized consequences is increasingly cost-prohibitive in light of the fact that humans, technology, basic utilities, and economic markets are so interconnected. Furthermore, as infrastructural changes are accomplished, the only remaining measures for risk management are more and more through organizational and behavioral changes, which carry long time horizons to complete and often face extensive resistance. Second, while the nature of some known threats are changing, such as coastal storm surge given sea level rise, there are also emerging threats, such as increased heating days and potential failures of technology (through intentional attack or delayed maintenance) that can compound more traditional threats. Third, risk management is focused on capital investment-based threat reduction and mitigation however, many governments or NGOs find that collecting and expending large amount of money to develop preventative measures against what are described as only "potential" events is politically or socially unpopular.

2.3 Resilience: A New Way Forward

Figure 2.1 describes the function of a generic system over time. The initial horizontal line describes business as usual. At the point that a disruptive event occurs, the system function rapidly decreases, and then once the threat has passed, the recovery phase begins. The level of functionality that is recovered depends on several factors; limited resources may prevent the system from full regaining its initial functionality, or conversely, ample resources and wise application of lessons learned may enable a greater level of functionality. Effective system management should aim to flatten out this entire curve, eliminating the disturbance basin, which would effectively indicate that performance holds constant despite an event. Risk analysis does not lend itself to this management goal because it really only describes the potential for initial loss, or maximum Δy. Risk analysis does not consider the sufficiency of the initial functionality (y_0) to provide for the community, or any component of time (Δx) including the shape of the recovery curve, or the final steady state achieved in anticipation of the next event (y_f).

In recognition of the shortcomings of risk analysis, the US National Academy of Sciences declared in "Disaster resilience: A national imperative" (Cutter et al. 2013) that a new paradigm is needed, and that this approach, resilience, is "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events." Former President Obama echoed this need for considering a system's

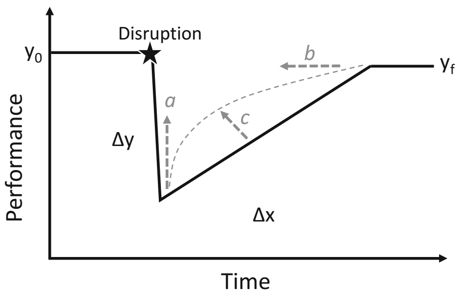

Fig. 2.1 System performance over the event cycle. Following a disruption, the initial performance (y_0) undergoes some change (Δy) but then recovers to a new steady state (y_f) of performance. The time period of recovery following the disruption (Δx) is a critical component of resilience. Resilience can be improved by reducing the magnitude of the disruption (**a**), reducing the time period of recovery (**b**) or changing the shape of the recovery curve (**c**)

entire functioning in a Policy Directive, stating that "'resilience' means the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recovery rapidly from disruptions" (The White House 2013). The European Commission followed by adopting a definition that says "resilience is the ability of an individual, a community or a country to cope, adapt and quickly recover from stress and shocks caused by a disaster, violence or conflict" (European Commission 2016). The emergence of these descriptions clearly indicate that traditional risk assessment must be augmented because it is not expansive enough to address the needs of modern societies for resilience (Linkov et al. 2014). Risk analysis only describes passive vulnerability of, or effects on, a system. The above definitions of resilience require understanding of a system's capacity to perform throughout a disruptive event: anticipate, prepare, plan, absorb, withstand, cope, respond, recover, adapt. Although many of the resilience assessments that have emerged in recent years cite these definitions, they unfortunately fail to explicitly address the temporal component of the event cycle (Bakkensen et al. 2016) into the methodology, instead opting for methods that closely resemble enhanced risk or vulnerability assessment. Indeed, the several past decades of risk management have worked only to reduce and mitigate the risk, shown as arrow (*a*) in Fig. 2.1, and risk management is an important component of resilience. However, the remaining opportunities to contribute to resilience through risk-based mechanism are often technically challenging and costly. As we see, the aspects of resilience that have not been adequately addressed by previous work are through reduction in the overall recovery time (*b*) and/or change in the shape of the recovery curve (*c*) to re-establish higher performance at an earlier point after the threat has passed.

2.4 Development of the Resilience Matrix

In developing the resilience matrix (Fig. 2.2), Linkov et al. sought a way to explicitly capture the capacity of a system across the timeline of a disruptive event. In doing so, they drew on the doctrine of network-centric operations developed by

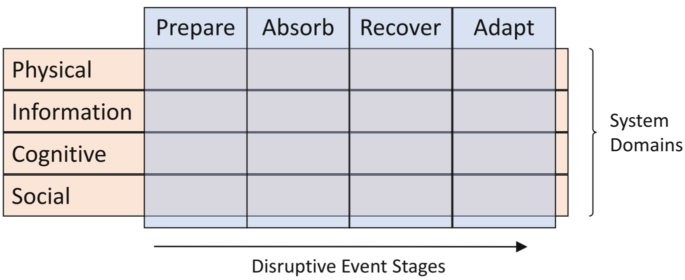

Fig. 2.2 Overview of matrix construction with the event cycle in the horizontal direction and system domains listed vertically

the US military's Command and Control Research Program (Alberts and Hayes 2003). This doctrine describes how a highly networked system is governed by domains that organize system components into measurable aspects. Organizing a system into these domains helps determine what the essential components of a system are and how they interact among themselves. The four domains are:

The **Physical domain** includes performance of the physical aspects of a system in space and time, dominated by the system infrastructure and equipment.

The **Information domain** includes the creation or collection, analysis, and dissemination of information. This can include sensor information about the health of the physical domain, demographic or behavioral information about the social domain, and methods for both gathering and sharing data in real time.

The **Cognitive domain** includes the organizational and institutional components of the system, specifically as they relate to decision making: who is empowered to make decisions and on what information are they basing decisions. This domain includes assessment of the degree to which plans and strategies exist, have been communicated and accepted throughout the organization, and if practice exercises have taken place to test and refine the plans.

The **Social domain** includes the human dimension of the system, especially those individuals not connected to the management and governance of the system. This includes individual citizens' and community groups' interaction, collaboration, and self-synchronization (Alberts and Hayes 2003).

A matrix emerges to facilitate a process for considering how each of the four system domains performs during each of the four stages of an event—prepare, absorb, recover, adapt—based on the National Academy of Sciences' definition of resilience.

The resulting matrix consist of 16 cells, each of which can be populated with metrics or other evaluations of performance. Most resilience assessments justify the inclusion of the various components of their assessments but few attempt to confirm that all of the relevant components have been captured. The 16 cells of the matrix capture how the system in question performs in the four general domains over 4 broad time steps of an event cycle. Collectively they describe the full system over time. By addressing each cell, users can be assured that they have not overlooked any major aspect of the system and that they have assessed the potential for an event to impact areas of the system that have not previously experienced problems. The process of utilizing the matrix to implement a resilience assessment and the ways in which each cell can be populated are described in the next sections of this chapter but some initial examples (Linkov et al. 2013) are:

- For a natural disaster, the capacity of the social domain to recover may largely depend on the financial resources of the community, diversity in the economy, and sense of place among residents.
- The cognitive-adapt cell can be used to capture how readily the existing regulatory and governance systems allow for the adjustment of current processes (such as building codes, critical services funding mechanisms, etc.) to accommodate the changing nature of the system and potential threats.

- In information-prepare cell, users can assess not only how well they can detect emerging threats and the state of knowledge that allows us to predict the timing, location, and severity, but also how well leaders understand the preparedness of the community and willingness to participate in mitigation activities.

The use of the matrix is based on a few key concepts of resilience. (1) Resilience is a property of a system, not a property of a component. For example, in this conceptualization, there is no meaning to a “resilient dam”, as the purpose of the dam is not to exist in perpetuity as a structure. Instead, the dam provides a service to the community such as flood protection, electricity generation, or maintaining water supply. What should be considered is the way in which the dam contributes to the resilience of the community system. (2) The focus of resilience is on maintaining functionality. Whereas risk assessment attempts to calculate the potential for losses and then prevent or mitigate those specific losses, the mindset driving resilience should be thought for what the critical requirements of the community are and how can those be maintained. This will be an important frame for generating resilience improvement plans. (3) As indicated in the definition of resilience previously cited, there must be an assessment of performance over an event timeline, and as such, (4) it will require collaboration across local, state, and federal partners, many of which are currently siloed into groups such as public works, emergency management, housing and economic development, and environmental protection. Lastly, (5) there must be elicitation and consideration of the values and preferences of the citizens and stakeholders. In a disaster, there will necessarily be trade-offs in performance between one area of the system and another. For example, roadways could be cleared more rapidly by pumping standing water and debris into nearby water bodies but this will reduce the water quality, affecting local habitats or environments that might be economically important (fisheries, tourism activities) or antithetical to local values. It is critical to engage stakeholders to understand their perspectives and generate acceptable solutions for improvement.

The goal of the resilience matrix is to provide a guiding framework to initiate conversation and engagement about resilience and to identify critical areas of poor performance for further investigation. As will be seen in the next section, the first steps are to define the system and the threat of concern, but independent of any assessment, the matrix can be used simply to identify and organize the relevant stakeholders and entities that have responsibility, authority, or capacity to perform in each of the cells. For an example, in Fig. 2.3 we examine a school seeking to assess its resilience to a tornado, an event that occurs with an annual season in the south-central plains of the United States.

In the physical domain, an engineer and the maintenance department are necessary to understand the current condition of the facilities and the potential performance during a tornado while the city department of transportation and/or publics works will need to be involved to understand the process of how roadway or pipeline damage will be repaired to restore access and service to the school building. The principal, superintendent and school board should be present to develop a common understanding of who is responsible for making the decision to

	Prepare	Absorb	Recover	Adapt
Physical	**Building Manager** Engineer	**Building Manager**	**Building Manager**	**Building Manager**
Information	Local Weather Forecast	Superintendent	School Board	Superintendent
Cognitive	**Principal**	**Principal**	School Board	School Board
Social	Teachers Students	Teachers Students	**Parents** Students School Board	Teachers **Parents**

Fig. 2.3 Resilience matrix populated with entities involved in each sector of a school anticipating a tornado event

initiate emergency procedures, based on what information, and how they will be implemented. In a tornado, it is generally best practice to shelter in place, therefore it will be critical to have teachers and students provide input on the current level of understanding and preparedness and the way in which directives are likely to be carried out in an emergency situation. In the past decade, the growing ownership of cell phones by students means that they can, and do, receive outside information, often before the school might have reached a decision point. Some students will individually choose to leave the classroom, causing disorder and reorganization of priorities for action among school officials. The school board will also have an understanding of what conditions any recovery plan must have to ensure that the education provided meets minimum standards. Representatives of parents and students should be able to indicate under what conditions and timeline they might choose to permanently move to another school. This will also be important to provide the district with information about the potential economic consequences since taxes on local homeowners provide the funds for the school budget. In sum, while the principal is usually the first to be identified as the leader of a school, there is a much broader net of stakeholders and experts involved in the system.

The matrix challenges the way the Corps of Engineers and the US federal government often approach problems and projects. While there is a general understanding that most community issues are interdisciplinary, a risk-based approach allows each agency to work on risk reduction within its mission and authority. For example, to prepare for a flood event, it could be that local leaders will work on educating residents and filling sandbags, states and counties will work on emergency shelters and supplies, and federal agencies, such as the Corps of Engineers, or the Federal Highway Administration will work on large infrastructure protection for their respective assets. The activities can be carried out largely independently; however, the recovery process necessitates much more interaction and communication. The emphasis of resilience on the effectiveness of the recovery and adaptation stages will require new organizational strategies.

2.5 Using the Resilience Matrix

The resilience matrix can also guide community leaders through a screening-level resilience assessment in a six-step process (Fox-Lent et al. 2015), as outlined below:

Step 1 Define the system. As demonstrated in the example above, a system may initially seem easily definable by its physical borders (e.g. a school building), but the integration of physical environment with other infrastructure and the humans who inhabit it, along with the various formal and informal decision making processes at play can rapidly expand the system boundaries. It is imperative that the user clearly select and define what will and will not be considered part of the assessment.

Step 2 Define the threat. Many approaches to resilience assessment attempt to offer an "all-hazards" approach. However, it is frequently clear by the metrics selected that the developer has used some internal set of threats to drive the development of the tool. For example, the methods that assess efficiency of emergency evacuation routes are not considering events like a tornado, where practice is to remain in place or terrorist attacks that occur without warning. In contrast, the method here simply asks users to define the threat, or suite of threats, under consideration to provide direction in the assessment and improve transparency of results.

Step 3 Identify critical functions. In this step, the resilience assessment process begins to differ from a risk analysis process. All systems perform functions, and while ranking them can be difficult, organizing them into tiers is often less challenging. Tier 1 functions are often those services directly related to securing life safety for inhabitants and can include shelter, fresh water, food, sometimes medical services, and sometimes electricity. These are the critical functions and are frequently necessary to ensure that Tier 2 functions can be re-established. Tier 2 functions are those that can acceptably experience decreased functionality during a disruption, but are important to return quickly in order to aid in recovery. While electricity and access to fresh water are only Tier 2 functions during the short duration of a tornado, their necessity to provide cooling during a heat wave make them Tier 1 functions for that scenario. Transportation may be a Tier 1 function during a forest fire to allow evacuation as the fire moves, but may be a Tier 2 function for a hurricane as it is not advised to travel during the hurricane, but many people many need to get to medical services afterwards. Education is mostly like a Tier 3 function for a community at large, but the school building itself may provide Tier 1 functions of shelter and a temporary medical triage site. While the environment or local ecosystem is rarely a Tier 1 function for most users, it can be an important Tier 2 function if the local economy is dependent upon environmental tourism (tourism, water sports, fishing) or is residents rely on the ecosystem for livelihood (organic agriculture, aquaculture, well water). A separate matrix will be completed for each critical function. To pare critical functions down to a manageable number for assessment, the list may be tailored based on the end purpose of the assessment. While it may be good to understand how well the electrical grids perform, these are largely managed by independent agencies therefore community leaders or state leaders will not be directly involved in making future investment decisions.

Step 4 Select performance indicators. The goal in this step is to select one or two measures that generally indicate the ability of the system to perform in each domain-phase (matrix cell). The goal is not to try to incorporate measures of every single process that occurs "on the ground". As a screening-level tool, the interest is in describing relative behavior amongst the cells to generate an overall picture of the system.

Previous work in the resilience field has led to the identification of several properties associated with resilience, among which are redundancy, flexibility, modularity, robustness, resourcefulness, rapidity, reliability, diversity, and adaptive capacity (Bruneau 2006; Norris et al. 2008; Renschler 2010). These principles can be used to generate performance indicators to populate each cells of the matrix. In general, the prepare phase will consider aspects of robustness within the system; similarly, the recovery phase will likely focus on rapidity or the timeliness of performance. However, there is no one-size-fits-all answer for pairing properties with components of a system. Some threats may warrant distributed and modular resources but centralized decision making while other system configurations may perform ideally with distributed decision making but centralized resource warehousing.

Some examples of indicators (Eisenberg et al. 2014) are:

- Information-Recover for bridge structure: Time required to gather—via visual inspection or sensor technology—necessary data to assess the extent of damage and develop a plan for appropriate repairs.
- Social-Prepare for an ecosystem: Measures of the initial species diversity, habitat, and diet.
- Physical-Adapt for a cybernetwork: Capacity of existing equipment to handle system-wide configuration changes, or, perhaps, given the business requirements, the fraction of hardware that can be physically separated from the global internet.

This step also allows the integration of "big data" to provide very specific metrics of performance over time. Yet as one point of caution, it is tempting to aim to incorporate all available data into the assessment despite some of it not being appropriate. Unfortunately it can often be the case that multiple measures in the data capture the same phenomenon or process. Forcing everything into the assessment can, at a minimum, be time consuming but more problematically can lead to over-weighting specific processes within the assessment (although the cellular structure of the matrix will minimize that effect).

Early on, the most useful data may not be available. In this case, the process of completing the matrix will help the user identify the need for any new data collection efforts. In the meantime, the framework allows for the incorporation of qualitative data. This can take the form of an expert assessment such as an engineer's "best professional judgement" or rubric used to select performance from a ranking scale such as "poor" to "excellent." To add rigor to qualitative measures, it can be useful to have several authorities with relevant experience make these judgements independently in order to gauge the variability or level of confidence in the result. In particular, it can be difficult to find indicators for the cognitive domain. More than likely, no objective measure for the quality of cognitive performance exists and a simple 'yes' or 'no' evaluation is not particularly useful. One option is to develop a checklist of increasing sophistication in the planning and decision process and use a count of the number of checkmarks as the indicators. For example, checklist items could include: does a plan exist? Were stakeholders involved in the development? Is the plan documented? Has the plan been disseminated to partners? Has there been a table-top exercise to practice and test the plan? Has there been a large-scale exercise in collaboration with other relevant agencies or groups? Is there a process to regularly revisit and revise the plan? This is similar to approaches used for assessment in the field of emergency management. Other examples of indicators, both qualitative and quantitative, are discussed in the latter case study sections.

Step 5 Calculate Scores. In this step, the indicators of performance are transformed into performance scores using established decision-analytic techniques (Linkov and Moberg 2011). This process establishes how the previously identified measurement falls within the context of locally acceptable performance. In most cases, a linear value function will be appropriate: the user defines two end points of unacceptable performance and ideal performance. The lower end point is set to 0 and the upper end point to 10 so that linear interpolation can be used to calculate the normalized value of the selected indicator. This is the most important step during which to engage with stakeholders, as setting the bounds establishes what the community considers to be good or poor performance and will drive priorities for new investments. For example, a metric for the social-prepare cell may be the percent of people who have participated in a community preparedness training. The worst possible end point would be 0% but while the best possible endpoint could be 100%, organizers may recognize that it is not achievable or cost-effective. Instead, it may be determined that 80% is an ideal target, under the assumption that the majority of citizens will then live in a household with someone who has taken the training and can share the knowledge. Continuing with this example, if 0% equals a score of zero and 80% equals a score of 10, and the actual measure is that 28% of community members are currently trained, then the cell receives a score of 3.5. Other value functions could be used; for instance, it may be justifiable to use an exponential curve for a value function if the measure selected clearly generates greater marginal benefit from each additional unit of improvement. Though, for a screening level tool, a linear value function is often adequate.

Step 6 Identify gaps and prioritize efforts. The final step is to examine and interpret the matrix results. At this point, the user will have generated a matrix for each critical function, each of which contains 16 scores. There is no single resilience score. Instead, these matrices collectively describe the performance of the system. In a first pass evaluation, the lowest scoring cells should be noted in order to highlight areas of overall lower performance. Since the four time stages comprise a cycle, and the four domains are integrally interconnected, resilience arises from strong performance across the system. This effort will be demonstrated in first case study. In a second pass, the matrix can then be used to evaluate and prioritize any proposed action plans by determining which cells of which critical functions should be targeted by the plans. Often, plans evolve to favor the most vocal representatives, the most visually apparent improvements, or the cheapest opportunities but these actions will have limited benefit if they do not address the lowest scoring cells. This process will be demonstrated in the second case study.

2.5.1 Case Study 1: The Rockaways, NY

In April 2014 an initial case study was undertaken by the USACE Risk and Decision Science team to test the application of the matrix. Hurricane Sandy made landfall in New Jersey as a post-tropical cyclone on October 29th 2012, generating a storm surge of 2.4–2.7 m along the southern coast of New York (Blake et al. 2013). The Rockaway Peninsula is a strip of land that extends between Jamaica Bay to the North and Atlantic Ocean to the South (Fig. 2.4). The Rockaway communities experienced the greatest effects of the storm in this region and in the post-storm activities several reports were published that provided data and community perspectives on the event. These reports were leveraged by Fox-Lent et al. (2015) to perform a retrospective pilot of the resilience matrix framework.

The system boundary was selected as the Rockaway Peninsula and the threat considered was a hurricane/tropical storm with significant storm surge. The area is largely residential and so for the pilot, a single critical function was selected (housing/shelter). The authors relied on several interviews with local community leaders, city after-action reports, and reconstruction plans to identify indicators. Indicators included “percent threatened population that report likely to evacuate before storm” for social-absorb, “time required to reconstruct beaches with dunes” for physical-recover, and “years for the Corps of Engineers to perform feasibility study, design, appropriate funds, and construct new flood risk reduction plan” for cognitive-adapt. As described in the previous section, the goal is to obtain an

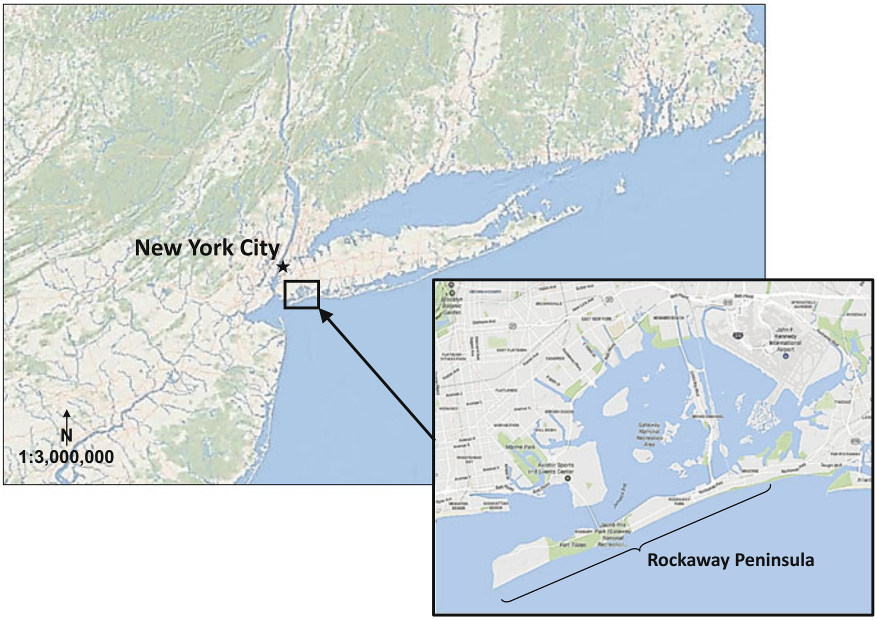

Fig. 2.4 Location of the Rockaway peninsula, New York City, United States. Map data: ESRI, Google

overview of the system by selecting indicators, not exact metrics or performance for each cell. Consequently, the matrix, shown in Fig. 2.5, summarizes the results using a relative color scale so as not to mislead users about the precision of the screening tool, but instead allow the identification of important trends.

The previous decades of effort at risk reduction and emergency management have led to stronger (or stronger perception of) performance in the prepare and absorb stages, while there is relatively weaker performance in recovery and even less for adaptation. The social domain appears to have adequate performance, perhaps in part due to the insular nature of these communities residing on a strip of land surrounded by water and with limited transportation connections. Although the indicator selected for the information-absorb cell shows weak performance, the

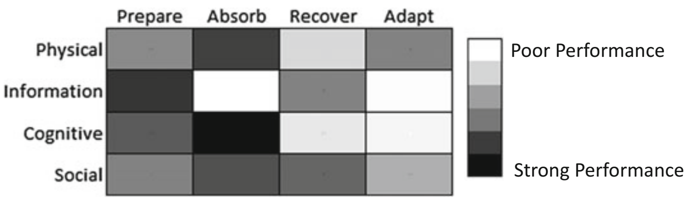

Fig. 2.5 Matrix results for the Housing/Shelter critical function at Rockaway. Adapted from Fox-Lent et al. 2015

cognitive and social domains exhibit strong performance during this stage. This may be a testament to the degree to which the preparation activities can support good performance even in the absence of good real-time information, or it may indicate the need to further investigate what non-traditional information pathways are being utilized. One goal of the matrix as a guiding framework is to organize data collection and facilitate communication. The act of performing the assessment can be an important learning process independent of any results. For example, in the execution of the above steps, the authors uncovered jurisdictional information that governs decision making in the study area. For example, the western end of the Rockaway peninsula hosts a private community, which means that they have sole responsibility for their land and neither state nor federal entities access the area. In direct contrast, on the eastern end of the peninsula, the majority of the residents live in city-owned public housing, which means that as individuals, residents cannot take the initiative to make any enhancements or investments in the physical infrastructure on their own. Thus, for more specific planning, it may make sense to create two separate matrices.

2.5.2 Case Study 2: Mobile, AL

On September 29th 1998, Mobile, Alabama experienced a Category 2 hurricane, Georges, that inundated the area both with rainfall and coastal flooding. Although Hurricane Katrina in 2005 eventually made landfall in New Orleans, earlier estimates of the storm track forecasted that the storm may have hit Mobile instead. In addition to the very present hurricane threat, Mobile is expected to experience up to 2.5 feet (0.76 m) of sea level rise over the next 100 years. As a result, area leaders have been keen to understand the region's resilience and in March 2015 a workshop was convened in Mobile through a collaboration of the National Oceanic and Atmospheric Administration (NOAA) and USACE to test and provide feedback on different research approaches to resilience assessment for the Mobile Bay region (Touzinsky et al. 2016). The resilience matrix was introduced to the workshop as an initial screening-level assessment to be considered by a panel of representatives from county and state planning and emergency management, environmental restoration, port management, and local commerce and construction.

The city of Mobile sits at the head of Mobile Bay (Fig. 2.6) and hosts both a large regional medical center, aerospace industry, and an active seaport, supported by growing populations on the eastern bank of the Bay. In addition, the Bay hosts fisheries and oyster beds and the barrier islands at the mouth of the bay area are a major regional destination for tourism and beach house investment (Swann and Herder 2014).

For the Mobile study, four critical functions were identified: housing/shelter, shipping, tourism, and the bay ecosystem. Although the workshop participants identified telecommunications and electricity as critical functions, these systems are privately or independently owned and operated and thus beyond the ability of the

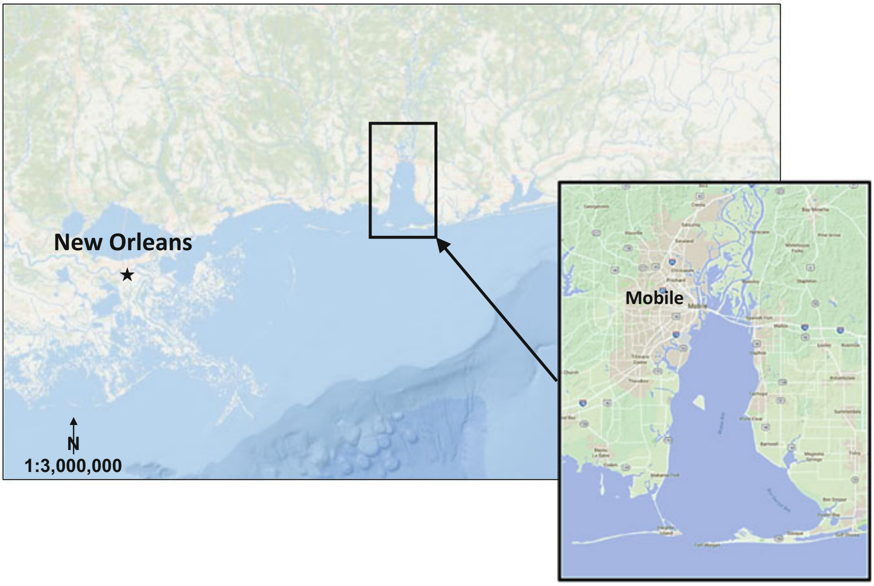

Fig. 2.6 Mobile Bay, AL. Map data: ESRI, Google, INEGI

local leaders to accurately assess. Participants were split into groups around each of the critical functions in order to discuss past performance, key issues, and ideal improvements. This activity was intended to benchmark the mental models of each participant to the same concept of what levels of performance constituted acceptable and unacceptable limits within the region. Next, each participant individually completed a survey asking about the capacity of the system to perform in each cell of the matrix. Figure 2.7 shows an excerpt from the Housing survey regarding the physical-adapt cell.

In this way, steps 4 and 5 of the resilience matrix method are combined to generate a score of strong or weak capacity to performance in each cell. The results of the workshop assessment are shown in Fig. 2.8. Initial observations reveal that the region has overall better capacity in the information and cognitive domains than in the physical and social domains. The tourism industry, as assessed, has strong

Physical Domain	**Not at all**	**Slightly**	**Moderately**	**Mostly**	**Very**	**Not Sure**
4) Adapt: How adaptable is the Mobile Bay Region community's housing/shelter assets to new storm conditions? Consider: • Ease and cost of adapting or moving housing/shelter assets to be more resistant • Room to add increased coastal protective structures as needed (increase dune height, add seawall, etc.)	○	○	○	○	○	○
	Increasing adaptability →					

Fig. 2.7 Example resilience matrix elicitation survey question for the Physical-Adapt cell of the Housing/Shelter critical function

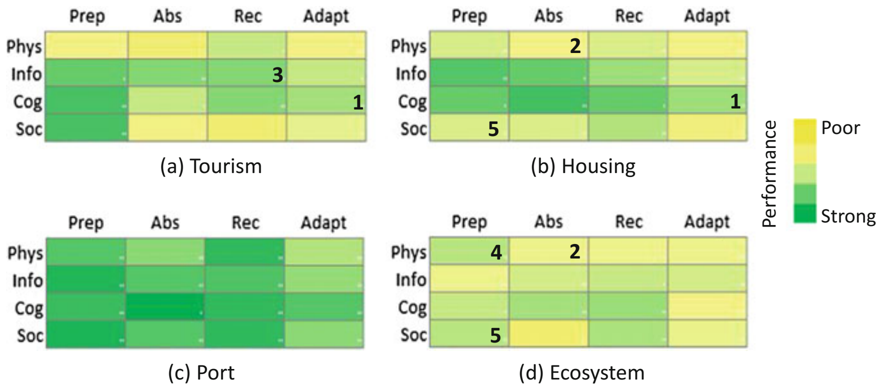

Fig. 2.8 Completed resilience matrices for four critical functions associated with Mobile, Alabama: **a** tourism to beaches, **b** housing for residents, **c** shipping activities at the port, and **d** ecosystem of Mobile Bay. Numbers indicate the cells which proposed improvements will affect

capacity in the prepare phase, but this does not appear to translate into supporting actual improved capacity to absorb. The sufficiency of the preparation activities may need to be reconsidered through community engagement. The port representatives reported a highly resilient capability for their part of the system to deal with immediate threats, but somewhat lower capacity to adapt to future conditions. Ecosystem advocate report that the historic focus has been on clean-up and recovery of the bay after storm events rather than efforts to prevent or minimize damage and this is borne out in the assessment.

To demonstrate the further utility of the resilience matrix in decision making, a selection of proposed resilience enhancements are evaluated by noting which cells of which critical functions each action will address. Five proposals are:

1. Building code improvements and enforcement for coastal structures, especially on the barrier islands.
2. Replace bulkheads along the bay with natural revetment and living shorelines to mitigate erosion.
3. Develop a network of licensed contractors certified in coastal storm damage mitigation techniques for businesses to access when making repairs.
4. Reduce impervious surfaces in new upland developments to retain natural drainage.
5. Continuing education on ecosystem services, fragility and human impact on ecosystem health.

The matrices in Fig. 2.8 have been marked with numbers 1 to 5 to indicate the parts of the system each project with affect. Even without attempting to quantify the extent of improvement in each cell, the matrices can yield information to help prioritize. Efforts to generate resilience improvement ideas suffer from some common challenges. It is difficult to generate fully new and innovative strategies so proposals tend to follow actions taken before. Depending on whom is involved, solutions can be overly focused on structural investments or other visual changes. By comparing the proposal to the assessed capacity of each cell, the user can determine whether the proposals meet the largest needs of the system or whether there are aspects of the system for which no proposals have be brought forth. Although the matrix methodology does not include a consideration of exactly how components of the system are related and interdependent, the default assumption is that in modern environments, any threat will have cascading effects throughout the system. To address this reality, the matrix can be used to assess proposals and select a portfolio of projects that collectively address the areas of the system with the lowest capacity for performance. In meeting this challenge, projects that address more than one critical function (or more than one threat), as do projects 1, 2, and 5, can be prioritized above those acting in the same areas but on only one function. This type of project evaluation can be used to describe qualitatively the benefits of any portfolio of projects and trade-off against cost, time, and other factors.

2.6 Lessons Learned

Urban environments often suffer from a tragedy of the commons. The density of inhabitants and the numerous public agencies can all to hope or assume that someone else is addressing looming threats. Landlords may assume that individual tenants will evacuate in some flooding events or otherwise take emergency measures while tenants may assume that the landlord has invested in protective measures for the building as a whole. Similarly, local governments may assume that the state or federal government will step into manage major disruptions, while the larger governments may expect local governments to be pro-actively preparing to manage themselves. The resilience matrix provides a framework to identify and bring together relevant players for urban planning, community development, disaster risk reduction and emergency management for structured conversations about performance expectations and responsibilities.

The two case studies described herein have gone further and attempted to assess local and regional resilience with both quantitative (Rockaway) and qualitative (Mobile) measures. There are several benefits of the matrix for resilience assessment. One, the use of qualitative measures allows communities to rapid screening level assessment even in the absence of qualitative data and funding. It is important to perform at least this initial level of assessment to avoid stagnation when there are a large number of unorganized stakeholders. The actual process of completing an assessment and examining the results can support further decision making in numerous ways. The gap analysis helps identify easy improvement actions that are broadly beneficial and the matrix itself is documentation to justify the shared use of funds between groups for these projects. For other actions, the assessment process can help explicitly bound the scope of collaboration so that agencies and community organizations can move forward independently, assured that their efforts are not redundant to or undermining others. Traditional risk analysis is often performed independently by each agency or organization and would fail to facilitate collaboration in this way. At the same time, risk analysis can still be an important component of a resilience assessment and the matrix can integrate the results of previous analyses as metrics within the cells.

In developing, testing, and sharing the resilience matrix the authors have revealed several challenges to this level of assessment. While a screening level assessment can help identify quick wins and other actions that are broadly useful, it likely cannot help differentiate between the benefits provided by similar alternatives. For example, with respect to coastal flooding, more detailed analysis will be needed to determine whether constructing a 3 m protective dune and purchasing 2 back-up generators provides more or less benefit than constructing a 3.5 m protective dune and purchasing only 1 back-up generator. Additionally, while the assessment process will reveal numerous relationships between different systems within a community, the matrix lacks a formal assessment of any interdependencies and their effects of overall resilience. As a consequence, the assessment can only consider components in the system with static properties. More advanced—though time-intensive—modeling, such as agent-based or network approaches, is necessary to identify emergent properties.

Two final limitations currently apply to all resilience assessments. First, the premise of resilience that the recovery period, beyond the immediate emergency response, is a critical component of resilience. However, to date, there are very few community or infrastructure systems with sufficient data on recovery processes. The matrix is able to incorporate estimates from professional judgement or rough indicators that can be drawn from public records (e.g. number of days until schools re-open, percent of homes still unoccupied at one-month after a disaster). The other limitation is that understating the performance of some public services such as electricity distribution and telecommunications is often crucial to helping a community recover. However, these are also often run by private or semi-private entities who keep performance information and emergency plans closely guarded both to protect a competitive edge in business and to protect knowledge of vulnerabilities for security purposes. The paucity of these data is a common challenge to urban planning, risk reduction, and resilience in general, but has been brought to the fore again in academic discussions due to the specific designation of the mid- to long-term recovery period as a focus of resilience.

Lastly, we return to the idea that resilience is about maintaining functionality rather than preventing specific losses. Traditional risk management results in investments or processes that are specifically intended to prevent some loss. Conversely, a resilience framework, such as the matrix, allows users to assess the contributions to the system as a whole for any proposed investment. A great example taken from the first case study is a neighborhood in East Rockaway that is constructing solar-powered street lights at the public library (NY Rising Community Reconstruction Rockaway East Planning Committee 2014). These lights will improve safety year-round and also will provide a lighted community gathering space with solar-power that can be tapped into for emergency operations.

The key component of the resilience matrix that supports this type of resilience decision making is the value function. Considering alternatives with respect to the value functions provides an assessment of marginal benefit that can be included in more traditional cost-benefit analyses to identify alternatives that not only enhance resilience to a specific disruption but also provides benefits to the community during the intervening times of normal operation. The field of urban planning has long used stakeholder engagement activities to gather input. Integrating the construction of value functions into these existing practices can help streamline the process and capture information in a mathematical formulation that can be used again for future decisions, whether for development, resilience, or risk reduction.

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