RESILIENCE TO EXTREME EVENTS

Lesley Ewing, PE, D.CE, M.ASCE[1] and Costas Synolakis, Ph.D. M.ASCE[2]

Coastal communities rely upon a range of protection elements, both constructed and natural, for resilience. Although extreme events might be assumed to be quite rare, given the level of protection that is available for many communities, extreme events can happen every few decades. Resilience of protection will diminish over time unless the elements are maintained, or in the case of natural systems, given the resources to expand and grow. As a result, communities with well-balanced and diverse resilience might find that resilience decreases with time. Extreme events or the consideration of extreme events through contingency planning and scenario development, provide valuable insights into the weaknesses in any resilience effort and help identify steps to enhance resilience for a broad spectrum of future conditions. This paper provides a definition for resilience that covers the pre-disaster conditions, disaster response and post-disaster recovery. It examines resilience of various protection management approaches for a hypothetical community. While a do-nothing approach can be the most cost-effective approach if there is no risk that an extreme event might happen, for situations where extreme events are possible, the resilience of a community can be enhanced by a modified status quo approach in which elements are maintained regularly and rebuilt to the current design standards when they experience significant damage.

Keywords: resilience, extreme events, coastal communities, contingency planning, disaster responses, adaptation, shoreline protection

INTRODUCTION

What is Resilience

Resilience is often identified as being a way to cope with disasters or hazardous situations and it is one of several poorly defined attributes such as sustainability or adaptive capacity that are often considered to be desired characteristics of a person, a community, or a system. In materials engineering, resilience is “the ability of material to absorb energy when it is deformed elastically and to return it when unloaded” (ASM International 2002) and in systems engineering, it is the “ability of a computer system to continue to operate correctly even though one or more of its components are malfunctioning.” (NTIA and FTSC 1996). To the person on the street, it is “the ability to recover quickly from difficulties” (OED, last visited 14 September 2012, www.askOxford.com).

The concept of resilience within a community or an ecosystem began to emerge in the 1970s, with work by C.S. Hollings and a group of resource scientists and ecosystem managers who established the Resilience Alliance (www.resiliencealliance.com) Within a community or an ecosystem context, resilience “determined the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving parameters and still persist.” (Holling 1973, p. 17) The concept of resilience was linked to adaptive capacity and an ability to deal with the unexpected -- “the ability of a system to absorb disturbance and still retain its basic function and structure.” (Walker and Salt 2006, pg. 1), or “the resilience framework … does not require a precise capacity to predict the future, but only a qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take.” (Holling 1973, pg 21)

Much has been written about resilience and it has been defined in a number of ways. Table 1 (included at the end of this paper) provides some of the many definitions that have been published recently. We add to this list, defining resilience in terms of both disaster response and post-disaster recovery. As such, **resilience is the ability to minimize the initial functional losses during a disaster (disaster response) and to achieve rapid restoration of critical functions following a disaster (post-disaster recovery)**. This post-disaster recovery does not necessarily require stability or a return to prior conditions. For example, the main function of a cargo port is to transfer, load and unload cargo. If a large part of a port’s cargo handling area had historically been dedicated to break-bulk cargo, but the port activity had shifted almost completely to containerized cargo, reconstruction of the pre-disaster proportion of break bulk facilities would not achieve recovery of the port’s function (i.e. transfer of cargo that is now coming into the port in containers). In the case of the port example, there will be known pre-disaster conditions that can be used to evaluate the recovery of the port and

---

[1] California Coastal Commission, 45 Fremont Street, Suite 2000, SF, CA 94105, USA
[2] Sonny Astani School of Civil and Environmental Engineering, Biegler Hall, BHE B12, University of Southern California, University Park, Los Angeles, CA 90089-0373, USA.

quantify its recovery, such as pre- and post-disaster revenues, TEUs (twenty-foot equivalent units), or value of goods shipped. Very often, there are no easily identified metrics to determine the pre-existing condition, the resilience losses, or the recovery. In some cases, "resilient systems may have no baseline to return to – they may reconfigure themselves continuously and fluidly to adapt to ever-changing circumstances, while continuing to fulfill their purpose." (Zolli and Healy 2012, pg. 13)

Resilience of Coastal Communities

One of the initial elements of resilience for coastal communities will be protection from coastal hazards – hurricanes, storms, tsunamis, erosion, flooding, and such. Communities can be protected using:

- Traditional engineering approaches such as seawalls, breakwaters, levees, revetments, beach nourishment and dune fields,
- Design efforts such as building elevation or fortification,
- Land use efforts that location key aspects of the community function in areas that are not subject to coastal hazards,
- Early warning and evacuation to remove people and key community elements from harm's way once a coastal hazard is imminent, or
- Some combination of all of these.

Resilient communities usually rely upon multiple efforts for protection, often using redundant systems for some of the most critical functions. This paper will focus on the roles of hard and soft armoring in community disaster planning and some of the lessons learned from recent disasters about the resilience of various protection measures.

What are Extreme Coastal Events

Extreme coastal events, as the name suggests, are somewhat rare or quite large storms or other coastal hazards. The Intergovernmental Panel on Climate Change (IPCC) defines extreme event, within a climate context, as "the occurrence of a value … above or below the threshold value near the upper (or lower) ends ('tails') of the range of observed values of the variable." (IPCC 2012, pg 30.)

For engineering structures, the design condition rather than the event history often provides the threshold for an extreme event. An extreme event will be anything beyond the design conditions of the structure. For example, if a levee is designed for no overtopping, then anything that causes overtopping might be considered to be an extreme event.

Since the start of the 21st century, there have been a number of coastal events that fit the definition of extreme. The Indian Ocean Earthquake and Tsunami (2004), Hurricanes Wilma (2005), Katrina (2006), Rita (2006), and Ike (2008), Cyclone Nargis (2008), the Chilean Earthquake and Tsunami (2010), and the Tohoku Earthquake and Tsunami (2011) were all disastrous events, causing loss of life and property, with coastal conditions far outside the realm of a "normal or average" event. These events were extreme, in that they were at or near the upper range of observed values. They also often exceeded the limits of the structures that had been constructed for community protection. Lessons from these events help determine possible options for improved future resilience – both in avoiding losses from future coastal hazard events and improving recovery following future coastal extremes.

LESSONS LEARNED FROM PAST EVENTS

The Importance of Engineering Details

For many coastal communities, engineering structures are a major aspect of the community protection from and resilience to coastal hazards. These structures provide resistance to the hazard, either as a physical barrier or through reduction of the incoming forces. Structures such as seawalls, bulkheads and levees provide protection from inundation and flooding by providing physical barriers between the water and the inland assets. Structures or features such as breakwaters, revetments, berms, and dunes provide protection by reducing incoming wave energy.

The effectiveness of physical barriers depends upon their being higher than the incoming water. Lessons from most of the recent coastal disasters have been that height and elevation are essential (Dalrymple and Kriebel 2005; Ewing and Synolakis 2010). The effectiveness of all the protective structures and features also depends upon their structural competence. The height of a structure is not important if the structure has collapsed. And, general observations by the authors from our experiences with post-disaster field investigations are that well-engineered structures often survive an extreme event. Engineering details that help hold a structure together during flooding or overtopping are good a solid foundation that is either deeply founded or anchored into bedrock; strong connections between elements (three-point contact for revetments or armor units, mechanical connections between concrete panels, caissons, wall segments, etc.); and walls that are tied into rock outcrops or a highly erosion-resistant material. (ASCE-COPRI-PARI Coastal Structures Team, submitted for publication).

Failures often propagate from a weak point. If foundations become unstable, connections fail, end points separate, or rock or concrete units get dislodged, additional failures or progressive losses can develop rapidly from one small point of failure. For example, many of the tsunami walls along the eastern Japan coast were earthen berms covered with concrete panels. Some of the dike failures that occurred during the Tohoku tsunami likely started as small movements of the concrete panels, possibly occurring due to uplift forces when the dikes were first overtopped. But once one panel became dislodged, the surrounding panels would become less stable. Continued overtopping could scour the earthen fill and remove more panels, rapidly reducing the cross-sectional area of the dike as well as its resistance to lateral loads from the incoming wave. The actual failure may result from lateral loads, yet the influence of overtopping, uplift forces and scour greatly reduced the stability of the dike, and assisted in the failure (ASCE-COPRI-PARI Coastal Structures Team, submitted for publication). And, if sections of the structure are not physically isolated by internal cell walls or other measures, once a small section of dike have been breached, the competence of the entire structure will be threatened. A cascade failure of adjacent wall sections often happens once one segment collapses.

Scour

Scour can be a major problem for structures exposed to high-energy or fast moving water. It is a well-recognized phenomenon; however, scour continues to be a source of many structural failures. It is often especially prevalent at the corners or end points of structures as well as at areas of flow convergence. For structures with little or no scour protection, structural failures or complete collapse can originate at these points of scour weakness (Ewing et al. 2011; ASCE Hurricane Ike Field Investigation Team, in production).

Beach scour is another type of sand loss that can be damaging to inland communities and facilities. The lower elevation can reduce stability of slab-on-grade foundations or foundations that are not deeply embedded. An overall loss of beach elevation reduces wave energy attenuation as waves break along the shore and rush up the beach face. This presents an additive threat to inland development, whereby the incoming waves are heightened by the reduced dissipation and the foundational support is compromised by the loss of sand.

Contingency Planning – Examining What-if Situations

One overarching lesson from disaster field investigations is the importance of contingency planning. Many of the collapsed shore protection structures along the eastern Japan coast had been designed with no inland scour protection and some without engineered protection of the inland face of the structure. Due to the height of the barriers, the design focused on the forces from the ocean, and did not consider the consequences of overtopping (ASCE-COPRI-PARI Coastal Structures Team, submitted for publication). Attention to scour protection, and inland stability might have improved the survival of some of the structures that breached or collapsed as a consequence of overtopping.

One goal of contingency planning is to avoid unplanned or catastrophic failure. This is done by trying to anticipate and understand all the possible failure modes, normally starts from scenario-based studies of risk and evaluation of vulnerabilities. It examines “tipping points” such as overtopping or a breach, or what can happen if one element of a protection system fails. Contingency planning also assumes that unexpected conditions may arise that pose threats beyond those that can be incorporated into the engineering design. It will be impractical, if not impossible to design all structures to withstand damage from an extreme event. Contingency planning can help identify the consequences of extreme events and lead to the inclusion of design elements that will control the propagation of small failures to prevent them from growing to become large disasters.

The Importance of the Survival of Protective Structures

There are several levels of success for coastal structures. The first level is that the structures perform as expected, provide complete protection to the inland community and remain stable and fully functional. The second level is that the structures do not provide complete protection to the inland community, but they retain their stability and can be used as part of the community recovery efforts. The third level of success comes from the protection provided by the structure prior to or in spite of collapsing. Prior to collapse, protective structures can postpone damage to inland areas, postponing the arrival of the disaster so that more people have time to evacuated. And, even in a collapsed condition, some structures may offer some protection. For example, the breakwater at Kamaishi collapsed during the Tohoku tsunami, yet it still reduced the inundation level within the coastal part of town from a modeled unprotected inundation height of 13.8 meters to an observed inundation height of 8 meters (Takahashi et al. 2011).

Even if the structures were not able to protect the inland community from an extreme event, if they remain stable and standing, they can be a valuable element of recovery. Their protection from smaller, less extreme events will still be important. Recovery takes time, and if a coastal community is left without any protection from waves or storm events, all the steps of recovery will be compromised by the threats from routine hazards. Structures that survive might not ultimately be appropriate for the overall rebuilding program and if that is the case, they can be removed or repurposed. Structures that fail offer no such option.

ENGINEERING COMMUNITY RESILIENCE

In general, extreme events occur when hazards either exceed the design conditions of the shoreline protection project or the project performance does not meet the design standards. Resilience covers efforts to more closely match design conditions to actual extremes that are at or near the upper limit of the observed values or the hazard, and efforts to improve project performance – both to reduce the losses that can result from an extreme event, as well as to hasten the community recovery following an extreme event. The response of a structure to conditions that exceed design conditions is an important aspect of resilience. If the structure collapses or experiences catastrophic failure, it might add to the inland damages. Also, community recovery would require reconstruction of the protective structure as part of the post-disaster activities. If the structure itself remains standing, there is the opportunity to incorporate that structure in the community recovery plan and in the post-disaster community and in future planning for resilience. The structure may not necessarily have to be part of the future community resilience plan; however, such planning flexibility is lost if the structure itself is destroyed or damaged beyond repair.

Project Design Conditions

In the United States, the 100-year design storm condition provides an arbitrary threshold for most extreme events, even though the 100-year event may not be near the upper range of observed values for the hazard. And, this threshold will decrease even further if the structure deteriorates or if the event is worsening over time such that the event with a 1% annual probability of exceedence becomes an event with a 2% or 5% probability of exceedence. Global sea level rise is one of the most frequently cited reasons for event probabilities to shift in frequency. A study of flood occurrence for San Francisco Bay had found that flooding associated with what is now considered to be the 100-year flood will become a 10-year event or even an annual with a rise in sea level of 1 to 1.4 meters (Knowles 2010). Other than sea level rise, land subsidence, shifting storm patterns and better understanding of the hazard event histories are other reasons for frequency shifts.

Project design conditions can also shift due to changing expectations. Extreme coastal events are, unfortunately, becoming annual occurrences. The consequences are fatalities and enormous property losses. In addition to the losses directly associated with the disaster, recovery efforts are expensive both financially and in terms of the building and material resources. Communities are questioning the utility of rebuilding protection of a similar type or efficiency to what had been in place prior to the disaster event. For example, long sections of the Galveston coast had relied upon coastal dunes with a geo-tube core for shore protection. Many of these protection structures were damaged or destroyed by Hurricane Ike and provided marginal protection from the hurricane (Ewing et al. 2009; Watson 2009). The authors were not able to find the design conditions for these structures; whatever the design level, it had been exceeded by Hurricane Ike. By 2009, the Texas Land Office and local governments removed the geo-tube structures from the beach whether damaged or not.

The levees around New Orleans are an example of structures that had been modified repeatedly to address changing conditions (Rogers 2008). After the failure of many of the levees around New Orleans during Hurricane Katrina, the city's flood defenses were examined and a redundant system has been developed. An Inner Harbor Navigational Canal Floodwall has been built 10 miles east of the city of New Orleans as a surge barrier that is expected to provide the primary defense storm defense and the levee system will provide secondary protection (DeSoto-Duncan, A. 2011). The New Orleans flood protection cost approximately $1 billion. However, the total damages from Hurricane Katrina range from $70 to $100 billion dollars (DeSoto-Duncan, A. 2011; USACE 2010; Blake and Gibney 2011). The surge barrier is designed to protect only a portion of the region that suffered damage from Hurricane Katrina; however, the $1 billion surge barrier is just 1% of the total damages from this one extreme event.

Structures do not maintain the same level of protection over time. For revetments, stones or armor units may move or become dislodged from the main structure. Movement of a few stones or armor units then reduces the three-point contacts within the revetment and reduces the overall stability of the structure. Concrete units may spall or crack following repeated exposure to wave attack and salt spray. Joints and connections can weaken with repeated impact. The end result is that, without monitoring and maintenance, the stability of most structures will diminish with time.

Resilience from Coastal Hazards

Resilience occurs at many temporal and spatial scales. Resilience elements that are very important at one scale may be rather ineffective at other scales. Drawing from the situation in Galveston, the geotube covered dunes were effective for small storm events and for keeping annual-level floods from over-washing the main roadway that served the communities south of the city of Galveston (Ewing et al. 2009). They were of minimal benefit for the large waves that accompanied Hurricane Ike.

The overall resilience to a coastal event results from multiple elements – some designed specifically for protection and others that have many purposes besides hazard resilience. In general, these multiple protection efforts fall into various spatial or temporal scales, as shown in Table 2. As an illustration from New Orleans of these difference resilience measures, the Inner Harbor Navigational Canal Floodwall and the coastal wetlands are the community-wide built and natural features, the levees and pumping system are the smaller local features and the building code and design of new structures will provide the site-specific resilience. The weather service and hurricane tracking system, augmented by educational material, practice drills, evacuations route signage and alert systems, provides the emergency warnings and evacuation features. The latter resilience element is useful for life-safety while the other elements address both property- and life-safety.

Table 2. Examples of Coastal Resilience Elements with Varying Temporal or Spatial Scales.

	Type	Spatial Scale for Effectiveness	Temporal Scale for Effectiveness	Financial Commitment
A	Constructed Structures Breakwaters, Surge Barriers	Community-wide	Decades to Centuries	Large Initial Cost Moderate Maintenance (Normally Public)
B	Natural Systems Beaches & Dunes, Wetlands, Reefs, Kelp, Coastal Forests, Mangroves	Community-wide to Local	Decades to Centuries	Low or No Initial Cost Moderate Maintenance Moderate to High Replacement Cost (Normally Public)
C	Seawalls, Bulkheads, Revetments, Levees, Pumps, Groins	Local to Site-specific	Years to Decades	Large Initial Cost Moderate maintenance (Public or Private)
D	Elevated buildings, Flood-proofing, etc.	Site-specific	Years to Decades	Small Initial Cost Low maintenance (Normally by owners)
E	Emergency Warnings & Evacuation	Regional to Community-wide	At time of an event	Moderate Initial Cost Small maintenance (Normally Public)

EXAMPLE OF COMMUNITY RESILIENCE AND EXTREME EVENTS

Resilience is an emerging community characteristic. There is no absolute system or upper limit for resilience. It is possible to generalize a community's resilience trend and use that trend to anticipate changes to resilience from various actions. The following example of resilience uses a hypothetical community and scenario based examination of likely risks and responses to hypothetical events. The hypothetical conditions are developed to help examine the consequences of the various scenarios and have value, only in their assistance in the comparisons between scenarios. The hypothetical community has a large offshore barrier system designed for the 100-year event. The natural shoreline features include submerged vegetation, scattered submerged reefs and offshore bars, and a beach. The more localized features are scattered seawalls and revetments, originally designed for the 50 to 100-year event, with limited maintenance since their installation. The buildings are of various ages with elevations for protection from 50-year to 100-year flood risk, also with limited maintenance since construction. The emergency warning and evacuation system is triggered for events greater than a 50-year event. The hypothetical events of significance over a 30 year period are small 10-year exceedence events in years 3 and 14, a large 100-year event in year 12, and an extreme event (i.e. one that exceeds 100-year design conditions) in year 27. This event scenario is arbitrary and intentionally places a large event and an extreme event within the 30-year window to test resilience to extremes. An examination for an actual community would be based on the resilience elements in place, local risk conditions, local building and repair costs, historic storm records and erosion and tsunami risk conditions.

The scenarios for consideration are:

- Do Nothing: community does nothing with any protective efforts; the effectiveness of the structures deteriorates over time; hazard conditions remain constant over time; if the structures are damaged, they are replaced or maintained to their original design conditions.
- Modified Status Quo: community maintains protective efforts at current effectiveness; hazard conditions remain constant over time; if the structures are damaged, they are replaced or maintained to 100-year design conditions or better
- Worsening Hazards plus Do Nothing: community does nothing with any protective efforts; the effectiveness of the structures deteriorates over time; hazard conditions worsen over time; if the structures are damaged, they are replaced or maintained to their original design conditions.
- Worsening Hazards plus Modified Status Quo: community maintains protective efforts at current effectiveness; hazard conditions worsen over time; if the structures are damaged, they are replaced or maintained to 100-year design conditions or better.

The resilience of the hypothetical community for these various scenarios is shown in Figure 1, assuming resilience from the various elements is additive. The scenarios assume that recovery may take multiple years for the various elements and that when more than one system is damaged or destroyed, the recovery efforts will focus on the larger systems first, drawing some resources away from the more local or site-specific elements. With this assumption, the more localized systems would take longer to recover after a large event than after a small event.

Hypothetical costs assume that a major regional structure would cost $500 million to build, local protection would be $100 million to build, and individual homes are $75,000. For each resilience element, a one-percent drop in functionality would be equivalent to 1% of the total cost for repairs or replacement. It’s also assumed that a 10-year event will damage or destroy 25 homes, a 100-year event will damage or destroy 750 homes and an extreme event will damage or destroy 2,500 homes. Finally, these scenarios assume that natural protection systems provide free resilience; they would retain the flexibility to adjust to changing conditions but would experience a drop in resilience after each major event. Figure 1 shows the temporal changes in resilience for these four scenarios.

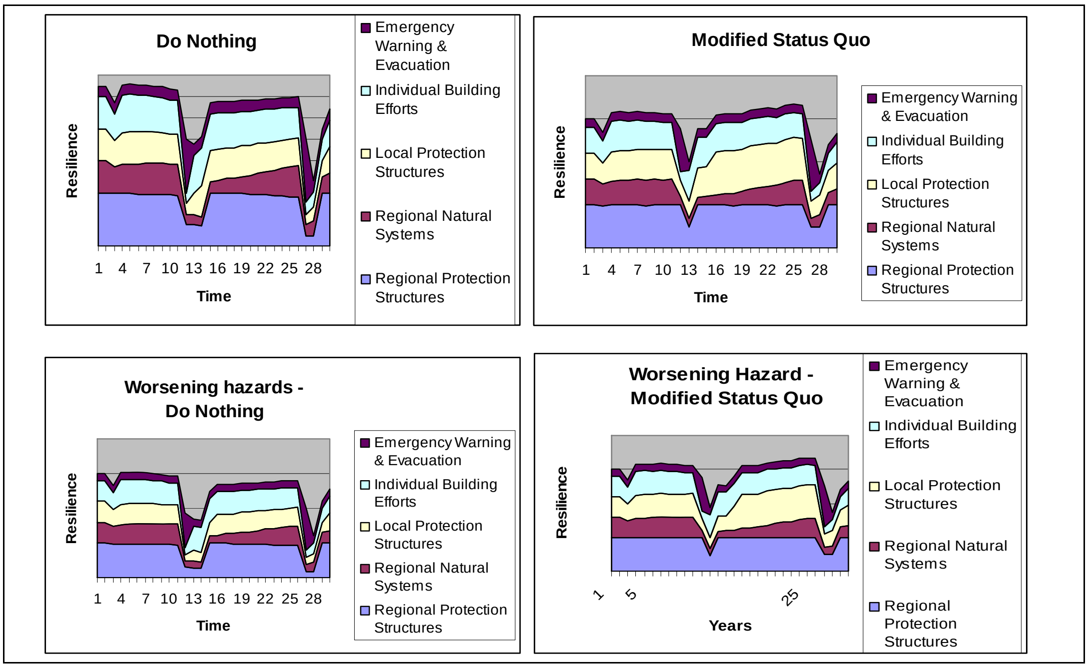

Figure 1. Comparison of resilience for four scenarios of hazards and patterns of repair and maintenance.

As can be seen from these hypothetical comparisons, the emergency warning and evacuation systems, while important for all scenarios, are more significant for the “do-nothing” scenarios than for the “modified status quo” scenarios in which systems are rebuilt to the 100-year design level rather than to their pre-event condition. And, as would be expected, the “modified status quo” scenarios maintain or improve resilience over time, even in the worsening hazards situation. The only improvement in resilience for the “do-nothing” approach comes from the increasing benefits assumed to result from natural system recovery. The improved resilience that develops in the “modified status quo” scenario from structural upgrades will level out over time as more of the structures are brought up to the 100-year design level. Under worsening hazard conditions, the 100-year design level would increase, causing a small increase in benefits for structural replacement as these higher design levels are incorporated into the mix of resilience elements. Eventually, a large turnover is structural design to a higher design level would only occur following an extreme event that would damage or destroy even the structures built to and continuing to perform at the 100-year design level.

The normal motivation for the do-nothing approach is financial. It’s often considered to be the least costly alternative – to avoid maintenance and then to do the minimum necessary to correct the problem. However, as shown in Figure 2, the benefits of inaction between damaging events might be lost through the costs of the post event response. Figure 2 only shows the hypothetical costs for the constructed protection; it does not include the costs that are transferred to the individual property owners as a result of lessening overall community-level protection and resilience. And, as the size of the event increases, the difference in post-disaster costs between the “do-nothing” and “modified status quo” increases as well.

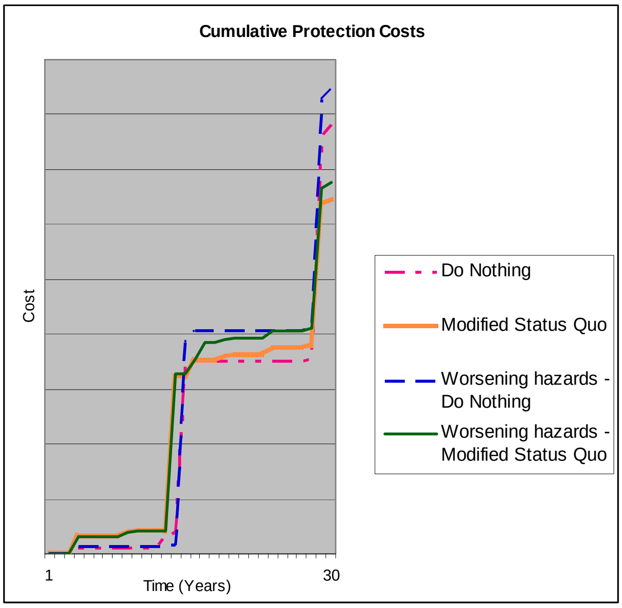

Figure 2. Comparison of hypothetical cumulative costs for patterns of repair and maintenance.

Modified Status Quo with Worsening Conditions -- An Example with Beach Nourishment

Beaches have become an important component of resilience for many coastal communities. Beaches provide social and recreational amenities, and also dissipate wave energy before it reaches the back shore. Some communities use beaches to protect from major storm events, whereas others rely upon beaches for smaller storm events and rely upon backshore structures for major events, or as a "last line of defense". However, beaches are dynamic systems and on eroding coasts, beach nourishment will provide only temporary relief from erosion. Thus, beach nourishment has, at times, been viewed as a pointless expense. Another perspective is that beach nourishment is an adaptive management approach that allows communities to extend the life of beach system beyond that time it would otherwise exist or in a more expanded condition that it might otherwise achieve.

The general purpose of beach nourishment is to add sand to a beach system to equal or exceed the volume of sand that is eroded away by wave action. Under a do-nothing approach, an eroding beach will continue to erode and eventually narrow so much that the back shore is at risk from erosion, inundation and flooding on a regular basis. The time until the beach narrows will accelerate under the do-nothing approach with worsening hazards scenario. The modified status quo scenario would add sand on a regular basis to maintain some desired beach width and the modified status quo with worsening hazards would add increasing amounts of sand to the beach to keep pace with the increased loss of sand that would be expected to occur for this scenario. And, many beaches will be able to persist during large storm events and under rising sea level conditions, with the regular addition of sand through nourishment.

The annual volumes of sand to keep pace with rising sea level are manageable – ranging between 300 to 10,000 m^3/km for most beach configurations and up to 18,000 m^3/km for very gently sloped beaches with a high elevation back berm (Flick and Ewing 2009). In a study of southern California beaches, approximately 600,000 m^3/km of nourishment would be needed over 100 years to maintain beaches with a 50 cm rise in sea level; with three major storms that would carry all the nourished sand off the beach, the nourishment volume would increase to about 1.5 million m^3/km for the same 100-year time period (Flick and Ewing 2009). For the 320 km of beach shoreline in southern California, the modified status quo scenario would require about 480 million cubic meters of sand. However, at $10/ m^3, the annual cost would be only about $48 million or less than 0.4% of the economic benefits associated with the existing beaches (Flick and Ewing 2009). As suggested by the relative costs shown in Figure 2, the costs to maintain various types of coastal protection is often well within the range of benefits provided by these systems.

CONCLUSIONS

This paper provides a range of definitions previously used to describe resilience and offered a new definition that explicitly covers the pre-disaster conditions, disaster response and post-disaster recovery. Resilience is a dynamic characteristic of the community and due to the different circumstances of each community, resilience, as now developed, can be used to only compare various options within a community and not to develop comparisons between communities.

Although extreme events might be assumed to be quite rare, given the level of protection that is available for many communities, extreme events can happen every few decades. Resilience of protection will diminish over time unless the elements are maintained, or in the case of natural systems, given the resources to expand and grow. As a result, even communities with well-balanced and diverse resilience might find that resilience decreases with time. Also, since sea level will continue to rise throughout the coming century, systems that maintain the same level of protection will be less resilience due to the increased threat from hazards associated with rising sea level.

Various management and maintenance options were examined for a hypothetical community. While a do-nothing approach can be the most cost-effective approach if there is no risk that an extreme event might happen, for situations where extreme events are possible, the resilience of a community can be enhanced by a modified status quo approach in which elements are maintained regularly and rebuilt to the current design standards when they experience significant damage. Drawing from a beach nourishment example from southern California, this modified status quo option has been found to be economically viable, based on the benefits offered by this activity.

Next steps for this examination of resilience will include the incorporation of cross-benefits from the resilience elements. The examination will also incorporate metrics to address the synergies and redundancies of the various resilience elements to assist communities in not only evaluating their current conditions, but to determine the benefits from enhancing or adding other components. Extreme events will rarely become the design standards for community protection and are not the main aspect for evaluation of a community's resilience. Nevertheless, extreme events or the consideration of extreme events through contingency planning and scenario development, provide valuable insights into the weaknesses in any resilience effort and help identify steps to enhance resilience for a broad spectrum of future conditions.

ACKNOWLEDGMENTS

The authors wish to thank Reinhard Flick for his involvement with the research about beach nourishment and contributions to the discussion of beach nourishment as a resilience element for coastal communities.

REFERENCES

ASCE-COPRI-PARI Coastal Structures Field Investigation Team (submitted for publication) ASCE-COPRI-PARI Coastal Structures Survey of the March 11, 2011 Great East Tsunami; May 11 – 17, 2011. American Society of Civil Engineers Special Report, Reston, VA.

ASCE Hurricane Ike Field Investigation Team (in production) A Report of Field Observations made 3 – 6 October 2008; sponsored by Coasts, Oceans, Ports and Rivers Institute and Geotechnical Institute of American Society of Civil Engineers.

ASM International. (2002) Atlas of stress-strain curves, 2nd e=Edition, ASM International

Berkes, F. and C. Folke. 2002. Back to the future: ecosystem dynamics and local knowledge. In Gunderson, L.H. and S. Hollings, *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press, Washington.

Blake, E.S. and E.J. Gibney. 2011. The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2010 (And other frequently requested hurricane facts). NWS National Hurricane Center, Miami. (http://www.nhc.noaa.gov/pdf/nws-nhc-6.pdf; visited 5 Sept 2012)

Dalrymple, R. A., and Kriebel, D. L. (2005). "Lessons in Engineering from the Tsunami in Thailand." *Bridge*, 35(2), 4 - 13.

Department for International Development, UKAID. ND. Defining Disaster Resilience: A DFID Approach Paper, pp. 20

http://www.dfid.gov.uk/documents/publications1/defining-disaster-resilience-DFID-Approach-paper.pdf)

Desoto-Duncan, A. 2011. The Inner Harbor Navigation Canal-Lake Borge Surge Barrier; presentation for the 2011 Infrastructure Systems Conference, Atlanta, GA; http://www.usace-isc.org/presentation/Civil%20Engineering/IHNC-Lake%20Borgne%20Barrier%20DeSoto-Duncan-Angela%20Revised.pdf; lasted viewed 5 Sept 2012.

Ewing, L, B. Jones, J. Marino, R. Noble, C. Petroff, S. Takahashi, Y. Tanaka, Y. Matsuzaki, K. Suzuki and H. Kojima. 2011. Performance of coastal structures in the March 2011 tsunami, Japan, *Shore & Beach*, v.79, n.3; 33 – 39.

Ewing, L., C. Synolakis. 2010. Community Resilience: Lessons from Recent Disasters, *Proceedings of the 32nd International Coastal Engineering Conference*, Shanghai, China, ICCE No. 32.

Ewing, L.C., D.K. Stauble, P.A. Work, B.L. Edge, S.M. Rogers, M.U. Loeffler, J.M. Kaihatu, M. Overton, J.P. Waters, K. Suzuki, R.G. Dean, M.H. Garrett, E. Wiggins, and G.H. Gregory. 2009. Field Investigation of Hurricane Ike Impacts to the Upper Texas Coast, *Shore & Beach*, v.77, n.2; 9 – 23.

Flick, R.E. and L.C. Ewing. 2009. Sand Volume Needs of Southern California Beaches as a Function of Future Sea Level Rise Rates, *Shore & Beach*, v.77, n.4; 36 – 45.

Godschalk, D.R. 2003. Urban Hazard Mitigation: Creating Resilient Cities, *Natural Hazards Review* 4(3) 136 – 143.

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

Intergovernmental Panel on Climate Change (IPCC). 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. *A Special Report of Working Groups I and II of the IPCC*, Cambridge University Press, New York.

Klein, R.J.T., R.J. Nicholls. F. Thomalla 2003. “Chapter 8: The Resilience of Coastal Megacities to Weather-related Hazards” pp. 101 – 120; in A. Kreimer, A., M. Arnold and A. Carlin (ed.). Building Safer Cities: The Future of Disaster Risk. 2003, The International bank for Reconstruction and Development, The World Bank. Washington, D.C.

Knowles, N. 2010. Potential Inundation due to Rising Sea Level in the San Francisco Bay Region. San Francisco Estuary and Watershed Science, v.8, n.1: http://escholarship.org/uc/item/8ck5h3qn

Luers, A.L. and S.C. Moser, 2006. Preparing for the Impacts of Climate Change in California: Opportunities and Constraints for Adaptation, California Climate Change Center, Sacramento, CA.

McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, K.S. and White. 2001.Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working group II to the *Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

National Science Technology Council, Committee on Environment and Natural Resources. 2005. Disaster Reduction 2005, *Grand Challenges for Disaster Resilience*., Washington, DC

NTIA and Federal Telecommunication Standards Committee. (1996). Glossary of Telecommunication Terms FED-STD-1037B, General Services Administration, Boulder, CO.

Rogers, J.D. 2008. Development of the New Orleans Flood Protection System Prior to Hurricane Katrina, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, v. 134, n. 5, 602 – 617; doi: 10.1061/(ASCE)1090-0241(2008)134:5(602)

Takahashi, S., Y. Kuriyama, T. Tomita, Y. Kawaii, T. Arikawa, D. Tatsumi, and T. Negi (2011) Urgent Survey for 2011 Great East Japan Earthquake and Tsunami Disaster to Ports and Coasts – Part I (Tsunami). *Technical Note of Port and Airport Institute*. Vol. 1231.

United National International Strategy for Disaster Risk Reduction. 2004. *Living with Risk: A global review of the International Strategy for Disaster Reduction* (UN/ISDR), Geneva, United Nations, p. 16 – 17.

U.S. Army Corps of Engineers (ASACE) 2010. IHNC-Lake Borge Surge Barrier; Fact Sheet; http://www.mvn.usace.army.mil/pd/projectslist/projectdata/300/300.pdf (last viewed 5 Sept 2012).

U.S. Indian Ocean Tsunami Warning System Program. 2007. *How Resilient is Your Coastal Community? A Guide for Evaluating Coastal Community Resilience to Tsunamis and Other Hazards*. U.S. IOTWS Document No. 27-IOTWS-07. Bangkok, Thailand.

Walker, B, C. Folke, S. Carpenter, M. Scheffer, T. Elmqvist, L. Gunderson, C.S. Holling. 2004. Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*. Vol. 35: 557 – 582.

Walker, B. and D. Salt. 2006. *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*, Island Press, Covelo.

Watson, R.L. 2009. Evaluation of coastal response to Hurricane Ike through pre-storm and post-storm aerial photography, *Shore & Beach*, v.77, n.2; 49 – 59

Zolli, A. and M. Healy. 2012. *Resilience: Why Things Bounce Back*. Free Press, Simon & Schuster. New York, p. 326.

Table 1: Various Definitions of Resilience

Definition	Focus	Source
The ability to minimize the initial functional losses during a disaster (disaster response) and to achieve rapid restoration of critical functions following a disaster (post-disaster recovery).	Pre-disaster conditions Post-disaster recovery	Ewing and Synolakis 2012
Coastal resilience is fundamentally about mitigating vulnerability for human communities and natural resources simultaneously	Socio-ecological systems Coastal areas Climate change	The Nature Conservancy (http://coastalresilience.org.strategy/faq)
Resilience is the capacity of human and natural/physical systems to adapt to and recover from change. (…) Enhancing resilience requires adjustment to day-to-day living as well as adjustments to processes of long-term settlement and development of coastal areas.	Coastal areas Climate change	Gulf of Mexico Alliance (http://www.gulfofmexicoalliance.Org/issues/resilience.php
Disaster resilience is the capacity of a community exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure.	Pre-Disaster conditions Communities	National Science Technology Council 2005
Resilience is determined by the degree to which the community is capable of organizing itself to increase its capacity for learning from past disasters.	Post-disaster condition Communities	National Science Technology Council 2005
Community resilience is the ability of a community to respond to or recover from systemic disturbances, including climate-related effects on the environment, economy, and society.	Post-disaster condition Coastal hazards Climate change	Oregon Sea Grant http://seagrant.oregonstate.edu/sgpubs/coastal-resilience
Coastal Resilience is an ecosystem-based coastal and marine spatial planning framework that utilizes sea level rise, storm surge, ecological, and socioeconomic spatial information to identify and implement ecosystem-based adaptation strategies	Socio-ecological systems	http://coastalresilience.org
Ecosystem resilience is the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes.	Disaster losses Post-disaster recovery	Resilience Alliance (http://www.resalliance.org/index.php/resilience)
A resilient community is one that takes intentional action to enhance the personal and collective capacity of its citizens and institutions to respond to, and influence the course of social and economic change.	Pre-disaster condition	United National International Strategy for Disaster Risk Reduction. 2004
The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures.		United National International Strategy for Disaster Risk Reduction 2004
The capacity of a community to adapt to and influence the course of environmental, social, and economic change.		U.S. Indian Ocean Tsunami Warning System Program 2007.
The capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedback.	Socio-ecological system On-going resilience	Walker et al. 2004
The capacity to manage through drought or other type of hazard without suffering lasting negative impact.	Socio-ecological system	USAID Resilience Vision Paper
The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner including through the preservation and restoration of its essential basic structures and functions.	Disaster Risk Reduction	UN International Strategy for Disaster Reduction
Disaster resilience is the ability of countries, communities and households to manage change, by		Department for International Development, UKAID.

maintaining or transforming living standards in the face of shocks or stresses – such as earthquakes, drought or violent conflict – without compromising their long-term prospects		
Coastal resilience refers to the ability of linked social, ecological and economic systems within the coastal zone to adapt to and recover from disturbances such as hurricanes, tsunamis, floods, sea level rise, and harmful algal blooms. A resilient coastal community can absorb shocks while maintaining function. When change does occur, resilience promotes renewal and reorganization.	Post-Disaster recovery Coastal areas	Berkes and Folke 2002
Coastal community resilience can be strengthened by decreasing the probability of a hazardous event, avoiding or mitigating the potential effects of a disturbance and/or facilitating recovery after a disturbance has occurred.	Disaster risk reduction Post-Disaster recovery	McCarthy et al. 2001
Common characteristics of resilient systems include redundancy, diversity, efficiency, autonomy, strength, interdependency, adaptability, and collaboration.	Disaster reduction	Godschalk 2003
Resilience is best used to define specific system attributes, particularly: • The amount of disturbance a system can absorb and still remain within the same state of domain of attraction; and • The degree to which the system is capable of self-organization.	Coastal mega-cities	Klein et al. 2003
The ability of a system and its components part to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.	Disaster reduction, Post-Disaster recovery	IPCC 2012
The capacity of a system, enterprise, or a person to maintain its core purpose and integrity in the face of dramatically changed circumstances. ,,,,, Resilient systems may have no baseline to return to – they may reconfigure themselves continuously and fluidly to adapt to ever changing circumstances, while continuing to fulfill their purpose.	On-going change	Zolli and Healy 2012