Opportunities for Climate Resilience

The Beaches of Stamford, Connecticut

A Report for the City of Stamford Land Use Bureau

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Executive Summary

What is the problem?

Historically, large coastal storms have damaged Stamford's beach parks. The high and powerful waves during these storms have flooded the parks, spreading the sand far beyond the beach. The flooding also has damaged park facilities and landscaping. Most recently, damage from Hurricane Sandy resulted in the closing of the parks for several weeks and in cleanup and repair costs of about $2.5 million. Scientists predict a higher frequency of large storms over the rest of this century, which means that the risk of damage to Stamford's beach parks will increase.

What is the solution?

The solution to this problem is to make Stamford's beach parks more resilient to storm damage. In other words, the solution is to improve the capacity to recover from or adjust to storms. In Stamford, greater resilience would mean less storm damage, reduced cleanup and repair costs, and shorter park closures. Cities in the United States that manage coastal areas typically have turned to engineering technologies, such as seawalls and dunes, to improve resilience. But improving resilience is more complicated than choosing among available technologies. Three main factors complicate finding a solution:

(1) Beaches are dynamic.

Beaches constantly change in response to natural processes such as waves, winds, and tides. Coastal storms, which alter the usual pattern of waves, winds, and tides, can cause beaches to change shape and location dramatically. Stamford witnessed this dynamism firsthand during Hurricane Sandy, when nearly two feet of sand was moved from the ocean and beach face up onto the Great Lawn and picnic area. As George Wisker (2013) Coastal Geologist for the state of Connecticut, put it: "There will always be beaches, they just may not be where you want them to be."

(2) The risk to Stamford's beach parks increases over time.

The Earth's temperature is increasing, which is likely to result in stronger coastal storms. Along with stronger storms, scientists forecast that sea level will continue to rise – even faster than it is today. These two changes together are expected to result in more instances of severe flooding. In the next 30 years, flooding that we currently expect to occur once every 100 years (1-in-100 year flood) is predicted to occur every 35 to 55 years.

(3) Uncertainty increases over time.

As is the case with any prediction, the uncertainty associated with the risk to Stamford's beach parks also grows with time. For example, scientists are virtually certain that sea level will continue to rise over the next five years, but they are less certain that this trend will persist a few centuries from now. Growing uncertainty means that any method for improving beach resilience ought to be adaptable to the changing climate.

Improving the resilience of beaches may be possible in the short term, under current or near-current climate conditions, through the use of engineering technologies. But as climate changes more drastically over time, engineering solutions may either fail or become overly expensive. The only real solution may be to yield to the dynamic nature of beaches, allowing them to move landward. Take Cove Island Park, for example: Hurricane Sandy deposited about two feet of sand on the Great Lawn – this area could become the location of the beach by the end of this century. Similarly, at Cummings Park, the parking lot could become the new beachfront.

How can Stamford make its beach parks more resilient?

Various engineering technologies exist for improving resilience to storm damage in the coming years. These technologies are divided into two categories: hard engineering and soft engineering. Hard engineering technologies include breakwaters, revetments, and seawalls – durable, solid structures designed to withstand high impacts and to last for a long time. These technologies tend to be expensive to construct and often can cause more problems (e.g., erosion) than they solve. Soft engineering technologies include beach nourishment and sand dunes – comparatively lower cost structures designed to mimic natural processes. Soft engineering technologies, however, tend to have a shorter lifespan. One of the important differences between hard and soft technologies is that soft engineering accommodates for changes in risk and uncertainty over time, whereas hard engineering does not afford this same flexibility.

In evaluating resilience options for the City of Stamford, we took into account three main factors: the goals of improving resilience to storm damage and preserving the aesthetic and recreational values of the beach parks; the increasing risk of damage from more frequent strong storms and sea level rise, which is the reality of changing climate conditions; and the dynamic nature of beaches. We concluded that technologies for improving resilience would have to be able to change over time. Interviews with coastal resilience experts and shoreline managers made it clear that even in the short term, static engineering technologies, such as revetments and seawalls, would not improve resilience.

We developed a set of criteria by which to evaluate the various technologies: (1) **feasibility,** (2) **effectiveness,** (3) **cost-effectiveness,** (4) **flexibility,** and (5) **additional benefits.** We found that vegetated sand dunes with geotextile tubes are the best option for improving resilience at Stamford's beach parks.

Vegetated sand dunes with geotextile tubes

Vegetated sand dunes are an effective way to block wind, to absorb wave energy, and to reduce flooding from storm surge. Constructing dunes with geotextile tubes, which are fabric tubes filled with sand, helps to stabilize and reinforce the dune. The use of this technology also makes the dunes more durable because the fabric is resistant to erosion. Once placed on the beach, the geotextile tubes are then covered with sand and native plants to secure the structure and give the appearance of a natural dune. Such dunes of appropriate dimensions and without any breaks could improve resilience by providing a buffer between the ocean and the beach parks. When storm surge is high and waves pound against the dunes, only the outside layer of sand is washed away – the inner tube structure remains in place.

- **Pros:** Can use geotextile tubes to create taller, steeper dunes than is possible with sand alone; and geotextile tubes resist erosion from storm damage, which makes the dunes more durable.
- **Cons:** If the geotextile tube center is exposed during stormy conditions, the beach area in front of the dune is prone to increased erosion; the use of geotextile tubes makes the dune less flexible as it cannot migrate naturally in response to changing sea levels and storm conditions; maintenance includes periodic beach nourishment, which can be costly; and these dunes are more costly to build than are un-enhanced dunes.

Another option is to **build vegetated sand dunes using only locally sourced sand and native species of plants** – that is, without geotextile tubes. Many geologists and coastal managers, whom we interviewed, said that these types of dunes are preferable because they work *with,* instead of *against,* the natural coastline systems.

- **Pros:** Dunes could migrate landward naturally, if infrastructure were adjusted, to adapt to changes in climatic conditions; and these are less costly to build than are dunes with geotextile tubes.
- **Cons:** These dunes may help to reduce damage from storms, but they likely would require substantial repairs after storms; if the dunes are overtopped by the water during a very strong storm, the sand from the dune may end up all over the parks like it did during Hurricane

Rendering of vegetated sand dune, which could include a geotextile tube in the center, at Cove Island Park.

Sandy; and maintenance includes periodic beach nourishment, which can be costly.

Though vegetated sand dunes are the most promising option for making Stamford's beach parks more resilient to storm damage in the short term, this technology will likely grow ineffective and unaffordable over time, as climate continues to change and the risk from storms increases. Therefore, in addition to constructing vegetated sand dunes – either with or without geotextile tubes – we recommend reducing the exposure of infrastructure at the beach parks.

Reduced exposure of infrastructure

Reducing the exposure to storm hazards entails making adjustments, both now and in the future, to the way that infrastructure is repaired, designed, and built at Stamford's beach parks. Reducing exposure may mean moving the pavilions at Cove Island and Cummings parks back from the shoreline, or elevating them, so that they aren't damaged by storm surge. Some states now are building structures one to two feet above the FEMA 100-year floodplain level to account for expected changes in sea level rise over this century. Reducing exposure at Stamford's beach parks also could mean eliminating parking lots in favor of grassy areas, which, over time, would be covered with sand and result in a larger beachfront. In this case, park goers would access the beaches by shuttle buses rather than by private vehicles. In the short term, reducing the exposure of infrastructure could improve resilience by minimizing damage; in the long term, this could improve resilience by allowing the beaches to move and relocate in response to changing climate conditions.

What is the future risk of storm damage?

For the beach parks in Stamford, future risk of storm damage is determined by the likelihood that these storms will occur, and by their intensity and duration. Strong storms and storms that last for more than one cycle of high and low tides cause the greatest damage to the beach parks in Stamford. **Scientific forecasts show that coastal storms will grow stronger and more frequent**: scientists predict that there is a greater than 50 percent likelihood that intense hurricanes will occur more often throughout the 21st century. Some scientists expect that the most intense Atlantic storms – Category 4 and Category 5 hurricanes – will occur twice as often by the end of the century as they do today. The largest increase in intense hurricane activity is predicted to occur in the western Atlantic Ocean between 20°N and 40°N; Stamford is located at 41°N.

Future risk of storm damage is also determined by the amount and likelihood of sea level rise in Stamford. **An elevated base sea level means that even small storms may cause flooding**, and given that Stamford's beach parks suffer from flooding even at today's sea level, future sea level rise poses a real threat. The scientific consensus is that it is extremely likely that sea level will continue to rise over the 21st century; they quantify the likelihood of this happening as greater than 95%. Sea level is also rising three to four times faster along the East Coast of the United States between Massachusetts and North Carolina, than it is globally. Such a trend further increases the risk of storm damage to Stamford's beach parks.

How can Stamford manage the risk of storm damage?

The City ought to be able to adjust its beach protection strategy according to changes in the risk of storm damage over time. This way, Stamford can better match the level of its investment to its risk. **A static strategy that does not account for increasing risk and uncertainty, and that is based on making a single long-term investment in beach protection, such as a seawall, will likely waste money.**

Such a risk management approach would consist of five repeating steps The steps, as adapted for Stamford, include: (1) understanding the potential for storm damage to Stamford's beach parks, (2) assessing the extent of these damages (e.g., cleanup costs and duration of beach closures) and the chance that these damages will occur, (3) developing a plan to address the risk of storm damage to Stamford's beach parks, (4) implementing this plan, and (5) monitoring and reassessing this plan to make sure that it is working (e.g., tracking any new developments in beach protection technologies and climate risk information).

"Every storm like Sandy is an opportunity to change the way we have been doing business. Let's take it."

- Rob Young & Andy Coburn, Geologists, 2012

Introduction

The beaches in Stamford are some of the City's most popular parks, attracting visits from about two-thirds of Stamford's population in any given year. They are places where residents go to unwind, to socialize with friends, or to enjoy a peaceful moment. "I am a beach person and feel lucky to have them in my town," says Tom Cingari, a native of Stamford. He frequents the beaches at least once a week. The beaches are more than just sand and water; they are a building block of Stamford's unique identity.

Recent storm activity reminds us that nature is a dynamic, sometimes fierce, force. The persistent storm surge and pounding waves brought by Hurricane Sandy revealed, once again, the vulnerability of Stamford's beaches. A changing climate exacerbates this vulnerability by altering the frequency, intensity, and duration of weather events (Intergovernmental Panel on Climate Change [IPCC], 2012). As sea level continues to rise, even small coastal storms in the coming years will cause inundation of Stamford's beach parks, effectively increasing the number and duration of storm-related floods (Horton, 2013). As the oceans continue to warm, North Atlantic hurricanes will likely become stronger, and may make landfall more often (Bender et al., 2010; Horton, 2013; Kunkel et al., 2008). Our changing climate poses significant threats to Stamford's beach parks. Given that the City of Stamford will likely be unable to afford the incurrence of damage like that from Sandy on a frequent basis, the City must manage these climate risks. Stamford must innovate and adopt new ways to live with and around the coast – new ways to reconcile the desire to enjoy the ocean with the risks that stem from coastal storms. Coastal management strategies need to be focused less on shoreline armoring and more on adaptable, flexible technologies (Beatley, 2009). We address the vulnerability of Stamford's beach parks with a risk management approach. In this report, we propose integrated, dynamic options that increase resilience to storm damage. We take into account the uncertainty associated with future climate, and recommend flexible and adaptable options for the City of Stamford.

Parking lot at Cummings Park after Tropical Storm Irene in 2011. By the end of the 21st century, this could be the location of the beachfront.

What is the problem?

At a Glance:

- **Stamford's beach parks are vulnerable to flooding and infrastructure damage by coastal storms.**
- **Unusually fast rates of sea level rise and the phenomenon of tidal amplification near Stamford exacerbate this vulnerability.**

Stamford's beach parks are vulnerable to coastal storms, which cause flooding and damage infrastructure, leaving behind ravaged beaches and high cleanup costs. For example, the City of Stamford estimates the total cost of the storm damages from Hurricane Sandy to be almost \$2.5 million (Hurricane Sandy FEMA snapshot, 2013). This is roughly equal to the City's yearly traffic and road maintenance budget. At Cove Island Park, Hurricane Sandy partially destroyed the seawall, which had suffered damage the year before during Tropical Storm Irene. The estimated repair cost for this structure is \$270,000 (Hurricane Sandy FEMA Snapshot, 2013). In addition, the picnic area, concession stand, sanitary facilities, and the SoundWaters educational center were flooded; and much of the park beyond the beach face was covered in up to two feet of sand (Murray, 2013). This sand had to be carefully screened for debris and then replaced on the beach face. This process cost the City of Stamford roughly \$300,000 (McKenna, 2013). Hurricane Sandy caused enough damage that it rendered the facilities at Cove Island Park closed to public use for several weeks. Similar destruction occurred at Cummings Park and West Beach. At Cummings Park, damages spanned from crushed railings along the marina channel to flooded electrical conduits and concession stands. At West Beach, the pavilion foundation was severely damaged, which contributed an additional $150,000 to the cost damages (Hurricane Sandy FEMA Snapshot, 2013).

Why are Stamford's beach parks vulnerable to damage?

To understand the vulnerability of Stamford's beach parks, it's important to understand the processes that cause damage. Coastal storms such as nor'easters and hurricanes typically have the largest impacts on the greater New York City region (Rosenzweig et al., 2011b). Nor'easters tend to produce smaller storm surges and weaker winds than do hurricanes, but they often coincide with high tides and last for several cycles of high and low tides; these storms therefore tend to cause substantial flooding (Wisker, 2013; Rosenzweig et al., 2011b). Hurricanes are stronger storms, which inherently produce larger storm surges and winds in excess of 74 miles per hour; these storms typically cause both flooding and highly energetic wave action (National Oceanic and Atmospheric Administration [NOAA], 1999). Both nor'easters and hurricanes are associated with heavy precipitation, which worsens flooding. High water levels due to storm surge, intense wave action due to sustained strong winds, and heavy precipitation are all hazards that contribute to damage at the beach parks in Stamford. (Please refer to *Appendix 1: Glossary of Terms* for working definitions of the terms used in this report.)

Central to the vulnerability of Stamford's beach parks are the climate hazards associated with a warming planet. We review these in detail in the section titled *What is the future risk of storm damage to Stamford's beach parks?*, but first, we discuss the significance of Stamford's geographical location. Stamford is situated along the western edge of Long Island Sound, which makes the city's beaches particularly vulnerable to damages and flooding from coastal storms and changes in sea level. The reason for this is two-fold: *First*, the eastern seaboard of the United States is experiencing sea level rise at a rate faster than the rest of the globe; *Second*, the geometry of Long Island Sound creates tidal resonance (i.e., amplification) in the western part of the inlet, which leads to higher tides and storm surges (Burgeson & Lochhead, 2013; Sallenger, Doran, & Howd, 2012). These two factors render Stamford's beach parks especially vulnerable to a rise in sea level and to an increase in intensity and frequency of strong coastal storms, both of which are predicted effects of climate change.

Why is sea level rising more quickly along the East Coast of the U.S. than other places?

Sea level has risen more than eight inches along the Atlantic Coast of the United States over the past 50 years, which is a rate slightly higher than the global average for sea level rise (Horton et al., 2010b). A study conducted in 2012 by U.S. Geological Survey scientists concluded that **sea level has risen along the eastern seaboard of the U.S. at a rate three to four times faster than the global average over the past 60 years** (Sallenger, Doran, & Howd, 2012). These scientists identified a 1,000-km stretch of coast between Massachusetts and North Carolina as a "hotspot" for sea level rise (Figure 1).

The comparatively greater sea level rise in this region likely is the result of a couple of factors. These include subsidence (i.e., sinking) of the East Coast, which is the result of the Earth's crust slowly

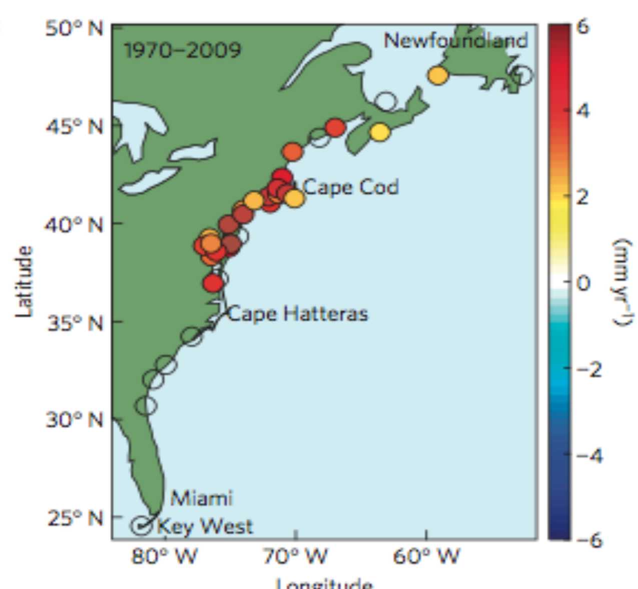

FIGURE 1

Sallenger et al. (2012) identify a 1,000-km stretch of the eastern coast of the United States as a "hotspot" for sea level rise.

adjusting to the melting of past ice sheets that once covered the land; and possible slowing of the Atlantic Ocean circulation belts caused by rapid melting of Arctic sea ice, which reduces the sea-surface pressure gradient along the East Coast and causes sea level to rise (Horton et al., 2011; Sallenger et al., 2012). Recognizing that sea level is rising far more quickly in the Northeastern United States than in other parts of the world – and understanding why this is occurring – will help us develop and implement a plan for improving beach resilience in Stamford.

How does tidal resonance affect Stamford?

The geometry of Long Island Sound causes large differences between high and low tide – differences far greater than those in the eastern part of the Sound (Burgeson & Lochhead, 2013). On average, the difference between high tide and low tide in Stamford is between seven and nine feet, whereas in New London, this difference is close to two and a half feet (Burgeson & Lochhead, 2013; NOAA, 2013). This occurs through a process called tidal resonance, which is the amplification of tides in an inlet because of the interaction between the shape of the inlet and the frequency of the tides (Godin, 1993). Just as tidal resonance creates higher high tides in Stamford, this same process creates higher storm surge. Thus, the storm surge in Stamford will be greater than that in the eastern parts of Long Island Sound. This increased tidal difference and storm surge height is key to both understanding and planning for climate change impacts in Stamford. The measures that the City of Stamford may take to improve the resilience of its beaches will differ considerably from those that nearby New London may take to accomplish the same goal.

What is the solution?

At a Glance:

- **Finding ways to improve resilience is complicated because beaches move and risk and uncertainty grow over time.**

- **Improving resilience in the short term may be possible through the use of engineering technologies, but these technologies may fail or become overly expensive in the long term.**

A logical solution to the problem of vulnerability is to make Stamford's beach parks more resilient to storm damage. In other words, **the solution is to improve the beach parks so that cleanup costs and durations of beach closures are reduced.** But finding ways to improve resilience to storm damage is complicated.

Why is improving resilience to storm damage complex?

(1) Beaches are dynamic

Beaches constantly change in response to natural processes, such as waves, winds, and tides. Coastal storms alter the usual pattern of waves, winds, and tides, and therefore can cause beaches to change shape and location dramatically. Stamford experienced this firsthand during Hurricane Sandy, when nearly two feet of sand was moved from the ocean and beachfront up onto the Great Lawn and picnic area. As George Wisker (2013), Coastal Geologist for the state of Connecticut, put it: "There will always be beaches, they just may not be where you want them to be." Another geologist explained that: "One of the very real realities is that you can do something now, but don't have the expectation that it's always going to stay there" (Dickson, 2013).

(2) Risk to Stamford's beach parks increases over time

Scientists believe that as our planet continues to warm, Stamford will experience stronger coastal storms. Along with stronger storms, scientists forecast that sea level will continue to rise. These two changes together are expected to result in more instances of severe coastal flooding. In the next 30 years, flooding that we currently expect to occur once every 100 years (1-in-100 year flood) is predicted to occur every 35 to 55 years. Therefore, as the Earth becomes warmer over time, the risk of damage from storm surge and wave action grows greater.

(3) Uncertainty increases over time

As is the case with any prediction, the uncertainty associated with the risk to Stamford's beach parks also grows with time. For example, scientists are virtually certain that sea level will continue to rise over the next five years, but they are less certain that this trend will persist 500 years from now. Growing uncertainty means that any method for improving beach resilience ought to be adaptable if climate conditions exceed scientists' predictions.

The issue of beach resilience involves geological and ecological processes, as well as increasing risk and uncertainty – all of which change over time. **Improving the resilience of beaches may be possible in the short term, under current or near-current climate conditions, through the use of engineering technologies. But as climate changes more drastically over time, engineering technologies may either fail or become overly expensive.** The only real solution may be to yield to the dynamic nature of beaches, allowing them to move landward. Take Cove Island Park, for example: Hurricane Sandy deposited two feet of sand on the Great Lawn – this area could become the location of the beach by the end of this century. Similarly, at Cummings Park, the parking lot could become the new beachfront. Janet Freedman, a geologist at the Rhode Island Coastal Resources Management Council, emphasized that communities must keep in mind the future of the shoreline. She explained that because the shoreline is moving landward, whatever is done to protect it will be fighting that natural process (Freedman, 2013).

How can Stamford make its beach parks more resilient?

At a Glance:

- **Various engineering technologies exist for improving resilience to storms, however soft options generally are preferable.**
- **The best beach resilience technology for Stamford is one that is feasible, effective, cost-effective, flexible, and beneficial beyond flood protection.**
- **Stamford could achieve improved resilience by constructing vegetated sand dunes, and by reducing the exposure of beach park infrastructure. But no practical technology will eliminate the City's problem.**

What are the options?

A number of different technologies are available to enhance resilience to storm damage in the coming years. These fall into two categories: macro engineering and micro engineering (Buonaiuto et al., 2011). Macro engineering consists of massive structures such as dikes, floodgates, levees, and storm surge barriers (Buonaiuto et al., 2011). These technologies are designed to reduce storm damage to highly urbanized areas with expensive infrastructure. Densely populated urban centers such as London, Rotterdam, and other areas in the Netherlands, rely on these technologies to protect their inhabitants and infrastructure (Aerts et al., 2009; NOAA, 2010; United Kingdom Environment Agency, 2010). Macro-engineering technologies require in-depth study before being implemented, and entail extensive economic, social, and environmental costs (NOAA, 2010; Rosenzweig et al., 2011b). The implementation of such technologies often requires billions of dollars, relocation of communities, and significant disruption of ecosystems and geologic processes.

Within the category of micro-level engineering exist hard and soft engineering technologies. Hard engineering technologies include solid structures such as breakwaters, bulkheads, groins, jetties, revetments, and seawalls (Buonaiuto et al., 2011; Rosenzweig et al., 2011b). These structures are designed to withstand large forces and typically have a long lifespan. Hard engineering technologies tend to be minimally flexible and require high initial and maintenance expenditures (Rosenzweig et al., 2011a).

Soft engineering technologies include beach nourishment, dewatering systems, oyster beds, salt marshes, creation and/or restoration of sand dunes (artificial and natural), and vegetation planting. Soft engineering technologies are designed to absorb storm impacts and tend to have a comparatively shorter lifespan. These technologies mimic the natural ecologic and geologic processes that improve resilience to storm damage (Rosenzweig et al., 2011b). As such, **soft engineering technologies generally are considered preferable to hard technologies** (Massachusetts Office of Coastal Zone Management, 2013). These technologies provide flexibility and usually require low-to-moderate initial capital expenditure, and moderate maintenance spending.

It is important to keep in mind that while engineered resilience technologies may be capable of reducing storm damage, they are not capable of preventing all storm damage. As Jennifer O'Donnell, a coastal engineer, explained, "Coastal towns [are] looking for the silver bullet that will solve the problem." Such a solution does not exist.

How did we evaluate these options?

In evaluating these resilience options, we took into account two main factors: *First*, we considered Stamford's goals of improving resilience to storm damage, specifically reducing cleanup costs and durations of beach facility closures associated with storm damage, and preserving the aesthetic and recreational value of the beach parks. *Second*, we considered the reality of our changing climate. Given that beaches change and move over time, and that the risk to Stamford's beach parks is expected to increase in the future, we concluded that technologies that could improve resilience to storm damage must be dynamic.

Coastal resilience experts and shoreline managers explained to us that in a changing climate – even in the short term – static engineering technologies such as revetments and seawalls would not improve resilience. A coastal geologist for the state of Connecticut explained, **"We're trying to maintain static structures in a dynamic environment – that's possibly becoming even more dynamic"** (Wisker, 2013). This approach no longer makes sense.

We therefore sought to determine whether or not each resilience technology was capable of accomplishing Stamford's goals, and whether or not each option was dynamic. With this lens, we developed a set of criteria by which to evaluate the various resilience technologies for Stamford. For the purposes of this project, we defined these criteria as listed in Table 1.

The first three criteria are those that must be considered in the evaluation of options for addressing any problem. The last two, flexibility and co-benefits/environmental performance, are specific to evaluating options for addressing dynamic problems - those that change and involve uncertainty.

Criterion	Definition
Feasible	Technology practical and reasonable for Stamford's beach parks.
Effective	Technology is capable of accomplishing Stamford's goals of improving resilience to storm damage (i.e., reducing cleanup costs and duration of beach closures) and preserving the aesthetic and recreational value of the beach parks.
Cost-effective	Cost of the technology saves Stamford money in the long term.
Flexible	Technology is capable of being altered in the future without compromising the initial investment.
Beneficial	Technology provides additional benefits (e.g., improves water quality or enhances bird nesting habitats) that increase the value of an investment in the technology.

TABLE 1
Definitions of evaluation criteria.

We evaluated the various resilience options in comparison to one another. In other words, we compared the relative rather than the absolute feasibility, effectiveness, cost-effectiveness, flexibility, and benefits of each option.

In evaluating **feasibility**, we determined whether the technology could be practically and reasonably implemented. For example, we deemed macro-level engineering technologies unfeasible because the exorbitant economic (i.e., on the order of billions of dollars) and environmental costs of these options are disproportionate to the social benefits they offer.

In evaluating **effectiveness**, we used the 100-year flood level as the standard. We deemed a technology effective if it was capable of reducing damage from a coastal storm that had an 8.6-foot flood height. This flood height corresponds with the current 1-in-100 year storm at the Battery in New York City. We assumed, however, that any technology would be a continuous structure that spanned the majority of the beachfront. It is crucial to understand that breaks in structures, such as those for walkways through sand dunes or seawalls, would reduce the effectiveness of the technology.

For our **cost** analysis, we compared rough cost estimates for building each technology with the approximate estimate of avoided clean up costs from Hurricane Sandy (i.e., $945,000). In evaluating the most viable technologies, we then discounted these costs over a period of 30 years and factored in the probability of storm-induced flooding to the 100-year level. These probabilities were based on climate projections that flooding to the 100-year level might occur as often as every 65 years. (See *What is the Future Risk of Storm Damage? Coastal Floods* section for more information.)

In evaluating **flexibility**, we determined whether the technology could be altered in the future to adjust for changing climatic conditions. Seawalls, for example, are inflexible as they cannot easily be moved or altered without compromising the initial investment in building the wall. Sand dunes, on the other hand, are quite flexible because they can migrate and move on their own in response to changing sea levels and storm conditions.

Finally, we considered all **additional benefits** that the technology could offer. Examples of co-benefits include the creation of nesting and breeding habitats for birds, and the improvement of water quality. Co-benefits increase the value of the technology because they guarantee advantages in the short term.

After identifying and defining these five criteria, we developed a basic decision tree through which we ran each engineering technology (Table 2).

Moreover, Stephen Dickson, Marine Geologist for the Maine Geological Survey, encouraged us to think of sand dunes as sacrificial. He explained that dunes protect the infrastructure behind them by eroding away during big storms and adding more sand to the beachfront (Dickson, 2013). This process elevates the profile of the beach, making it more resilient to storm damage and sea level rise.

Vegetated sand dunes with geotextile tubes

We found that three different types of sand dunes met all of our criteria. In order to differentiate among these options, we scored each technology for feasibility, effectiveness, cost-effectiveness, flexibility, and benefits. Though seawalls did not meet our evaluation criteria, we included two different seawall options because Stamford expressed an interest in this technology. A comparison of approximate initial costs can be found in Table 3.

What is the most promising option for Stamford's beach parks?

After evaluating these options using our five criteria, we found that vegetated sand dunes with geotextile tubes are the best option for improving resilience at Stamford's beach parks.

There are critical factors that Stamford must consider before building a dune system, however. **In order for dunes to work effectively, they must be built in the appropriate location, to the appropriate dimensions, and with the appropriate materials.** Dune location must be determined through a careful site analysis of Stamford's beaches. Coastal engineers and geologists must assess a variety of factors including beach profile and geometry, wave direction and height, sand volume, tide levels, and sea level rise projections. Douglas Glowacki, an Emergency Management Program Specialist for Connecticut, explained that dune width and height should be determined based on the worst-case scenario (i.e., a strong storm hitting at high tide). Jennifer O'Donnell, a coastal engineer at Coastal Ocean Analytics, told us that if the dunes were to be built with breaks in them, then water would rush through the openings and collect behind the dunes. Dunes with breaks could trap the water and hold it in place instead of letting it retreat naturally back to the ocean as surge dissipates after a storm. A dune system with breaks in it therefore could cause more problems than it solves for Stamford. An alternative to breaks is an elevated boardwalk, which would provide public access to the beaches without compromising the effectiveness of the dunes. Finally, dunes should be constructed using materials that are native to the Stamford area. Juliana Barrett, a scientist from the Connecticut Sea Grant, underscored the importance of using sand of the appropriate grain size, and selecting plant species that thrive on the Connecticut coastline

Vegetated sand dunes are an effective way to block wind, to absorb wave energy, and to reduce flooding from storm surge. Constructing dunes with geotextile tubes, which are fabric tubes filled with sand, helps to stabilize and reinforce the dune. The use of this technology also makes the dunes more durable because the fabric is resistant to erosion. Once placed on the beach, the geotextile tubes are then

1	Is the technology feasible for Stamford's beach parks?	
	NO Macro-level engineering (e.g., dikes, levees, flood gates)	**YES** Micro-level engineering (i.e., hard and soft technologies)
2	**Is the technology effective?**	
	NO Breakwater (floating) Breakwater (submerged) Breakwater (submerged) with artificial reef Bulkhead Dewatering system Groin Jetty *Oyster bed* *Salt marsh* *Vegetation planting*	**YES** Revetment Sand dune (via beach nourishment) Sand dune with geotextile tube Sand dune with mesh core log Seawall
3	**Is the technology cost-effective for Stamford?**	
	NO Seawall	**YES** Revetment Sand dune (via beach nourishment) Sand dune with geotextile tube Sand dune with mesh core log
4	**Is the technology flexible?**	
	NO Revetment	**YES** Sand dune (via beach nourishment) Sand dune with geotextile tube Sand dune with mesh core log
5	**Does the technology provide additional benefits?**	
	NO	**YES** Sand dune (via beach nourishment) Sand dune with geotextile tube Sand dune with mesh core log

TABLE 2

Evaluation criteria decision tree. The italicized technologies (oyster bed, salt marsh, and vegetation planting) are not effective individually, but could be combined with other technologies to enhance overall resilience.

covered with sand and native plants to secure the structure and give the appearance of a natural dune. Such dunes of appropriate dimensions and without any breaks could improve resilience by providing a buffer between the ocean and the beach parks. When storm surge is high and waves pound against the dunes, only the outside layer of sand is washed away – the inner tube structure remains in place.

Building vegetated sand dunes requires a large initial investment, however. In order to better understand how the cost of doing nothing – that is, continuing with business as usual and cleaning up after damaging storms – compares with the cost of building a sand dune, we conducted a discount analysis. We compared the cost of doing nothing with the cost of building a dune with geotextile tubes over a 30-year period. It turned out that the cost of cleaning up after storm damage is far less than the cost of building a dune. The present value of these two options (i.e., doing nothing: ~$140,000, and building a dune with geotextile tubes: ~1,300,000) is shown in Figure 2.

Though dunes may not seem like the best investment, there is more to consider than money. Stamford may deem it valuable to build dunes to avoid having to close its beach parks, or to lessen the shock that comes with storm damage. The City may also decide that building dunes is an opportunity to introduce to its residents the idea of climate risk – that beaches are vulnerable.

Some pros and cons to this technology are as follows:

- **Pros:** Can use geotextile tubes to create taller, steeper dunes than is possible with sand alone (Roach, 2013); and geotextile tubes resist erosion from storm damage, which makes the dunes more durable.
- **Cons:** If the geotextile tube center is exposed during stormy conditions, the beach area *in front* of the dune is prone to increased erosion; the use of geotextile tubes makes the dune less flexible as it cannot migrate naturally in response to changing sea levels and storm conditions; maintenance includes periodic beach nourishment, which can be costly; and these dunes are more costly to build than are un-enhanced dunes (Table 3).

Another option is to **build vegetated sand dunes using locally sourced sand and native species of plants** – that is, without geotextile tubes. Many geologists and coastal managers say that these types of dunes are preferable because they work *with* instead of *against* the natural coastline systems.

Rendering of vegetated sand dune, which could include a geotextile tube in the center, at Cove Island Park.

Some pros and cons to this technology are as follows:

- **Pros:** Dunes could migrate landward naturally, if infrastructure were adjusted, to adapt to changes in climatic conditions, and these are less costly to build than are dunes with geotextile tubes (Table 3).
- **Cons:** These dunes may help to reduce damage from storms, but they likely would require substantial repairs after storms; if the dunes are overtopped by the water during a very strong storm, the sand from the dune may end up all over the parks like it did during Hurricane Sandy; and maintenance includes periodic beach nourishment, which can be costly.

For descriptions of these and other resilience technologies that we considered for Stamford, please see *Appendix 2: Options for Improving Resilience.*

Technology	Unit Cost	Total Cost for All Three Beach Parks
Vegetated sand dune	~$370 per linear foot	$1,550,000
Vegetated sand dune with geotextile tubes	~$250 per linear foot of tube and $50 per ton of sand	$1,860,000
Vegetated sand dune with mesh core logs	~$760 per linear foot (includes all components)	$2,353,000
Traditional vertical seawall	~$2600 per linear foot	$8,060,000
Stepped-face seawall	~$11,600 per linear foot	$35,960,000

TABLE 3
Comparison of approximate initial costs of resilience technologies.

Though vegetated sand dunes are the most promising option for making Stamford's beach parks more resilient to storm damage in the short term, this technology will likely grow ineffective and unaffordable over time, as climate continues to change and the risk from storms increases. In other words, dunes offer only a short-term solution. Stamford also must keep in mind that sand dunes

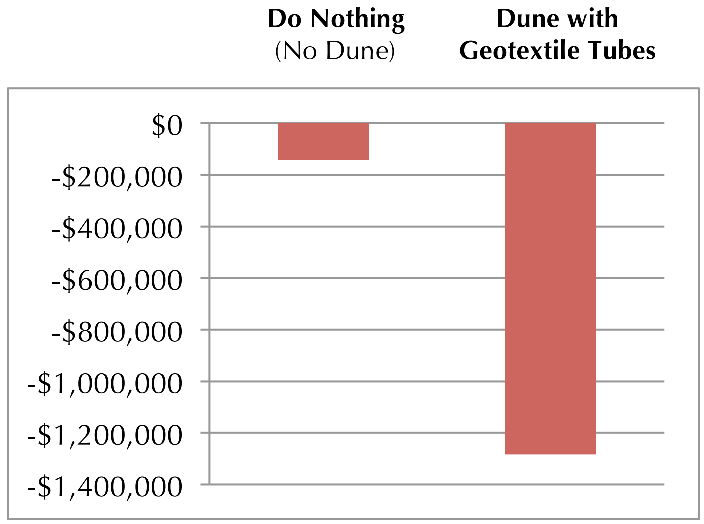

FIGURE 2
Net present values of doing nothing (i.e., no dune) and building a dune with geotextile tubes. Both options cost money, but building a dune would put Stamford much farther "into the red" than would continuing to clean up after storms.

can *reduce* the risk of storm damage, but they certainly cannot *eliminate* it. Therefore, in addition to constructing vegetated sand dunes – either with or without geotextile tubes – we recommend reducing the exposure of infrastructure at the beach parks.

Reduced exposure of infrastructure

Reducing exposure to damage is important in cases where a storm overpowers the beach protection technology. Reducing exposure entails making adjustments, both now and in the future, to the way that infrastructure is designed, built, and maintained at Stamford's beach parks. Such adjustments may include moving the pavilions at Cove Island and Cummings parks back from the shoreline, or elevating them, so that they aren't damaged by storm surge. **Some states now are building structures one to two feet above the FEMA 100-year floodplain level to account for expected changes in sea level rise over this century** (Slovinsky, 2013). Reducing exposure at Stamford's beach parks also could mean eliminating parking lots in favor of grassy areas, which, over time, would be covered with sand and result in a larger beachfront. In this case, park goers might access the beaches by shuttle buses rather than by private vehicles. In the short term, reducing the exposure of infrastructure could improve resilience by minimizing damage; in the long term,

LEARNING FROM OTHERS

Rhode Island & North Carolina Prohibit Structural Shoreline Protection Structures

The Rhode Island Coastal Resources Management Council has banned the installation of revetments, bulkheads, seawalls, groins, breakwaters, jetties, and other erosion control structures along all barriers and ocean-facing coastline. North Carolina has implemented a similar policy, citing that such structures "may cause significant adverse impacts on the value and enjoyment of adjacent properties or public access to and use of the beach" (NOAA, 2010).

this could improve resilience by allowing the beaches to move and relocate in response to changing sea levels and storm conditions.

In addition to building vegetated sand dunes and reducing the exposure of infrastructure, we recommend enhancing and expanding the **salt marshes** that currently exist at Stamford's beach parks. Salt marshes are known for their adaptive capacity, and for providing coastal protection by absorbing floodwaters (e.g., from storm surge) and by defending against erosion. Salt marshes have extensive root systems, which enable them to withstand brief storm surges, buffering the water impact on upland areas. Salt marshes can be built in phases, which would allow Stamford to build up a marsh over time. They are said to be cost-effective depending on the kind of salt marsh, seeds from a nursery run from $15 to $35 per thousand pure live seed), and provide habitat for fish, while acting as filters by absorbing or trapping pollutants and reducing the pollutant load entering estuaries. Salt marshes would keep Stamford's water clean and protect against erosion, and contribute to its recreational value by attracting popular marine fishes, shellfish, and crustaceans.

We also propose adding **oyster beds** at selected locations, such as where the salt water enters the creek at Cove Island Park. Oysters are easy to cultivate, and add complementary benefits to beach protection because they help absorb wave energy (Coastal Resilience, 2012). Additionally, they act as an indicator species by reflecting the marine habitat's health, and by filtering nutrients and sediments from water (Oyster Reef Restoration, 2009).

Oyster beds installed in tidal marsh.

LEARNING FROM OTHERS

Florida Uses Oyster Beds to Improve Benefits to Community

Florida recognized the importance of oyster beds and reefs as a vital source of food and shelter for ecologically and economically important fish and invertebrate species (Oyster Restoration, 2009). Therefore, an oyster bed project was implemented. The results, thanks to a close monitoring of the project and a stabilizing effect of water salinity because of the oyster beds, were long-term and significant ecological improvements to the water systems and the provision of social, recreational, and economic benefits to the community (Oyster Reef Restoration, 2012).

What is the future risk of storm damage?

At a Glance:

- **As the planet continues to warm, we are no longer able to rely on observations to predict future behavior.**

- **Coastal storms are expected to become stronger, and the strongest storms are predicted to happen more often.** Scientists predict that by the end of the 21st century, the strongest Atlantic hurricanes – Category 4 and Category 5 hurricanes – will occur twice as often as they do today. The greatest increase in intense hurricane activity is expected to occur around Stamford.

- **Scientists predict that coastal flooding will grow more severe, will happen more often, and will last longer during this century.** Thirty years from now, coastal flooding to the current 100-year flood level is expected to occur every 15 to 35 years.

- **Sea level is expected to continue to rise, which means that even small coastal storms may cause substantial flooding at Stamford's beach parks.**

- **Climate information tells us that the future risk of storm damage to Stamford's beach parks is high.** Many coastal geologists, engineers, and shoreline managers expect that as our climate continues to change, and the associated risk of storm damage continues to increase, engineered technologies will do little to improve resilience.

For the beach parks in Stamford, future risk of storm damage is determined by the intensity and duration of coastal storms, by the extent of sea level rise, and by the likelihood that these things will occur. Climatic changes, such as sea level rise, more frequent intense precipitation events, and stronger coastal storms all are likely to exacerbate damages to Stamford's beach parks. The City of Stamford can use scientific predictions for changes in climate and associated hazards to determine the appropriate location and size of enhanced vegetated sand dunes, and to decide how and when to reduce exposure of infrastructure at the beach parks.

Experts in climate science typically discuss predicted climatic changes in terms of four main categories: temperature, precipitation, sea level rise, and extreme events (e.g., hurricanes). **For Stamford, changes in extreme events and sea level rise are most relevant, as these will directly affect the beach parks.** It is important to understand, however, that it is the change in the Earth's surface *temperature* that drives these climatic changes. Sea level rise, greater frequency of intense precipitation events, and increased intensity of coastal storms, for example, all are caused by changes in temperature. The expected climatic changes that are likely to affect Stamford's beach parks are discussed below, in order of most to least relevant. (Though temperature is central to all of the predicted climatic changes, it is not discussed in this report, as it is unlikely to directly impact Stamford's beaches.)

Extreme Events

Coastal Storms

The two types of coastal storms that have the largest influence on the Stamford region are nor'easters and hurricanes, and Stamford is no stranger to either (Rosenzweig et al., 2011b). Notable storms include the "Long Island Express" hurricane of 1938; two back-to-back hurricanes, just a week apart, in 1955; Tropical Storm Floyd in 1999, and of course, Tropical Storm Irene and Hurricane Sandy in 2011 and 2012, respectively (Connecticut Department of Environmental Protection, 2010). **The extent of damage caused by coastal storms is determined by storm strength, duration, angle of approach upon landfall, and timing within the tide cycle** (Hall & Sobel, Submitted).

Nor'easters are cyclonic winter storms that occur along the northeastern coast of the Untied States. These storms tend to last for more than one cycle of low and high tides, often make landfall at high tide, and cause substantial precipitation – often in the form of snow. As a result, nor'easters often cause coastal flooding. Hurricanes are severe tropical cyclones that are categorized based on sustained high wind speeds (Table 4). Because of the storm surge, high winds, and heavy rains that typically accompany hurricanes, these storms top the list of natural disasters with the greatest destructive potential in the state of Connecticut (Connecticut Department of Environmental Protection (2010). Past observations of coastal storm behavior indicate that, on average, Category 1 hurricanes make landfall in or near Connecticut once every 10 to 15 years, Category 2 hurricanes make landfall in or near Connecticut once every 23 to 30 years, and Category 3 hurricanes make landfall in or near Connecticut once every 46 to 74 years (Connecticut Department of Environmental Protection, 2010). As the planet continues to warm, though, we are no longer able to rely on past observations to accurately predict future behavior of storms. Instead, we must look to climate projections to understand how storms may behave.

Scientific forecasts suggest that the intensity of tropical cyclones, which are the origins of hurricanes, will increase in the future. Most climate experts agree that the frequency of both nor'easters and the strongest Atlantic hurricanes will increase (Bender et al., 2010; Kunkel et al., 2008). Rosenzweig and colleagues (2011b) quantify the likelihood that intense hurricanes will increase in frequency throughout the 21st century as greater than 50 percent. **However, the frequency of smaller storms is expected to decrease in the future** (Bender et al., 2010; Kunkel et al., 2008). One group of scientists offers additional specificity; they indicate that by the end of the 21st century, the frequency with which the most intense Atlantic hurricanes (i.e., Category 4 and Category 5 hurricanes) occur will have increased by a factor of two (Figure 3) (Bender et al., 2010). **Furthermore, scientists expect to see the largest increase in very intense hurricane activity in the western Atlantic Ocean between 20°N and 40°N (Bender et al., 2010).** This prediction is particularly relevant to Stamford given that the city is located at 41°N.

In addition, some climate scientists have argued that changes in the jet stream are likely to affect how often coastal storms make landfall (Horton, 2013; Sobel, 2013). Because the jet stream, which runs parallel to the East Coast of the United States, is driven by the temperature gradient between the equator and the North Pole, changes in this gradient are likely to affect its course. Some scientists maintain that the melting of Arctic sea ice caused by Earth's increasing temperatures is causing the jet stream to weaken (Francis & Vavrus, 2012). They argue that this weakening of the jet stream allows powerful storms, such as Hurricane Sandy, to make landfall (Francis & Vavrus, 2012). Storm expert Adam Sobel (2013) disagrees with this idea, however, explaining that all of the best climate models predict that the opposite will occur: powerful storms will veer out into the North Atlantic instead of making landfall. As is evidenced by this disagreement, scientists do not yet fully understand if and how the jet stream is affected by changes in climate.

Category	Definition & Likely Effects
1	74-95 mile per hour sustained winds. Very dangerous winds will produce some damage, primarily to trees and shrubbery. Some coastal road flooding and minor pier damage.
2	96-110 mile per hour sustained winds. Extremely dangerous winds will cause extensive damage: Some damage to roofs and building exteriors. Considerable damage to vegetation and piers. Coastal flooding hours before arrival of storm center.
3	111-129 mile per hour sustained winds. Devastating damage will occur. Some structural damage to buildings. Destruction of small structures near the coast due to coastal flooding.
4	130-156 mile per hour sustained winds. Catastrophic damage will occur: Some complete roof failures. Major erosion of beaches. Major damage to lower floors of structures near the coast. Extensive coastal flooding may require massive evacuation.
5	157 mile per hour or higher sustained winds. Catastrophic damage will occur: Complete roof failure on many structures. Major damage to lower floors of structures near the coast. Massive evacuation of residential areas near the coast may be required.

TABLE 4
Saffir-Simpson Hurricane Wind Scale, adapted from NOAA (2013c).

In addition to the strength and duration of the storm, the angle of approach also determines the amount of damage a coastal storm can do (Hall & Sobel, Submitted). The closer the angle of approach is to perpendicular, the greater the storm damage (Hall & Sobel, Submitted). **A weakened jet stream suggests the possibility that coastal storms may make landfall**

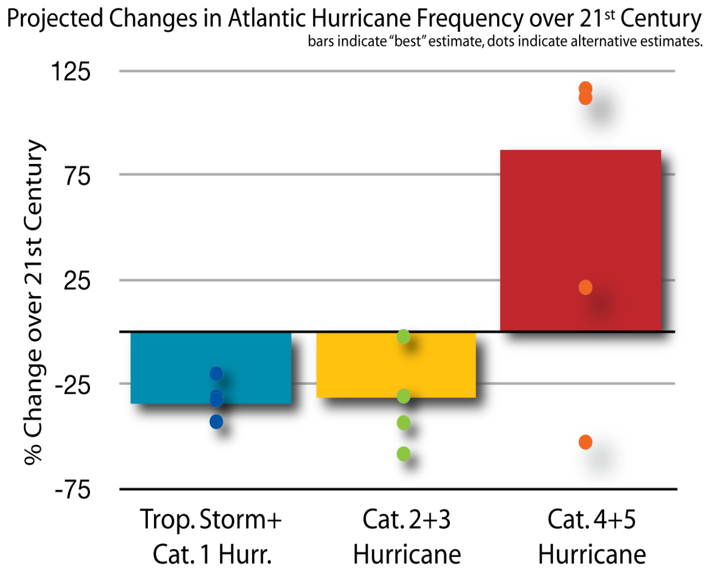

FIGURE 3

Bender et al. (2010) predict that Category 4 and Category 5 hurricanes will occur twice as often by the end of this century. However, they expect that smaller storms will occur less frequently.

at more direct angles, thereby increasing the amount of associated damage.

Finally, the timing of when a coastal storm makes landfall contributes to the amount of damage caused. If a coastal storm hits Stamford at high tide, the damage will be more extensive than if it makes landfall at low tide. During storms, tides are further amplified when winds pile up water along the East Coast of the United States; this additional piling up of water is called storm surge. Despite the destruction that Hurricane Sandy caused, the damage would have been much worse if the storm had hit Stamford during high tide (Burgeson & Lochhead, 2013). Such an occurrence could have added upwards of four feet of water to the storm surge in Stamford (Burgeson & Lochhead, 2013). Currently, there is no way to predict when future storms will make landfall.

Coastal Floods

The majority of the damage to the beach parks from Tropical Storm Irene and Hurricane Sandy was in the form of coastal flooding (Murray, 2013). Past observations indicate that hurricanes are more likely to cause coastal flooding to the 100-year levels, while nor'easters are the main source of annual coastal flooding (Rosenzweig et al., 2011b). **Scientists predict that the intensity, frequency, and duration of coastal flooding will increase over the 21st century** (Rosenzweig et al., 2009). These authors quantify the likelihood that these changes will occur as greater than 90 percent. Recent reports indicate that by the 2020s in the Northeastern United States, coastal flooding to the 100-year flood level will occur approximately once every 65 to 80 years. By the 2050s, these same flood levels will recur roughly every 35 to 55 years, and by 2080, flooding to the 100-year flood level will happen every 15 to 35 years (Rosenzweig et al., 2009). In other words, scientists expect that by the end of the century, 1-in-100 year floods will occur roughly four times as often as they occur today (Rosenzweig et al., 2009).

Perhaps of greater interest to the City of Stamford are coastal flood predictions to the 10-year flood level. Scientists expect that decadal floods (i.e., floods that occur, on average, once every 10 years) will occur every eight to 10 years by the 2020s and every two to six years by the 2050s (Rosenzweig et al., 2009). By the 2080s, coastal flooding to the 10-year flood level is expected to occur every one to three years (Rosenzweig et al., 2009). These changes in flood frequencies are based solely upon projected sea level rise, and do not take into consideration the expected changes in coastal storm intensity. **The intensity, frequency, and duration of flooding are very likely to increase further if the intensity of coastal storms escalates as predicted** (Horton et al., 2010b). Under present conditions, coastal floods to the 100-year flood level cause water to rise 8.6 feet above normal sea level, and decadal floods cause water levels to rise 6.3 feet above sea level at the Battery in New York City (Table 5) (Rosenzweig et al., 2009). This rise is a measure of the still water level and does not take into account the height of wave action that may occur on top of this (Rosenzweig et al., 2009). **Scientists estimate that flood heights will increase substantially over the 21st century; most notably, by the 2050s, the 100-year flood height will be 9.2 to 9.6 feet above still water level. Given that Stamford's beaches have a maximum elevation of about six to eight feet, these predictions are especially troubling.**

Note: Flooding that reaches the 100-year flood level is an event that has a one percent chance of occurring in any given year. This does not mean that only one 100-year flood will occur in a century,

Flood Type	Flood Frequency	Flood Height	Time Period*
1-in-10 Year Flood	Once every 8-10 years	6.5-6.8 feet	By the 2020s
	Once every 3-6 years	7.0-7.3 feet	By the 2050s
	Once every 1-3 years	7.4-8.2 feet	By the 2080s
1-in-100 Year Flood	Once every 65-80 years	8.8-9.0 feet	By the 2020s
	Once every 35-55 years	9.2-9.6 feet	By the 2050s
	Once every 15-35 years	9.6-10.5 feet	By the 2080s
1-in-500 Year Flood	Once every 380-450 years	10.9-11.2 feet	By the 2020s
	Once every 250-330 years	11.4-11.7 feet	By the 2050s
	Once every 120-150 years	11.8-12.6 feet	By the 2080s

** Time Periods reflect a 30-year average around the specified decade. The 2020s is defined as 2010-2039, the 2050s is defined as 2040-2069, and the 2080s is defined as 2070-2099.*

TABLE 5

Predicted changes in flood frequencies and heights by flood type. Adapted from Rosenzweig et al., 2009.

however. Rather, in a 100-year period, there is a 63-79% chance that flooding to the 100-year level will occur one or more times. In a 30-year period, there is a 26-37% chance that flooding to the 100-year level will occur one or more times. Probability calculations can be confusing and misleading, but the important thing to keep in mind is that Stamford likely will experience multiple 100-year floods in a given century. Chances are that Stamford will experience flooding to the 100-year level even more frequently in the future because our climate is changing.

Sea Level Rise

Stamford's coastal location makes the City particularly vulnerable to sea level rise. An elevated sea level means more flooding from high tides and storm surge. Sea level rise occurs for two main reasons: first, as water warms, it expands, and thus occupies a larger volume; and second, as land-based ice, such as the Greenland Ice Sheet and West Antarctic Ice Sheet melt, the melt-water enters the ocean and increases the volume of the water (Solomon et al., 2007). **The extent of damage caused by sea level rise will be determined by how fast the Earth warms and thus how quickly land-based ice**

Current Federal Emergency Management Agency (FEMA) 100-year flood map showing substantial inundation at all three beach parks. This inundation is expected to increase in severity and to occur more often in the future.

melts.

Sea level has risen more than eight inches along the East Coast of the United States over the past 50 years, and approximately one foot along the greater New York area since 1900 (Horton et al., 2011; Horton et al., 2010b). This trend is projected to continue in the future. Scientists predict that one of the following scenarios will occur: either sea level will rise gradually, with a two to five inch increase by the 2020s, a seven to 12 inch increase by the 2050s, and a 12 to 23 inch increase by the 2080s; or sea level will rise rapidly with a five to ten inch increase by the 2020s, a 19 to 29 inch increase by the 2050s, and a 41 to 55 inch increase by the 2080s (Rosenzweig et al., 2009). The rate of warming will determine which of these scenarios occurs. A few years ago, scientists thought that gradual warming and thus a gradual rise in sea level would be the most likely scenario. Today, though, we have more information about how quickly land-based ice is melting, and experts are beginning to think that the rapid sea level rise scenario may be more realistic. Radley Horton, an expert in regional climate change scenarios, explains in a recent interview that: **"We've lost about 70 percent of the volume of September sea ice compared to three decades ago. No climate models, when you provide them the amount of greenhouse gases in the atmosphere over the last three decades, have been able to predict that rate of decline. That raises some questions: when the community does climate projections, are we capturing the full range of possible outcomes?"**

Scientists quantify the likelihood that sea level will continue to rise over the 21st century as greater than 95 percent. **The most important thing to keep in mind about sea level rise is that an elevated base sea level means that even small storms will cause flooding** (Horton, 2013). Given that Stamford's beach parks suffer from flooding even at today's sea level, future sea level rise poses a severe threat to the beaches.

Precipitation

Though Stamford's beach parks tend to sustain damage primarily from coastal flooding rather than from rain associated with coastal storms, precipitation is likely exacerbate flooding in the years to come. Over the past 50 years, average annual precipitation has increased by approximately five percent globally (Karl et al., 2009). Similar to the shift in temperature, this change in average annual precipitation patterns has resulted in increased extreme precipitation events (e.g., heavy downpours of rain). To illustrate this point, Kunkel and colleagues (2008) note that the amount of precipitation that has fallen in the top one percent of the heaviest rain events has increased by 20 percent over the past 50 years. Furthermore, the Northeastern region of the United States has experienced some of the greatest increases in heavy precipitation during this time period (Karl et al., 2009). **"Shifts in average temperature and average precipitation mean that climate extremes will become even more severe, even without any change in frequency or climate variability"** (Horton et al., 2010b).

Climate scientists anticipate that this upward trend will continue in the future. Models suggest that average annual precipitation will increase in the greater New York City area by zero to five percent by the 2020s, zero to 10 percent by the 2050s, and five to 10 percent by the 2080s (Rosenzweig et al., 2009). The likelihood that average annual precipitation will increase throughout the 21st century is greater than 50 percent (Rosenzweig et al., 2009).

Scientific predictions also show that the frequency of intense precipitation events will increase, and that the length of time between these events will increase (Karl et al., 2009). In other words, heavy downpours will be likely to occur more often than they do today, but there will be more time between the downpours than there is today. Climate scientists attribute this phenomenon to increased man-made aerosols in the atmosphere. Man-made aerosols, such as particulate air pollution from the burning of fossil fuels, are far smaller than their natural counterparts, such as sea salt and dust. Aerosols are the basis for cloud formation: water vapor in the air condenses around these particles. The smaller the aerosols, the smaller the condensed water droplets, which means that it takes more aerosols and droplets for clouds to reach a critical size – and thus to precipitate. When precipitation finally occurs, the clouds rain out the large accumulation of water in heavy downpours (Solomon et al., 2007).

Of particular relevance to Stamford is the prediction that heavy precipitation events will increase especially in the northern mid-latitudes (IPCC, 2012).

The primary impacts of increased frequency of intense precipitation events will likely be increased erosion and flooding at Stamford's beach parks.

Climate information tells us that the future risk of storm damage to Stamford's beach parks is high (Table 6)**. Many coastal geologists, engineers, and shoreline managers expect that as our climate continues to change, and the associated risk of storm damage continues to increase, engineered technologies will do little to improve resilience.**

How are climate projections made?

Future climate projections are based on general circulation models (GCMs), which draw upon the laws of physics and mathematical equations to create three-dimensional gridded representations of the climate system. These dynamical models aim to simulate the motion of and interactions between the atmosphere, the ocean, land, ice, moisture, and heat (Horton et al., 2010). Models are assessed for accuracy through the practice of hindcasting, which

Climate Hazard to Stamford Beaches	Description of Climate Hazard	Description of Impact of Climate Hazard to Stamford Beaches	Time Period*	Likelihood of Climate Hazard Occurring
Extreme Events	Increased intensity, frequency, and duration of coastal flooding associated with storms	Increased chance of damage to beach park infrastructure, decreased number of operational days for beach parks	Throughout the 21st century	>90%
	Increased intensity of coastal storms	Increased chance of damage to beach and beach park infrastructure due to heightened storm surge and increased intensity of wave action, decreased number of operational days for beach parks		Not quantified
	Increased frequency of the most intense coastal storms (i.e., Category 4 and Category 5 hurricanes)			>50%
Sea Level Rise	Increase in sea level by 2-5 inches (gradual), or by 5-10 inches (rapid)	Decreased land area of beach, inundation of beach infrastructure by water, increased chance of flooding associated with nor'easters and hurricanes	By the 2020s	>95%, unknown
	Increase in sea level by 7-12 inches (gradual), or by 19-29 inches (rapid)		By the 2050s	>95%, unknown
	Increase in sea level by 12-23 inches (gradual), or by 41-55 inches (rapid)		By the 2080s	>95%, unknown
Precipitation	Increase in mean annual precipitation by 0-5%	Increased chance of sand erosion, increased chance of flooding beach park infrastructure	By the 2020s	>50%
	Increase in mean annual precipitation by 0-10%		By the 2050s	>50%
	Increase in mean annual precipitation by 5-10%		By the 2080s	>50%

** Time Periods reflect a 30-year average around the specified decade. The 2020s is defined as 2010-2039, the 2050s is defined as 2040-2069, and the 2080s is defined as 2070-2099.*

TABLE 6
Summary of climate hazards and impacts to Stamford's beach parks. Adapted from Rosenzweig et al., 2009.

entails inputting the initial climate conditions for known time periods and comparing the model results with actual observations. The climate models that scientists currently use are able to reproduce, through hindcasting, the global warming trend that we've seen over the past century (Hegerl et al., 2007).

What is the uncertainty associated with climate projections?

Despite their predictive skill, climate models have limitations. These models lack the accuracy to account for certain complex physical processes and are limited by resolution and computational ability (Horton et al., 2010b). The intricacies of the climate system at the regional scale have yet to be fully captured by models. Because of these limitations, regional climate projections are less certain than their global counterparts (Horton et al., 2010b). For Stamford, this means that the predicted increase in the strength of coastal storms to hit the Northeast is inherently less certain than the predicted increase in the strength of Atlantic hurricanes in general. Despite recent efforts to downscale GCMs to the regional level, global predictions still remain far more certain at this point in time.

Though it is important to be aware of these constraints, the climatic changes associated with the "unknowns" are expected to be smaller than those associated with the known greenhouse gas emissions over the next 100 years (Horton et al., 2010b). Climate models have been consistent in successfully reproducing the overall climate in North America, and therefore should not be disregarded as effective prediction tools (Solomon et al., 2007).

How can Stamford manage the risk of storm damage?

At a Glance:

- **Take a risk management approach, which allows for adjustments to be made according to change in risk over time.**
- **A fixed strategy that does not account for increasing risk likely will waste money.**

Risk Management Framework

It is important that the City be able to adjust its beach resilience strategy according to changes in the risk of storm damage over time. This way, Stamford can better match the level of its investment to its risk. A fixed strategy that does not account for increasing risk and uncertainty, and that is based on making a single long-term investment in beach protection, will likely waste money.

Risk management is dynamic in that it accounts for increasing risk and growing uncertainty. This approach consists of five steps that are meant to be completed, one after another, to form repeating cycles (Figure 5). The steps, as adapted for Stamford, include:

(1) understanding the potential for storm damage to Stamford's beach parks;
(2) assessing the extent of these damages (e.g., cleanup costs, duration of beach closures) and the chances that these damages will occur;
(3) developing a plan to address the risk of storm damage to Stamford's beach parks;
(4) implementing the plan; and
(5) monitoring and reassessing this plan to make sure that it is working.

Most importantly, the risk management framework offers the City of Stamford a process for better understanding and dealing with risk.

Climate change adds complexity to devising a strategy for improving the resilience of Stamford's beach parks: as the planet continues to warm, causing sea levels to rise and intense coastal storms to become more frequent, the risk to Stamford's beaches grows over time.

Similarly, the uncertainty associated with future climate change predictions increases over time. This combination of risk and uncertainty means that any method for improving beach resilience ought to be adaptable if climate conditions exceed scientists' predictions. The risk management framework accounts for uncertainty and allows for adjustments to be made as needed. Climate scientists explain that: **"The way forward is robust decision making under uncertainty."** (Horton et al., 2010b)

FIGURE 5
The five basic steps of risk management.

Though the scope of our project was limited to steps one through three of the risk management approach, we include recommendations for completing steps four and five in the following sections of this report.

What are some next steps in the short term?

At a Glance:

- **Locate additional site-specific information to assess opportunities for climate resilience more accurately.**
- **Draw on professional expertise to advance this preliminary analysis.** Consult coastal engineers and geologists, as well as coastal resource councils.
- **Monitor legislation on beach protection.**
- **Pursue funding opportunities.**

Locate Additional Information

Our analysis of opportunities for climate resilience at Stamford's beach parks was limited by several factors. These include lack of training in and knowledge of coastal engineering practices, and limited availability of climate risk information that is specific to Stamford. Therefore, we recommend that the City locate key additional information – especially in the above-mentioned areas – before pursuing any of the other recommendations set forth in this report. Coastal engineers, coastal geologists, and shoreline protection experts emphasize that **accurate, site-specific information is essential to developing and implementing a beach resilience plan.** We recommend that Stamford conduct site analyses of the three beach parks in order to obtain this additional information.

Draw on Professional Expertise

In addition to locating more information, we recommend that the City draw on professional expertise to advance our analysis of opportunities for resilience. Consulting with experts from public organizations, such as the **U.S. Army Corps of Engineers**, the **Connecticut Sea Grant**, and private contractors such as **All Habitat Inc.** is vital when tackling a complicated issue like beach protection. We learned a great deal from speaking with many of these professionals while conducting our analysis (Table 7). Though their insights informed our thinking about beach resilience and our approach to developing recommendations for Stamford, we recognized that we were unable to capitalize on their expertise fully because we could not engage them in a site analysis of the beach parks.

Experts who are directly engaged could develop, vet, and implement projects that are appropriate for Stamford. **Engineers**, **geologists**, and **contractors** can offer perspectives on the impacts that a resilience technology may have.

Organizations such as the National Oceanic and Atmospheric Administration (NOAA) offer expertise and experience in coastal management and NOAA is recognized for its expertise in conducting threat and vulnerability assessments, as well as in developing integrated coastal management systems.

Consulting with both domestic and international experts, such as **habitat restoration coordinators**, **coastal resource managers**, and **erosion specialists** could provide Stamford with valuable guidance. In addition, developing a network of knowledgeable people who Stamford can periodically consult would be helpful in tracking best practices in coastal resilience.

Some important and useful collaborators of this knowledge network may include:
(See *Appendix 3: Contacts* for a complete list of contacts.)

- Connecticut Department of Energy & Environmental Protection, Office of Long Island Sound Programs (DEEP)
- The Nature Conservancy
- UCONN's Surge Modeling Program
- RI Coastal Resources Management Council
- Groton, Connecticut's Coastal Climate Adaptation Workshop
- The Governor's Adaptation Subcommittee on Connecticut's Climate Change (GSC)
- Stamford's Office of Cashiering & Permitting
- Project GreenShores
- Coastal Dune Management, New South Wales (NSW) Department of Land and Water Conservation, Coastal Unit, Ecosystems Branch

Monitor Legislation on Beach Protection

Many states oppose shoreline protection. Rhode Island, Maine, and North Carolina, for example, have enacted legislation to ban hard engineering technologies. In the state of Maine, even geotextile tubes are considered to be "hard" engineering, and, therefore, are not permitted on shorelines. It will be important for Stamford to stay up-to-date on changes in rules and regulations pertaining to beach protection in the state of Connecticut.

The Connecticut Coastal Management Act (CCMA), which was enacted in 1980, prescribes the natural hazard mitigation program. This program was designed to assist Connecticut coastal communities on the Long Island Sound in managing hazards. The program sets standards for mitigation in tidal, coastal, and navigable waters. The regulations affect local planning and zoning boards.

The DEEP has jurisdiction over flood hazard and mitigation activities in the State of Connecticut, including activities occurring in tidal wetlands and/or water ward of the high tide line.

Expert	What We Learned
Janet Freedman, Coastal Geologist at RI Coastal Resources Management Council	The shoreline is moving landward. Whatever is done to protect it will be a fight against this inevitable movement. This is not something that's going to reverse itself. Any community needs to keep in mind that shorelines change, and that this can happen rapidly.
Juliana Barrett, Educator at CT Sea Grant Program	Localized impacts from storm damage depend on the wind direction and the distance the wind travels over water (known as fetch). The longer the fetch, the higher the waves can get. A wave analysis is critical in order to determine how successful dunes will be.
Anthony Zemba, Director of Conservation Services at CT Audubon Society	Adding woody vegetation on the back sides of dunes makes them more stable and resilient. It's important to consult with an ecologist about planting the right vegetation.
Stephen Dickson, Coastal Geologist at ME Geological Survey	Seawalls are their own worst enemies in the long term. With seawalls, the beach scours away, lowers in profile, and reflects even bigger waves, which causes even more erosion. Putting in a bigger seawall is a recipe for disaster in most settings.
Jennifer O'Donnell, Engineer at Coastal Ocean Analytics	If you have breaks in dunes, the water is going to rush through the openings. You'll therefore get water in the back, behind the dunes. And because you have dunes, you'll have a problem with retreating water – the dunes will hold the water in place and slow it from retreating back to the ocean once the storm passes.

TABLE 7
Selected insights learned from interviews with experts.

The Office of Long Island Sound Programs (OLISP) administers Connecticut's Coastal Management Program, which is approved by the National Oceanic and Atmospheric Administration (NOAA) under the Federal Coastal Zone Management Act. The City of Stamford must file an application to OLISP in order to undertake any hazard mitigation or restoration project. OLISP reviews the application and collaborates with DEEP, as needed.

Pursue Funding Opportunities

Some funding programs to protect the ecological, recreational, historical, or aesthetic value of U.S. coasts and beachfronts are available to Stamford. Some funding resources are state-specific, while others are specific to a cause, such as purchasing coastal and estuarine lands. The City of Stamford could pursue funding opportunities for protecting Connecticut's beaches; these include the Environmental Protection Agency (EPA), the Connecticut Department of Energy and Environmental Protection (DEEP), and other state and federal entities.

The EPA's Beaches Environmental Assessment and Coastal Health (BEACH) Act Grant of 2000 provides about $10 million in grants annually. These grants are given to eligible coastal and Great Lakes states for improving coastal and beach water quality, and for helping beach managers to better inform the public about water quality issues. Grants for each state range from $150,000 to $516,000 depending on factors such as beach season length, total miles of shoreline, and coastal county population. In 2012, based on the eligibility criteria and factors, Connecticut's allocation was estimated at $222,000 (EPA BEACH Act, 2012). Cities like Stamford could use BEACH Act grant monies to fund beach initiatives.

The DEEP's Connecticut Coastal Management Program is supported by the Long Island Sound License Plate Program. The program receives revenue from drivers who purchase "Preserve the Sound" license plates for their cars, boat trailers, and other vehicles. These funds support public access projects (e.g., the creation of boardwalks), education, outreach, habitat restoration, and research (e.g., to improve management decisions about the Long Island Sound's natural resources) (DEEP, 2013). Stamford could pursue this funding opportunity for building a boardwalk over sand dunes, for example.

The Long Island Sound Futures Fund also supports preservation and conservation projects. This program is a public-private initiative made possible by the EPA, the National Fish and Wildlife Foundation, the Fish and Wildlife Service, the Department of Agriculture, the Natural Resources Conservation Service, and Wells Fargo (EPA, 2012). In 2012, the Program granted a total of $757,922 to 20 Connecticut conservation projects (Connecticut Land Conservation Council, 2009).

In 2012, a partnership between the DEEP and the Long Island Sound Futures Fund raised more than $750,000 for marine habitat restoration and management plan preparation, among other activities. Such partnerships could be curtailed to focus on the resilience of Stamford's beach parks.

The Connecticut Land Conservation Council (2009) matches grantors to grantees for conservation initiatives focused on coastal resource stewardship. This organization provides useful information on funding programs and is a good starting point for identifying grant monies.

What are some next steps in the long term?

At a Glance:

- **Monitor and reassess changes in the effectiveness of the resilience technology, as well as new climate risk information.** Continuous monitoring and reassessment are key components of managing risk.
- **Eventually, consider yielding to the dynamic nature of beaches.**

Monitor & Reassess

Monitoring and reassessing are essential in successfully managing risk. We recommend that Stamford monitor the effectiveness of the implemented resilience technology. If the City opts to build vegetated sand dunes, monitoring may consist of tracking the beaches' sand budget on a monthly or annual basis. Simple measurements of things like dune dimensions and mean high water line can help to provide rough estimates of sand budget (Dickson, 2013). We also recommend that Stamford track changes in climate risk information. This means staying up-to-date on new global climate projections as well as any climate predictions specific to the New York City and/or Stamford areas.

It also may be useful to track seasonal weather forecasts. Weather differs from climate in that weather occurs over short periods of time, whereas climate is the behavior of the atmosphere over long periods of time. Most climate scientists define climate as the average weather for a particular region over a 30-year period (NASA, 2005). Seasonal weather and storm forecasts, such as those issued by Colorado State University, could help Stamford plan for short-term storm activity. Additional seasonal forecasts from Colorado State University are expected to be released in early June of 2013 and then again in early August of 2013. **It is important to keep in mind, however, that improving resilience requires long-term planning.** While it may be possible to truck in and pile up sand along the beaches a few days before a big storm is forecast to hit Stamford, this strategy is not nearly as effective as building well-constructed vegetated sand dunes. The town of Westport, Connecticut piled up sand a few days before Hurricane Sandy made landfall. Despite this last-minute effort to reduce flooding and cleanup costs, Westport spent about $335,000 cleaning up sand and replacing it to the beachfront once the storm had passed (Westport, Connecticut Board of Finance, 2013). Well-established vegetated sand dunes are far more effective than makeshift piles of sand because the roots of the vegetation hold the sand in place when confronted with winds and waves from storms. Geotextile tubes can also contribute to the durability of dunes, as is described in previous sections of this report.

In addition to monitoring, the City must continually reassess any decisions surrounding beach resilience technologies. Because the risk of storm damage is expected to grow over time, and, as a result, maintaining beach resilience technologies is expected to become more and more expensive, the City must reassess its decision to use these technologies. At some point, it is likely that Stamford will be unable – or perhaps unwilling – to pay for beach protection. Therefore, the City must continually reassess any investment it makes in these technologies.

Yield to the Dynamic Nature of Beaches

By the end of the 21st century, Stamford's beaches likely will be in a different place than they are now. It is probable that in the future, the beaches will move inland, re-shaping the current look of the beach parks and land area behind them.

Imagine, for a moment, the current lawn area at Cove Island Park the way it was coved by sand after Hurricane Sandy. Near the end of this century, the grassy area may become the new beachfront, as the current beach is lost to rising waters. Imagine the area without the current walkways, paved paths, concession stands, and buildings. Similarly, imagine Cummings Beach Park located where the current parking lot is, and the concession stands moved farther back from the water – or even removed altogether. Under such conditions, Stamford may have to relocate structures further inland to accommodate the new shoreline.

Throughout Earth's history, coastlines have been moving inland during periods of warmer weather and moving out to sea during periods of cooler weather. Earth is currently in a warming period, which means that shorelines will move landward. It is only because we settled and developed the coast that shoreline movement has become a problem. If developments did not encroach on coastlines this natural movement would occur unnoticed as it has for thousands of years (Needleman, 2012).

Coastlines have never been stationary. There may come a point, and that point may be soon, when the cost of protecting beaches becomes too expensive, very difficult, or both. When this occurs, it may be appropriate for Stamford to yield to the natural movement of beaches.

Habitat restoration as well as the creation and expansion of open space are emerging as best practices for coastal management. **Through observation, people are discovering that naturally occurring dunes protect the land behind them better than any of the man made structures.** Reefs and marshlands absorb a lot of excess water that storms bring about, helping to decrease flooding. People also are noticing that big storm events actually deposit new sediment on land. This works as a counter-balance to erosion, which carries sand back to the ocean bottom for storage (Crooks, 2012).

As land continues to be reclaimed by the expanding sea, the shoreline will continue to move. To deal with this reality, some local governments have started to to update zoning requirements that determine what and how structures are built. Such requirements may be used in Stamford to ensure that structures be set back a certain distance from the water, be elevated to a specified height, or be flood-proofed. The goals of these requirements would be to reduce damage to the parks, to lessen the cleanup costs after coastal storms, and, most importantly, to preserve the public's continued enjoyment of the beaches. Some governments have deemed strategies like these economically beneficial in comparison with doing nothing (Ocean & Coastal Resource Management, 2007).

Such zoning laws that limit and discourage infrastructure development would be appropriate for Stamford's beach parks. Using this type of regulation to expand and restore the open areas adjacent to the beaches, more so than any engineered solution, will allow the continued use of Stamford's beaches into the future.

Conclusion

After examining both hard and soft engineering measures, we conclude that the most promising option for Stamford's beach parks is vegetated sand dunes, enhanced with geotextile tubes. We recommend that the City take steps to reduce the exposure of beach park infrastructure by making adjustments to the way infrastructure is designed, built and maintained. Stamford must keep in mind, however, that these are short-term solutions; the solution for the long term is quite different.

As risk to Stamford's beach parks increases over time, trying to stop oceans from encroaching on land is likely to become impossible. At that point, the City may find it impractical and overly expensive to maintain beach protection. Stamford may then have to yield to the natural forces that make the beachfront migrate landward. We recommend a risk management approach that meets Stamford's goals of improving resilience to storm damage and preserving the aesthetic and recreational values of the beach parks in the short-term, but that also allows the City to adjust to changing conditions, such as sea level rise and more intense coastal storms, in the future.

Though we cannot be sure about what will happen in the future, climate predictions suggest that the oceans and sand will overtake the parking lots and grassy areas that exist at Stamford's beach parks today. Residents of Stamford will continue to enjoy its beach parks, but the parks may look very different than they do today.

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Appendices

Appendix 1: Glossary of Terms

100-year flood: an event that has a 1% chance of occurring in any given year. This does not mean that only one 100-year flood will occur in a century, however. In a 100-year period, there is a 63% chance that flooding to the 100-year level will occur one or more times. In a 30-year period, there is a 26% chance that flooding to the 100-year level will occur one or more times. Probability calculations can be confusing and misleading, but the important thing to keep in mind is that Stamford likely will experience multiple 100-year floods in a given century.

All Habitat Inc.: a private contractor specializing in engineering, design, and construction management.

Beach nourishment: the process of adding sand to either create a new beach or to expand the area of an existing one (Technologies for Climate change adaptation, Coastal Flooding and Erosion).

Breakwater: a barrier that breaks the force of waves, for example outside a harbor (Allan, 2006). Breakwaters are typically constructed using durable materials such as rock or concrete.

Bulkhead: a vertical shoreline stabilization structure that primarily retains soil and provides minimal protection from waves (Coastal Systems International, 2006).

Climate: the average weather for a particular region over a 30-year time period (NASA, 2005).

Coastal and Estuarine Land Conservation Program (CELCP): The Coastal and Estuarine Land Conservation Program (pronounced "kelp") is a program aimed at providing state and local governments with funds to purchase coastal and estuarine lands (NOAA, 2013b).

Coastal Zone Management Act (CZMA): is an Act of Congress passed in 1972 to encourage coastal states to develop and implement coastal zone management plans (CZMPs). This act was established as a United States National policy to preserve, protect, develop, and where possible, restore or enhance, the resources of the Nation's coastal zone for this and succeeding generations (NOAA, 2013).

Connecticut Coastal Management Act (CCMA): enacted in 1980 to ensure a balanced growth along the coast; to restore coastal habitats to improve public access; to protect water-dependent uses, public trust waters, and submerged lands; to promote harbor management; and to facilitate research (Department of Energy and Environmental Protection, 2013).

Connecticut Sea Grant (CTSG): works towards achieving healthy coastal and marine ecosystems and consequent public benefits by supporting integrated locally and nationally relevant research, outreach, and education programs in partnership with stakeholders. CTSG is funded principally through the National Oceanic and Atmospheric Administration (NOAA), with matching funds from the State of Connecticut, through the University of Connecticut (Connecticut Sea Grant, 2013).

Department of Energy and Environmental Protection (DEEP): an agency in Connecticut charged with conserving, improving, and protecting the natural resources and the environment of the state of Connecticut as well as making cheaper, cleaner and more reliable energy available for the people and businesses of the state (Department of Energy and Environmental Protection, 2013).

Dewatering system: a system designed to pump water from the beachfront to maintain a dry and stable condition in order to prevent erosion (Williams Engineering, 2013).

Dike: an embankment for controlling or holding back the waters of the sea or a river (National Geographic, 2013).

Federal Coastal Zone Management Act: an Act of Congress passed in 1972 to encourage coastal states to develop and implement coastal zone management plans (CZMPs) (NOAA, 2013).

Fetch: the distance wind travels over water. Fetch is important determining the height of waves hitting the beach: generally speaking, the longer the fetch, the higher the waves.

Filtrexx Dura-Soxx: mesh logs similar to geotextile tubes, but smaller in size and more porous. The logs come in various diameters, and can be filled with sand, dirt, or compost materials.

Floodgate: a massive gate useful in coastal and inland environments to control the flow of rising waters from flood, storm surge, or other similar events (IBS Engineered Products Limited, 2013).

Geotextile Tube: a large tube made of specially engineered fabric that is filled with sand and lined up along the shoreline to potentially prevent erosion and property damage (TenCate, 2012).

Geotube ®: a geotextile tube manufactured by TenCate.

Groin: a coastal structure constructed perpendicular to the coastline to trap long-shore sediment transport or control long-shore currents.

Hard engineering technologies: these include solid structures such as breakwaters, bulkheads, groins, jetties, revetments, and seawalls. These structures are designed to withstand large forces and typically have a long lifespan. Hard engineering technologies tend to be minimally flexible and require high initial and maintenance expenditures (Rosenzweig et al., 2011).

Hurricane Sandy: the deadliest and most destructive tropical cyclone of the 2012 Atlantic hurricane season, as well as the second-costliest hurricane in United States history (Sharp, 2012).

Indicator species: a species whose presence, absence, or relative well being in a given environment is a sign of the overall health of its ecosystem (The Encyclopedia of Earth, 2012).

Jetstream: a fast flowing and relatively narrow air current found in the atmosphere around 10 kilometers above the surface of the Earth (WSI Corporation, 2013).

Jetty: a long, narrow structure designed to protect a coastline from the currents and tides. A jetty is usually made of wood, earth, stone, or concrete, and stretches from the shore into the water (National Geographic, 2013).

Levee: a man-made structure, usually comprised of an earthen embankment, designed and constructed to contain, control or divert the flow of water in order to provide protection from temporary flooding (Federal Emergency Management Agency, 2013).

Long Island Express: the first major hurricane to strike New England since 1869, which grew into a Category 5 hurricane before making landfall as a Category 3 hurricane on Long Island on September 21, 1938 (Mandia, 2012).

Macro-level engineering: consists of massive structures such as dikes, floodgates, levees, and storm surge barriers (Buonaiuto et al., 2011). These technologies are designed to reduce storm damage to highly urbanized areas with expensive infrastructure that are designed to withstand large forces and typically long lifespans.

Micro-level engineering: consists of smaller-scale structures such as seawalls, beach nourishment, and revetments.

National Oceanic and Atmospheric Administration (NOAA): an agency within the Department of Commerce that maps the oceans and conserves its living resources; predicts changes to the earth's environment; provides weather reports and forecasts floods, hurricanes, and other natural disasters related to weather (NOAA, 2013).

Nor'easter: a storm along the northeastern coast of the United States and Atlantic Canada, which gets its name from the direction of the winds that create these. Nor'easters typically bring wintery weather such as snow and sleet, and often span several tidal cycles. (The Weather Channel, LLC, 2012).

Office of Long Island Sound Programs (OLISP): an agency run by Connecticut's Department of Environmental Protection and a part of the Department of Energy and Environmental Protection (DEEP). It implements a variety of permitting programs for work conducted in tidal wetlands and in tidal, coastal or navigable waters of the state. The purpose of these programs is to conserve and protect the water and natural resources of the state and to protect life and property from erosion and flood hazards (Department of Energy and Environmental Protection, 2013).

Oyster bed: a place on the seabed where oysters breed and grow naturally or are cultivated for food or pearls (United States Department of Agriculture, 2011).

Resilience: the time required for an ecosystem to return to an equilibrium or steady state following a perturbation (like a hurricane). Also defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker, Holling, Carpenter, & Kinz, 2004).

Revetment: an onshore structure built to protect the toe of a bluff/bank from erosion caused by wave action (Ohio Department of Natural Resources, 2013).

Risk management framework: a circular and flexible approach that accounts for uncertainty and encourages adjustments to be made as needed. Components of this framework include: understanding the problem, understanding the chances of a problem happening, planning on how to deal with a problem, and continually monitoring the situation.

Salt marsh: an area of terrestrial plants between land and open salt water, which is able to trap and absorb water, and sediment (Florida Department of Enviromental Protection, 2010).

Sand dune: a mound, hill, or ridge of sand that lies behind the part of the beach affected by tides, and formed over many years when windblown sand is trapped by beach grass or other stationary objects. A sand dune can be natural or artificial (New Hampshire Department of Environmental Services, 2013).

Sea-surface pressure gradient: a physical quantity that describes which direction, and at what rate, the pressure changes the most rapidly around a particular location over the ocean. The pressure gradient constitutes one of the main forces acting on the air to make it move as wind. Pressure gradients always move from high to low (Coastal Systems International, 2006).

Seawall: a structure that provides shoreline protection from waves and also retains soil (Coastal Systems International, 2006).

Soft engineering technologies: include beach nourishment, dewatering systems, oyster beds, salt marshes, creation and/or restoration of sand dunes (artificial and natural), and vegetation planting. Soft engineering technologies are designed to withstand small to moderate forces, absorb storm impacts, and typically have short to medium lifespans. These technologies mimic the natural ecologic and geologic processes that improve resilience to storm damage (Rosenzweig et al., 2011b).

Storm surge barrier: a specific type of floodgate designed to prevent a storm surge or tides from flooding the protected area behind the barrier (Yglesias, 2012).

Tidal resonance: the amplification of tides in an inlet because of the interaction between the shape of the inlet and the frequency of the tides. Tidal resonance occurs when the tide excites one of the resonant modes of the ocean (Platzman, 1991).

U.S. Army Corps of Engineers (USACE): a U.S. federal agency under the Department of Defense and a major Army command, making it the world's largest public engineering, design, and construction management agency. USACE is involved in a wide range of public works throughout the world. The Corps of Engineers provides outdoor recreation opportunities to the public, and provides 24% of U.S. hydropower capacity. The Corps' mission is to provide vital public engineering services in peace and war to strengthen the nation's security, energize the economy, and reduce risks from disasters (U.S. Army Corps of Engineers Headquarters, 2013).

Vegetated sand dune: a dune that is covered with native plants. Over time, the roots of these plants grow deep into the dune and help to hold the sand in place and trap additional sand. This helps the dune to grow over time.

Weather: the way the atmosphere behaves in the short term (NASA, 2005).

Appendix 2: Options for Improving Resilience

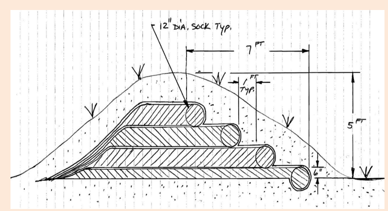
Vegetated Sand Dune with Geotextile Tubes

	Vegetated Sand Dune with Geotextile Tubes (e.g., Geotube ®)
Overview	A vegetated sand dune constructed with geotextile tubes is a dune that has a semi-solid core made of specially engineered textiles that are filled with sand. These textile tubes are placed along the shoreline to prevent erosion and damage from storms. Geotextile tubes can be placed individually or stacked to create a pyramid. In most cases, the installation is permanent (Ginter, 2013). The tubes are then covered with sand and vegetation; once construction is complete, they look like naturally occurring sand dunes. Each tube can be hundreds of feet long, up to 45 feet wide, and filled to 6.5 feet tall (Ginter, 2013). 
Feasibility	Dunes with geotextile tubes have been approved in many places as effective ways to prevent damage from storm surge and erosion (Ginter, 2013). Stamford could use this technology to reduce the impacts associated with storm surge.
Effectiveness	Geotextile tubes can be used to construct sand dunes designed to protect against the flood height associated with the current 100-year storm.
Cost-effectiveness	The cost to construct a vegetated sand dune with geotextile tubes is approximately $250 per linear foot (Ginter, 2013).
Flexibility	Geotextile tubes can be removed if necessary; this involves uncovering the tubes, draining the sand, and hauling the textiles away. To upgrade the geotextile tube system, a contractor would have to carefully dig or excavate the tubes so as not to damage the fabric (Ginter, 2013).
Additional Benefits	Once construction is complete, these dunes function just like natural sand dunes. The co-benefits of sand dunes include providing habitats for animals – for example nesting, breeding, feeding, and refuge areas for birds; and creating a more serene beach experience for visitors by blocking views of parking lots and other urbanized scenery.
Advantages	Geotextile tubes be used for both small- and large-scale projects. When covered with sand, they offer the same appearance as natural, unenhanced dunes. Geotextile tubes can be reinforced using additional fabric "shrouds" to prevent damage. The fabric used in Geotubes ® does not biodegrade over time, so these structures are expected to last (Ginter, 2013).
Drawbacks	If the geotextile tube is exposed during a storm, the tube can act as a hard structure and increase erosion in front of the tube. The use of Geotubes ® requires at least 50 feet of beach face in front of the tubes so that they are not exposed and damaged during mild storms (Ginter, 2013). Tubes can fail if they are not kept covered with sand, so maintenance requires nourishment. Any holes or tears in the fabric must be repaired quickly to prevent failure (Ginter, 2013).
Spotlight	The U.S. Army Corps of Engineers chose to use geotextile tubes for a project that aimed to rebuild and restore the shoreline of the hurricane-damaged beaches in the Gulf Coast. Nearly six miles of geotextile tubes were installed to form a protective barrier, to reduce erosion, and to re-nourish the storm-damaged beaches of Grand Isle. This project consisted of 30,100 linear feet of 30-foot circumference tubes, seven-foot circumference anchor tubes, and 35-foot wide scour aprons. Sand was hydraulically pumped into the geotextile tubes, which were filled to 5.5 feet tall. These were then covered with three feet of sand to create the look and profile of a natural dune. Sand-colored polyuria coating was used for the geotextile fabric to provide strength, durability, and an aesthetic appearance. Weeks after the project was completed, Tropical Storm Ida struck Grand Isle. This storm caused an old levee to breach, but the geotextile tubes suffered no damage at all (TenCate, 2007).

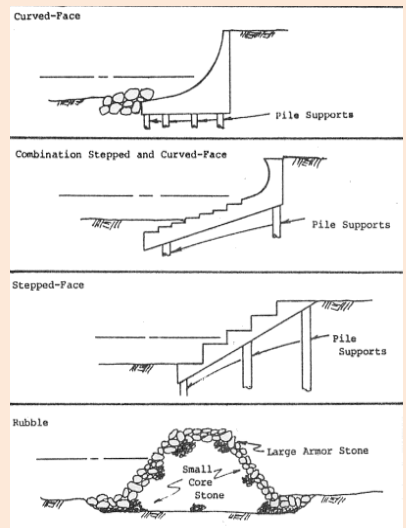
Vegetated Sand Dune

	Vegetated Sand Dune
Overview	Sand dunes are nature's way of protecting land from flooding. They also serve as sand storage banks for beaches (Broome, 1982). Sand is made of eroded soil and rocks, and forms when this material is broken down over time. Big storms move sand from deeper offshore areas to the beach face. Once it's deposited on the beach face, the wind moves the sand to form dunes. Over time, sand accumulates in areas to form dunes. Vegetation helps to capture this sand as it is blown by the wind, thereby causing the dune to grow. For areas where sand is scarce or does not occur naturally, like in Stamford, beach nourishment can help to improve sand volume (Stout, 1988). 
Feasibility	It is unlikely that dunes would form on their own at Stamford's beach parks because this is a highly engineered environment. Natural vegetated dunes therefore would have to be built in Stamford. Dunes can be constructed with bulldozers by piling and shaping sand into dunes. This is typically done at the same time as beach nourishment. Beach nourishment often is accomplished by trucking sand onto the beach from a nearby source of sand (e.g., gravel pit, dredged inlet). Once the dune is shaped then native vegetation can be planted in the sand to stabilize the dune so that it's not eroded away. Native plant species include American beach grass, switch and panic grass, Sea Oats, Bitter Panicum, Saltmeadow, and Seashore Elder (Barrett, 2008). The availability of sand and the magnitude of the forces that move the sand, such as wind, tides, and waves, would affect the success of natural dunes in Stamford (Barrett, 2008). Therefore, it is essential to consult with coastal engineers to better understand the local conditions for dune formation in Stamford.
Effectiveness	A vegetated natural sand dune provides an effective way to protect beaches and the land behind them by absorbing the impact of waves and reducing flooding.
Cost-effectiveness	The cost to construct a vegetated sand dune is approximately $370 per linear foot.
Flexibility	Sand dunes move and change shape by themselves in response to winds, waves, and tides. They therefore can adjust to changes in sea level and storm frequency over time – but only if they are allowed ample space for movement. Infrastructure such as paved surfaces and buildings will prevent the natural movement of sand dunes, and thus the long-term benefits they provide.
Additional Benefits	Sand dunes play an important role in coastal ecosystems. They provide habitats for a wide variety of wildlife including shore birds; invertebrates such as crabs, insects, and mollusks; and small mammals. Habitats include nesting, breeding, feeding, and refuge areas. Sand dunes also create a more serene beach experience for visitors by blocking views of parking lots and other urbanized scenery.
Advantages	Vegetated sand dunes are part of the natural beach ecosystem.
Drawbacks	The natural movement and migration of this type of dune requires a large open space. This is something that Stamford does not have right now. Dune vegetation must be protected from foot traffic – trampling these grasses can kill them. Protecting the dunes may mean fencing off areas of the dunes, and building a boardwalk over the dune, which could take away from recreational space on the beach and increase the cost of the project.
Spotlight	In North Carolina, vegetated sand dunes have proven to provide protection from waves and storm-induced erosion during infrequent but severe coastal storms such as hurricanes. These dunes have acted as buffers against the dynamic movement of the ocean during storms. As vegetated dunes grew in height and density, areas farther landward became incorporated into the dune. 

Vegetated Sand Dune with Mesh Core Logs

	Vegetated Sand Dune with Mesh Core Logs (e.g., Filtrexx Dura-Soxx)
Overview	A vegetated sand dune with mesh core logs is a dune that has a pyramid-like structure at its core. This core is made of mesh logs, such as Filtrexx Dura-Soxx, which are similar to geotextile tubes but are smaller and more porous (Roach, 2013). The Dura-Soxx logs are then covered with sand and plants; once construction is complete, the dunes look like naturally occurring sand dunes. The logs come in diameters of 12 or 18 inches, and can be filled with sand, dirt, or compost materials. 
Feasibility	Constructing sand dunes using the Dura-Soxx logs is a viable option for Stamford. Because the beaches are not very wide, the logs would be able to build height for the dune without taking up too much beachfront space.
Effectiveness	A vegetated sand dune with mesh core logs sustained damage during Hurricane Sandy, but was not destroyed and was effective at protecting the beach and minimizing the loss of sediment (Roach, 2013). The vegetation and top layer of sand were lost, however, and the Dura-Soxx logs were exposed, but the core structure was not damaged (Roach, 2013).
Cost-effectiveness	The cost to construct a vegetated sand dune with mesh core logs is approximately $760 per linear foot (Roach, 2013).
Flexibility	Once the Dura-Soxx logs are stacked and tied together, they function as a single unit and transform into a solid structure (Roach, 2013). The log center does not allow for much modification; however, if the dune is damaged during a storm and the Dura-Soxx logs are exposed, there is some opportunity to modify the dune's core structure.
Additional Benefits	Once construction is complete, these dunes function just like natural sand dunes. The co-benefits of sand dunes include providing habitats for animals – for example nesting, breeding, feeding, and refuge areas for birds; and creating a more serene beach experience for visitors by blocking views of parking lots and other urbanized scenery.
Advantages	Mesh core logs can be stacked up to create a taller structure much faster than is possible with a natural dune (i.e., made of sand and vegetation only). Filtrexx Dura-Soxx are most effective when they are made from COIR, a tightly woven coconut fiber mesh fabric that is resistant to salt water and that is biodegradable over time (Roach, 2013). When this fabric gets wet, it tightens up, making it even stronger (Roach, 2013). 
Drawbacks	This type of dune is not able to move and migrate landward like a natural dune can. In other words, the core log center adds stability but prevents movement over time. These dunes must be maintained, which involves periodic nourishment with sand and replanting with vegetation as necessary.
Spotlight	A dune was constructed at the edge of an eroding beach in Stratford, Connecticut using Filtrexx Dura-Soxx. The height of the dune varied between four and six feet, and the width varied between 10 and 15 feet. Nine Dura-Soxx logs were installed altogether; the first four logs were 750 feet long and the last five logs varied in length. These were stacked and arranged strategically, and soil envelopes were added between the logs for beach grass planting. The Dura-Soxx logs were covered with a mixture of 70% sand and 30% organic matter. A nine-inch planting scheme was used to plant 38,000 stems of beach grass. During Hurricane Sandy, the dune sustained damage but it survived the storm. The construction of the dune cost $350 per linear foot, including labor and materials. In addition, the landowners spent $20,000 on consulting services prior to the start of dune construction. The cost of reconstructing this dune is estimated at $100,000, to cover the logs with fill material, and re-plant grass.

Stepped-face Seawall

Stepped-Face Seawall	
Overview	Seawalls may be vertical, curved, stepped, or sloped. The design varies based on the goals for the seawall and the location of the structure (USACE, 1984). Curved-face seawalls are designed to accommodate the impact and run-up of large waves while directing the flow away from the land behind it. These are massive structures that require adequate foundations and study toes. Combination seawalls incorporate the advantages of both curved and stepped seawalls. Stepped-face seawalls are designed to limit wave run-up and overtopping. They generally are less massive than curved-face seawalls but the structural requirements are similar (USACE, 1995). Rubble seawalls are similar to breakwaters in structure, but they are placed directly on the beach instead of in the water. The rough surface is designed to absorb and dissipate wave energy with minimum wave reflection and scour (Buck, 1992). 
Feasibility	Given that Cove Island Park's rubble seawall was damaged in both Tropical Storm Irene and Hurricane Sandy, it seems that the rubble seawall structure is not appropriate for Stamford. The space needed to build a curved-face or combination seawall is significant and would take away from the recreational area of the beaches. These options therefore are less appropriate for Stamford. The most appropriate seawall technology for Stamford is the stepped-face seawall.
Effectiveness	Stepped-face seawalls are very effective against storms that cause high flood levels and damage from wave action.
Cost-effectiveness	The cost to construct a stepped-face seawall is approximately $11,600 per linear foot (Krecic & Wagstaff, 2005). Although the stepped-face technology is expensive, the construction costs may be justified by the addition of recreational space and thus value. Many coastal towns in Europe have allowed rezoning and adding high-value beach front properties behind stepped-face seawalls to offset their costs.
Flexibility	Seawalls do not allow for future modification should climate conditions change.
Additional Benefits	A stepped-face seawall adds seating, thereby contributing to the recreational area of the beach front.
Advantages	Provides additional space for seating and lounging along the beach.
Drawbacks	This technology is very expensive.
Spotlight	The city of Chicago has an eight-mile shoreline along Lake Michigan. In the past, Chicago has used rubble seawall structures to protect their shoreline. As this photo illustrates, much of the rubble seawall suffered significant damage over time. The rubble structure also negatively impacted the aesthetics of the Chicago shoreline. To fix this problem, the City implemented a stepped-face seawall, which offers a much cleaner look is far more durable than its rubble counterpart. Instead of acting as a standalone structure such as a vertical seawall or rubble revetment, the stepped-face structure merges with the recreational area. The stepped-face seawall adds seating and recreational area to the coastline. The photo below shows a beachfront in Cleveleys, England, where a massive stepped-face seawall structure stands. 

Appendix 3: Contacts

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