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Integrating a Resilience Scorecard and Landscape Performance into a Geodesign Process

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Abstract

Uncertainty about the impacts of sea level rise make the ability to forecast future spatial conditions a necessary planning/design tool. Geodesign integrates multiple fields of science with change/impact models and planning/design strategies. Proactive planning analyses such as newly developed scorecards allow for plan evaluation; design strategies can now be quantitatively assessed using landscape performance calculators. Neither have been explored as Geodesign tools. A Geodesign process was developed using the resilience scorecard to assess flood vulnerability using projections for the 100 year floodplain with sea level rise by 2100. Projections were used as a guide to develop a resilient master plan for League City, TX, USA. Future impacts of the plan are projected using landscape performance measures.

Keywords

Geodesign; resilience; landscape performance; geographic information systems; hazard vulnerability

Introduction

The use of innovative digital tools, such as Geographic Information Systems (GIS), to analyse and design geographic space is referred to as Geospatial Design (Geodesign). Geodesign, in part due to its flexibility in representing futures-to-come on multiple scales, has become more integrated in a number of applications (Wilson, 2014). For example, Geodesign can be applied as a mechanism to inventory, analyse and project a future state of affairs for geographic space (Goodchild, 2012). The framework for a Geodesign process (Stenitz, 2012) specifies six key models to be produced, including representation, process, evaluation, change, impact and decision. Representation and process models can be more interpretive than evaluation, change, and impact models in that they are typically a means of gathering and translating what data exists for a given landscape/urban environment. Decision

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models, then, are simply suggestions based on data, information, and knowledge gained from the other previous models.

As part of an initiative proposed by the Landscape Architecture Foundation, landscape architecture firms and academic institutions have been collaborating to quantitatively assess the environmental, economic and social benefits of urban design projects (Yang and Binger, 2016). This effort, known as landscape performance, encourages evidence-based designs that are grounded in quantitative performance measures. Unfortunately, many of these performance measures have not yet been fully incorporated into the Geodesign process. There are other analytical-planning methods, such as the resilience scorecard (Berke et al., 2015), which use quantitative performance measures to reduce losses from hazard events through conditional analyses and policy review, rather than projections or post-implementation evaluation metrics. However, while these types of analyses can provide a sound foundation for evaluation models, they are still quite separate from Geodesign approaches.

The application of Geodesign approaches are important due to their ability to integrate concepts and methods derived from geography, spatial sciences, and design based professions (Steinitz, 2012). In this research, the Geodesign approach allows the integration of the concepts of flood resilience and community design with the fields of landscape architecture, regional planning, land use management, and hydrology in a community of approximately 100,000 residents located on the Texas Gulf Coast. The effects of climate change, such as sea level rise, have had observable ecological, social, and economic impacts on the built environment in this region. Sea level rise has already had a significant impact on Gulf Coast communities, resulting in wetland loss, increased coastal erosion/inundation, and increases in the duration and frequency of flooding from storm surge (Horton et al., 2014). The National Oceanic and Atmospheric Administration (NOAA, 2015) predicts that (in a med-high scenario) the mean sea level will rise at least 0.82 inches per year in the U.S. Gulf Coast, reaching 6.29 feet by 2100. In 2008, Hurricane Ike caused extensive damage to the Texas Gulf Coast, causing 113 deaths and $29.5 billion in damage; approximately 200 of the damaged homes were located in League City, TX (Rego & Li, 2010). League City, due to its location on the Texas Gulf Coast, is highly vulnerable to flood events and other issues related to sea level rise.

Working in partnership with city officials, the authors developed and executed a Geodesign process which integrated the resilience scorecard (Berke et al., 2015) as the evaluation model, a vertical buffer tool (as a process model) to project sea level rise, and landscape performance (as an impact model). The project included an assessment of flood vulnerability and projection of the 100 year floodplain in the year 2100, accounting for increases due to sea level rise. This information is used as a guide for the location of future development, as well as to inform the development of a master plan for a resilient community within a 97-acre site surrounded by urban development in League City. In light of the community's vulnerabilities and the sea level rise projections revealed through the Geodesign process, a series of adaptive flood attenuation mechanisms for protecting the newly designed community from flood events and the eventual impacts of sea level rise are suggested.

Finally, landscape performance projections are conducted to measure potential impacts of the proposed master plan. Table 1 outlines the full Geodesign process and tools utilized.

Literature Review

U.S. coastal counties, which comprise 17 percent of the land area in the United States and 52 percent of its population, typically have lower overall resilience but higher flood vulnerability (Beatley, 2009). Both in the U.S. and globally, total population is growing in vulnerable areas (e.g. the 100-year floodplain) and development and urbanization are also occurring in high hazard areas (Cutter et al., 2008; Douglas et al., 2008; Easterlings et al., 2000). The impacts from the combined effects of rapid environmental change and the increasing severity of natural hazards have necessitated new approaches intended to address concerns related to climate change (Walker & Salt, 2006; Folke et al., 2010).

Adopting integrated approaches into the design process to develop land use-based solutions to mitigate hazards requires long-term strategies and forward thinking to reduce hazard vulnerability (NRC, 2012). Several studies conclude that it can be challenging to choose an appropriate spatial scale to advance master plans to manage hazards, and that greater emphasis should be placed on the local level to reduce the frequency of hazards (May & Deyle, 1998; Olshansky et al., 2012). For example, the mitigation of flood hazards – that is, adopting sustainable strategies to reduce hazard risks and impacts on people – relies upon tools such as building codes, zoning, land-use plans, encouragement of better communication and citizen involvement in development related decision making. An often overlooked element of mitigation is the capability to forecast future circumstances. Communities that have suffered from high hazard exposure often increase pressure on local governments to include resiliency and sustainability in decision-making. From a design/planning perspective, master plans are the most effective tool for long-term action (Schwab, 2010). Unfortunately, most master plans do not take into account long-term impacts of climate change or utilize future scenarios to inform decision making.

Vulnerability (the degree to which the human environment is at risk from flood) and hazard exposure (the frequency of disaster events) are the two major factors influencing community resilience (Walker & Salt, 2006). Resilience is an approach that assumes that people interact with and shape their environment on macro-, meso-, and micro-scales and that the environment can provide services to sustain the well-being of human societies (Berkes & Folke, 1998; Berkes et al., 2003). While many definitions of resilience exist across the fields of hazards and disasters research, it is typically defined as the measure of a system’s capacity to obtain, withstand, and recover from a hazard event (Timmerman, 1981; Li & Buckle, 1999; Klein et al., 2003). Resilience can also be interpreted in terms of the propensity of certain social units to move toward mitigation, resistance of natural hazards, recovery from impacts, and the reduction of vulnerability through adaptive strategies (Peacock et al., 2008; Maguire & Hagan, 2007; Bruneau et al., 2003). Resilient communities strive to build capacity to address different, largely unpredictable, changes. Based on this definition, a combination of three characteristics can help to delineate the resilience of a socioecological system: 1) the magnitude of shock that the system can absorb and remain within a given state, 2) the degree to which the system is capable of self-organization, and 3) the degree to which the system can build capacity for learning and adaptation (Folke et al., 2002).

Several key factors can lead to unsustainable coastal development and reduced resilience, such as coastal population growth, demographic trends, desires to enjoy coastal living, and policies or financial systems that encourage coastal land development (Beatley, 2009). A lack of awareness of long-term risks and threats associated with living in high-hazard areas can contribute to imprudent development patterns. sprawl, loss of farmland, replacement of natural areas and open spaces with impervious surfaces, and substantial losses of wetlands and other habitats that provide natural buffers from flooding can further exacerbate vulnerability (Newman et al., 2014; Sohn et al., 2014; Newman et al., 2016a). Evidence from a growing body of evidence suggests that natural habitats such as wetlands, dunes, green infrastructure, sea grasses, coral reefs, and barrier islands can reduce the chronic risk of coastal flooding that stems from rises in sea level (Newman et al., 2016b). Thus, negligent undervaluing of natural ecosystems and their services can effectively compromise the safety of coastal communities.

Resilience is typically characterized by levels of physical and social vulnerability. Masterson et al. (2014) defined physical vulnerability as an area’s sensitivity to hazard damage that is caused by the interaction between hazard exposure and the built environment. Physical characteristics can consist of structures, such as homes and businesses, and infrastructure such as roads, water/sewage systems, and critical facilities. Social vulnerability can be defined as the capacity of a person or group to anticipate, resist and recover from the impact of natural hazards (Masterson et al., 2014). The geophysical forces that render coastal communities vulnerable to hazards can include hurricanes, coastal storms, rising sea levels, climate change, earthquakes, tsunamis, drought, heat waves, wildfires, and coastal resource depletion. Physical vulnerability addresses the interaction between geophysical forces and human decisions (Beatley, 2009). Specifically, such vulnerability stems from human decisions to place property in precarious positions. On the other hand, social vulnerability is a multidimensional measure of a population’s susceptibility to natural hazards and its ability to recover from them (Cutter and Finch 2008). A disaster is a social event, since the consequent damage results from the failure of the community’s social system to adapt to an environmental event. Individual- and household-level factors can be identified to measure social vulnerability and the influence of a community’s ability to respond to natural hazards including race and ethnicity, gender, household composition, education, poverty, age and housing tenure (Masterson et al. 2014).

The degree of vulnerability should heavily influence growth plans within a city and highly vulnerable jurisdictions should mandate the integration of mitigation plans with land use planning and climate change adaptation (Berke et al., 2015). Different types of local plans can play a role in reducing the destructive effects of hazards. These effects can be evaluated by using a resilience scorecard to assess both physical and social vulnerability to flooding, sea-level rise and other hazards. The development of a resilience scorecard can help integrate and improve local plans and reduce losses from hazard events by focusing on reducing both physical and social vulnerability. A scorecard can be used by planners to assess how well different local plans coordinate their objectives and can also help guide communities to revise and improve plans by regularly evaluating the link between multiple local plans and vulnerability outcomes over time. A resilience scorecard can also use geospatial indicators to evaluate networks of plans (e.g. land use plans, mitigation plans, infrastructure plans, etc.) and their integration, specifically in regards to sea level rise and hazard vulnerability.

Research Objectives

This project integrates policy analysis methods used in developing the resilience scorecard (Berke et al., 2015) with landscape performance tools in a unified Geodesign process. Then, Geodesign change models are used to develop design/planning strategies that promote better responsiveness between local plans and losses from hazard events, including sea level rise. This research seeks to answer the question, how can plan evaluation and landscape performance assist in Geodesign processes to improve resilience in neighbourhoods experiencing high hazard exposure? The process of effective design/planning for local climate change depends on a combination of variables that pertain to the planning, design, policy and health impacts of sea level rise. As part of this process, we 1) identify high socially and physically vulnerable neighbourhoods through a series of GIS-based spatial operations, 2) identify future flood prone areas in accordance with sea level rise projections on municipal and local scales, 3) design a master plan based on these findings and 4) project future impacts of this master plan using landscape performance measures.

Methods

Study Area

According to Pielke (2007), storm frequency has increased to 14 instances per year in the United States since 1995, compared to an average of 10 storms annually between 1950 and 1990. Moreover, most coastal communities are highly vulnerable to rising sea levels. Titus and Richmond (2001) assessed that 23,166 square miles along the Gulf and Atlantic coasts were situated less than or equal to 1.5 meters above sea level. The most vulnerable states along the coasts include Florida, Louisiana, North Carolina, and Texas. The Texas Gulf Coast already experiences extreme storm activity from hurricanes and tropical storms. NOAA predicts that sea levels will increase and storm surge will become more frequent along the Texas coast (NOAA, 2015). In general, sea level is projected to rise by up to 6.29 feet by 2100 along the U.S. Gulf Coast. Specifically, flooding and hurricanes are major concerns along the Texas Gulf Coast since the frequency of a normal hurricane along any 50-mile segment of the Texas coast is about one every five years, with a major hurricane occurring approximately every 15 years (Rego & Li, 2010).

League City, located along the Gulf coast near Galveston, is exposed to many hazards, all of which have the potential to disrupt the community, cause morbidity and mortality, and damage or destroy property. Of particular concern to the city are the effects of flood events. League City would likely be significantly inundated by storm surge from hurricanes of Category 3 and higher (See Figure 1). The city recognizes that it will continue to be exposed and subject to the impact of current hazards, as well as hazards that may develop in the future. Within League City, a site (see red outline in Figure 1) was chosen by city representatives and researchers for further exploration, planning and analysis. The site selection was based on several relevant criteria consistent with an extensive literature on higher hazard zone occupancy by socially vulnerable populations (Cutter et al. 2009; Peacock et al. 2008; Blaikie et al. 2014). First, the site is highly exposed to flooding and storm surge, and parts of it are located in both the current and future 100-year floodplains. The site is currently vacant, yet slated for urban development in the city's future land use plan. It is surrounded by relatively dense land uses with high hazard vulnerability. Thus, it is an ideal location to test the efficacy of the proposed integrated analysis and design/planning.

Methods and Results

Current Policy

Using the scorecard method described above (Berke et al., 2015), we assessed League City's network of plans – including its comprehensive plan, hazard mitigation plan, and parks and open space plan – to better understand the policy climate in the community. From the scorecard evaluation, it appears that League City is generally supportive of environmentally-sensitive design and prioritizes increasing resilience in the study site and surrounding areas. Figure 2 shows that the study side within League City is within a relatively high scoring area and that policies currently in place are generally aligned to similar goals across plans (Supplemental Table 1 has been provided, which shows the policy scores for the network of plans for League City). Policies in three of the city's plans support vulnerability reduction in this part of the community. The local hazard mitigation plan, for instance, restricts new home construction in the most flood-prone areas and supports the elevation or acquisition of properties that are repeatedly flooded. The hazard mitigation plan also has a stated goal to 'preserve, rehabilitate, and enhance natural systems to serve natural hazard mitigation functions' (League City Local Mitigation Plan, 2010 p. 118). This goal is echoed in the city's parks and open space plan, which includes several provisions to preserve or acquire open space, and to use that space as a (mostly passive) community amenity. However, while the preservation of current open space is a priority, additional open space provisions are not necessarily mandated. According to League City's Future Land Use Plan, the city is projected to grow by more than 50% in residential development, but only by 1% in green space (League City Comprehensive Plan, 2010).

League City's comprehensive plan, which guides future development and management of the community, also gives significant attention to reducing flood vulnerability. Several of its policies focus on limiting development in natural and sensitive areas, including wetlands and 100-year floodplains, and suggesting ways to accomplish this—e.g. land acquisition, buffer zones, and clustering development outside the sensitive zones. It is also supports the 'hardening', elevating, and other creative ways to 'flood-proof existing structures that frequently flood' (League City Comprehensive Plan, 2010 p. 8–6).

The population of League City is growing rapidly, increasing by more than 80% between 2000 and 2010, which makes new development all by inevitable, including within the study site (Office of the State Demographer 2014; U.S. Census Bureau 2016). As a designated 'urban character' area, the site is identified as a preferred location for future infill development and as a potential focus area for higher-density mixed-use (League City

Comprehensive Plan, p. 5–24). Given the pressures—and indeed, the *plans* — to develop in this area, it is clear that smart, holistic planning and design is needed to ensure resilience at this site and others like it. The Geodesign process described in this case study is an important step toward accomplishing that goal and reinforcing the city's generally forward-thinking strategy.

Sea Level Rise Projection

Sea-level rise was forecast to surfaces using the FEMA 100-year flood elevations on Digital Flood Insurance Rates Maps (DFIRM). This method is consistent with methods used to support the rebuilding of structures that received FEMA public assistance funds after Hurricane Katrina (U.S. Army Corps of Engineers [USACE], 2014). This approach delineates the extent of flooding using a 1% probability of occurrence, and subsequently adds the level of sea rise projected by NOAA. Data derived from the U.S. Army Corps of Engineers's (USACE) sea-level rise calculator provides alternative scenarios of sea level increases by 10-year increments up to 2100. By adding sea-level rise to the base elevation of the 100-year floodplains, we determine the projected expansion of current flood zones (Berke et al., 2015). A limit in this approach is that adding sea-level rise in this way may not account for other changes in climate (e.g., storm intensity that could affect storm surge heights). However, results show that by 2100, nearly 50% of the League City case site will be covered by the FEMA 100-year floodplain (See. Figure 3). Should a 6 feet sea level rise occur; 76% of the land on the design site will be effected (See Figure 4), with the entire site being covered by the 500-year floodplain.

Vulnerability Projection

To assess the potential impacts of current hazard conditions on the human environment, a series of raster maps were overlaid integrating factors contributing to vulnerability using weighted overlay procedures, a form of suitability mapping in GIS. Suitability mapping is an ArcGIS application aimed at identifying appropriate future land uses based on specified requirements and raster map overlays (Malczewski, 2004). Suitability mapping combines multiple raster datasets by applying a common measurement scale of values to each raster which can be weighted according to importance then integrated into a single output (Mutke et al., 2001). Weighted overlays are a useful technique for combining multiple rasters by applying a common measurement scale of values to each raster which can be weighted according importance and then used to create an integrated output (Mutke, et al., 2001). In this case, hazard vulnerability was measured using factors consistent with the indicators previously validated by Masterson et al. (2014). Table 2 shows each variable examined for the suitability output.

Each factor was treated as an individual data layer, rasterized and then reclassified on a scale of one to five (one = less regeneration potential; five = more regeneration potential). The reclassification scheme allowed for simplification of interpretation of the raster data based on the ability to assign values to each raster cell. For example, cells with the highest income per census block were assigned a value of 1 while cells with the lowest income per census block were assigned a score of 5, as it was assumed that areas with lower income would be more likely to have increased vulnerability to hazards. This type of logic was applied when scoring all raster maps. Assumptions were made which were consistent with an extensive literature on higher hazard zone occupancy by socially vulnerable populations (Cutter et al. 2008; Peacock et al. 2011; Blaikie et al. 2014). Raster maps were overlaid using equal weighting to produce a final suitability output. The final output was then reclassified into five equal categories from high to low based on scores per raster cell.

After overlaying social and economic raster data sets in GIS to map factors contributing to flood vulnerability, the GIS output shows that more than 41% of League City has high flood vulnerability, including the entire 97-acre case study site, which has the highest flood vulnerable area in the city (See Figure 5). In regards to the catastrophic damage these conditions have had on ecosystems, nearly 96 acres of freshwater wetlands and 154 acres of wetlands in the region have been lost since 2008; the design site itself has lost 43% of its wetland area in the past 20 years (See Figure 6).

Master Planning Strategy

Community Engagement and Feedback—Although enhancing resilience in areas vulnerable to flooding is most effective with participation from the local community, local stakeholders are often left out of the design/planning process. (Steven et al., 2010). The engagement process used to develop this master plan relied on feedback loops that support resilient design and planning. Research and design on these issues in this neighborhood were undertaken using a participatory approach in cooperation with local community members and the senior planners for League City. Green infrastructure, open space planning and community design scenarios were developed through several engagement sessions assisted by community input.

For this project, participatory involvement was initiated four times over an eight-month period. The design was able to incorporate information provided by the senior planners that was used to 1) conduct a site inventory, 2) determine and locate flood-prone areas, 3) develop desired functions for new land uses and, 4) suggest potential infrastructure based on climate change projections. First, an introductory meeting allowed the design team to discuss site-specific problems with League City senior planners, initiating a general discussion to help identify high risk areas within the floodplain, as well as pinpoint current and future flood vulnerable areas. A second meeting presented the city with findings from an initial site analyses. Feedback from the community provided further insight in identifying unseen conditions as well as generated ideas for future land use functions to be incorporated in a conceptual master plan. A third and fourth meeting involved a feedback loop between community members and the design team in which a series of design scenarios were presented and critiqued by neighborhood members. Responses from the community to the design team were then utilized to condense the scenarios into one unified revised master plan.

Master Plan Development—A master plan incorporates a series of adaptable flood attenuation mechanisms (both structural and non-structural) responsive to both current and future hazard exposure on a community scale. Structural mechanisms are engineered infrastructure used primarily to block and control heavy floods. Non-structural mechanisms primarily rely on natural systems and green infrastructure to reduce flooding, store stormwater, and soften the potential effects of frequent flooding events. Both of these mechanisms are applied throughout the study site, and together compose a protective system to defend the site from current and future flood issues while simultaneously providing recreational, housing and economic opportunities (See Figure 7). For example, the designed green space bordering Clear Creek (a water body connecting to the Gulf of Mexico) protects the community from floods and surge and is designed as a park with an amphitheatre, recreational pier, riparian edge, hotel and other cultural amenities. It is connected to the designed green infrastructure system through strategically placed bio-swales, elevated trails and eco-levees; engineered based residential areas, commercial space, and transportation lines also act as multifunctional protective structures to help decrease flood vulnerability.

Borrowing from a national and international series of resilient community design cases, the design develops and incorporates a series of flood attenuation mechanisms (both structural and non-structural). Structural mechanisms include 1) an elevated highway which doubles as an integrated flood wall 2) an engineered levee which acts as a gradual and vegetated slope mimicking a natural levee, 3) a sector style gate which can close when upstream floods occur and, 4) elevated buildings which are built on stilts. Non-structural mechanisms included in the design include 1) a collection of preserved and restored wetland areas and vegetated waterfront edges acting as a riparian zone, 2) dredging locations and excavated sediment in strategic locations to store flood water which is then reused to increase the elevation of developed areas and, 3) bioswales acting as streetscape and urban plaza amenities which convey floodwaters to storage areas and allow for infiltration and filtration of stormwater. The structural and non-structural typologies are strategically applied throughout the site into the green and grey network/fabric, to protect residents and deliver valuable ecological and economic benefits. To accomplish such a large undertaking, the design is to be implemented in three phases (See Figure 8):

- *Phase 1) Retreat from flood* – This phase focuses on placing development in areas with higher elevation area and integrating green infrastructure. The designed medium density commercial and mixed-use spaces are connected with existing arterials and integrated into the surrounding residences but are strategically placed outside of flood prone areas to limit vulnerability. Public urban spaces with landscape features and permeable paving provide connections to neighbours and promote infiltration, retention, biological treatment, and evapotranspiration processes.
- *Phase 2) Flood mitigation* – This phase develops lower density residences and green infrastructure to provide protection during frequent storms, as well as grey infrastructure to mitigate larger flood events. Diverse housing types bring in residents from different age groups and backgrounds. New institutional land uses such as a climate change museum provide engagement and educational opportunities for communities.
- *Phase 3) Flood control* – This phase completes major installations of structural and gray infrastructure to create a multi-functional armour system to block and control heavy floods and regulate hydrologic activity during extreme hazard

events. Simultaneously, an interconnected circulation system including pedestrian trails, boat launch points, pedestrian bridges, and bicycle paths enhance local connection to the waterfront, attract tourists, and create economic opportunities.

Projected Impact

A large portion of the non-structural mechanisms integrated into the plan to increase resiliency are different types of green infrastructure. Often green infrastructure-based approaches are combined with modifications to other traditional engineered infrastructures as support mechanism to help control for frequent floods. Green infrastructure is now being recognized for its value as a means for adapting to the emerging and irreversible impacts of climate change (Foster et al., 2011). Green infrastructure approaches have become increasingly used to help to achieve resilience goals in the face of climate change. The climate adaptation benefits of green infrastructure are related to their ability to moderate the impacts of extreme precipitation and include storm-water runoff management, water capture and conservation, loss flood ponding/settling, flood prevention, storm-surge attenuation, defense against sea-level rise, and floodplain management (Foster et al., 2011).

Many measures have recently been developed through landscape performance related research to more scientifically evaluate impacts and more accurately measure the effectiveness with which landscape solutions fulfil their intended purpose and contribute to sustainability. One such tool for measuring landscape performance is the National Green Values™ Calculator (Jayasooriya & Ng, 2014), a tool used in this research to project the performance, costs, and benefits of the green infrastructure utilized within the design (Supplemental Table 2 describes the input and output data utilized in the Calculator). Compared with conventional approaches, the Green Stormwater Best Management Practices (BMPs) of the study site design decrease the site impermeable area by 26% and capture 30.3% of the runoff volume required. Simultaneously, the study site design can capture 221,921 ft^3 of runoff, creating $419,901 in annual green benefits by reducing air pollutants and energy use, providing pollution treatment, increasing carbon dioxide sequestration, escalating the compensatory value of trees, and improving groundwater replenishment (these economic benefits reach $13,305,657 by 2100). Facilities proposed for the study site not only create economic and ecological benefits, but also create enormous cultural and social benefits. The study site design decreases the 100-year flood plain with sea level rise from 74 acres to 15 acres by the year 2100 (from 76% coverage to only 16%) and 221,921 ft^3 of runoff can be captured. Also, nearly 2,400 new residents are protected, over 3,000 jobs are created, around $23 million in physical damage is avoided, and nearly $1.3 billion are generated by life cycle benefits by 2100 (See Figure 9).

Conclusion

This case study integrated the resilience planning scorecard, Geodesign tools, and landscape performance calculators to project current flood vulnerability, future flood plain alteration, and potential design impacts for a site in League City, TX. As part of the case study, we sought to determine how plan evaluation and landscape performance can assist Geodesign processes in improving resilience in neighbourhoods experiencing high hazard exposure. The emergence of new approaches to the techno-scientific blending of integrated research, geography and design (Wilson, 2014; Steinitz, 2008), makes the process presented in this paper a potentially useful method to improve decision making in support of a more resilient future. As indicated by this research, Geodesign, as a movement, is much more than a platform for utilizing GIS for spatial analysis. It can become a data-driven means of analysing, measuring, predicting, and strategically determining the layout or layout options for geographic space, which can be supported through landscape performance metrics and resilience planning analytics.

Based on the presented findings, there are four key benefits for flood prone communities when integrating these tools into a Geodesign process. First, the process allows city officials to develop new knowledge about flood related spatial conditions. Local knowledge related to current issues and desired land uses can be incorporated, while local planners simultaneously gain the ability to spatially distinguish where effective policy to reduce flood risk is already in place and which areas could be in the 100-year flood plain in the future. Second, current and new knowledge can be used as a basis for design- and planning-based decision making. Typically, economic and aesthetic concerns are the primary drivers of design-based decision making. However, the Geodesign process presented here allows for better placement of new development as well as the strategic allocation of necessary infrastructure to help protect it, all based on knowledge generated from representation, process, evaluation, and change models. Third, according to the impact models, the master plan creates a more resilient community compared to conventional development practices. The 60% reduction of the area of the 100-year flood plain due to structural and non-structural placement of flood attenuation mechanisms and the 30% runoff reduction due to green infrastructure show that resiliency is increased. Finally, the process not only allows for increases in current resiliency, but can also better prepare neighborhoods for the future impacts of sea level rise. Most modeling and projections for climate change occur ant the regional scale or larger. As demonstrated in this project, community scaled conditions can be used to proactively inform community layout resulting in longer-term stability, reductions to future flood risks, and an increased sense of place.

The process presented here is a primarily digital (workflow-based) method of designing multi-scalar space that streamlines the analysis process directly into the design output through design concepts based on logic models developed by the designer/planner and their corresponding collaborative team. As such, there are also several limitations to this approach. First, determinants of geographic arrangement are dependent upon the identified goals of the project, the needs of the region/community, the rationale used by the design/planning team, data availability, the development of innovative technological tools/programs that address contemporary issues and the capability to operate these tools. To be relevant to the current needs of both hazards researchers and practitioners, these logic models must be based on a key issue(s) and use technology as a means for beginning the process of solving this issue. Second, success is limited by data availability, the collaborative team's knowledge of multiple topic areas and the ability to successfully operate a multitude of (sometimes difficult or time consuming) technologies. The ability to build a Geodesign team that can keep up with the rapidly changing technologies and other new and relevant tools for design and analysis is a key component to successful collaborations. Finally, the process we conducted would need to be streamlined to make it more widely available for municipal or other planning actors who do not have access to the same technical equipment and human capital. This requires a network of engaged scholars and planners who are utilizing the process and are willing to share data and provide technical assistance to cities. While cities would run their own impact models - based on their specific master plans - all other models could be provided by outside parties. However, this is most successful when there are dedicated teams that work directly with cities utilizing the process to help develop a master plan that includes meaningful engagement of community stakeholders.

In traditional planning/design, there are an infinite number of possibilities for the future development of a space. It is the planner/designer's responsibility to determine, based on these possibilities, what the best use of the space is. Perhaps the greatest strength of the framework presented here is that it provides a quantifiable, evidence-based rationale upon which to justify design choices. The framework's ability to predict the impact of future scenarios makes it more powerful that traditional planning/design, combining GIS with other technologies while maintaining the creative aspects of the undertaking so that the role of data in decision making can be somewhat tempered. While theory and analyses can be used to reinforce design-based decision making, the creative intent of the planner/designer can counterbalance some analytical conclusions, making science the primary medium to improve and validate design decisions while still allowing for the creative process to occur.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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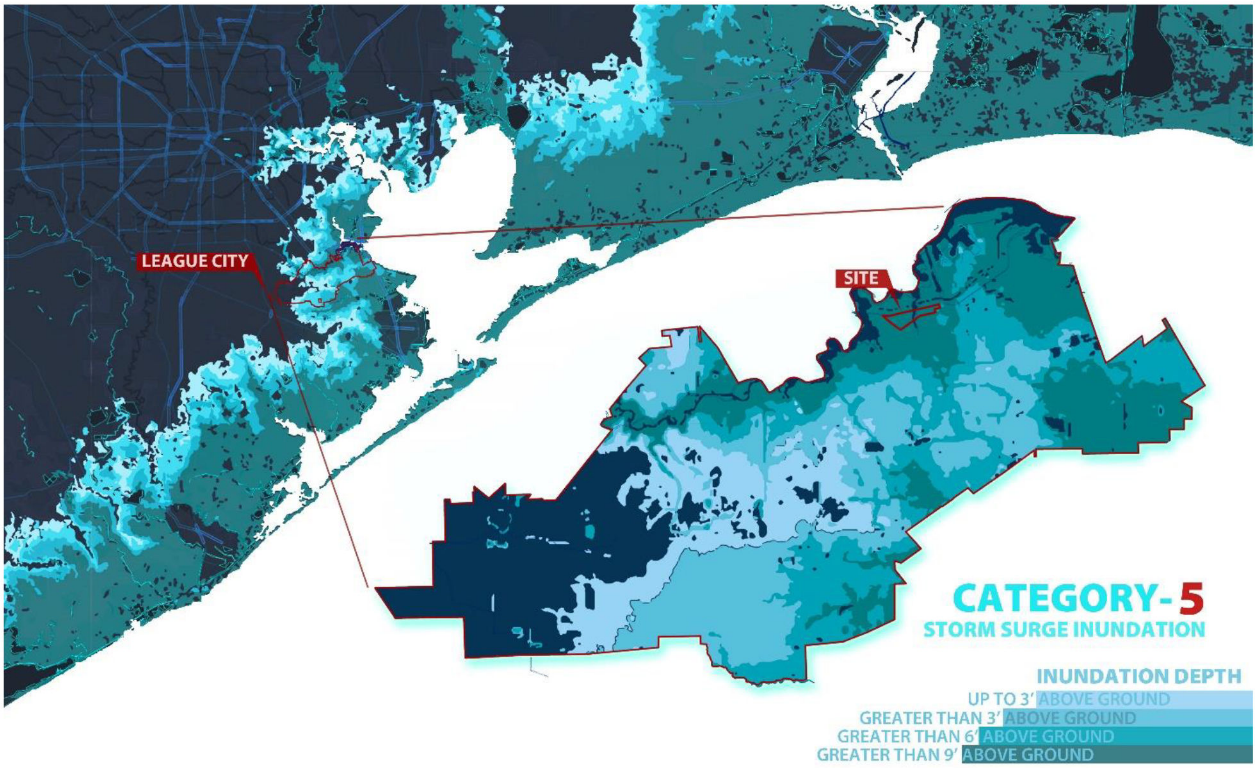

Figure 1.
Category Five Hurricane Storm Surge Slosh Minimums along Gulf Coast and League City, TX

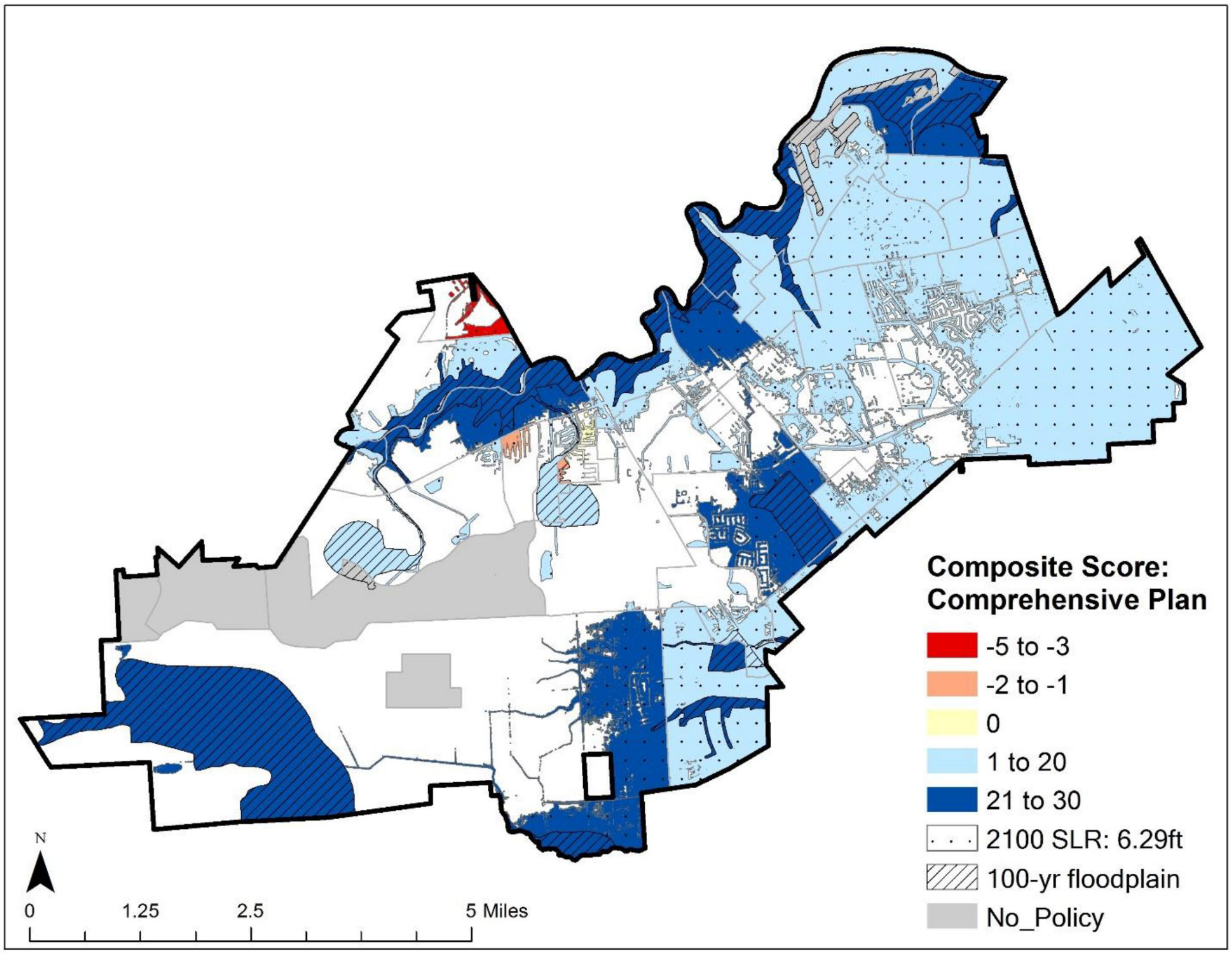

Figure 2.
League City Resilience Scorecard Composite

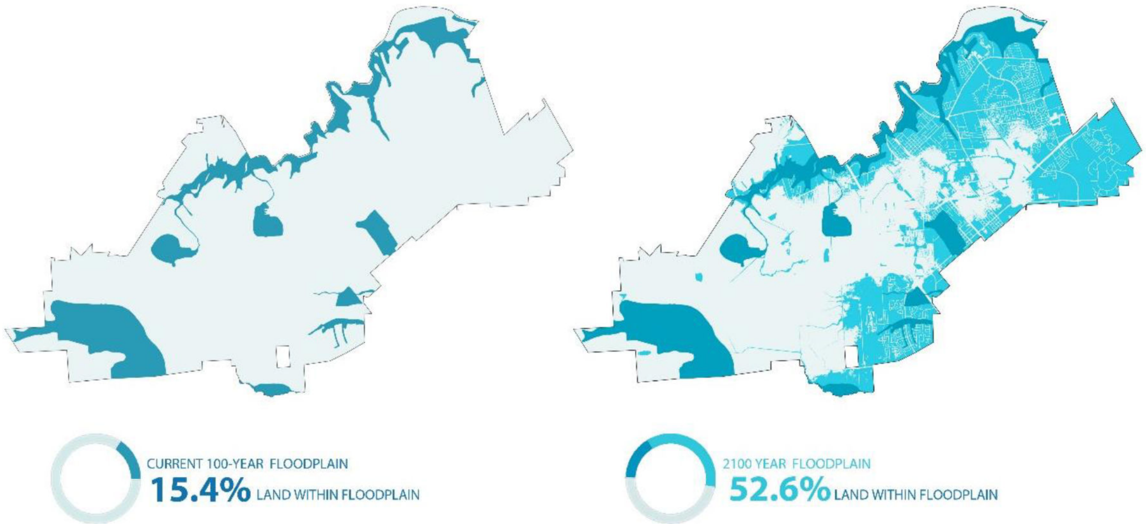

Figure 3.
Projected FEMA 100-year Flood Plain using Vertical Buffer Tool by 2100 in League City, TX

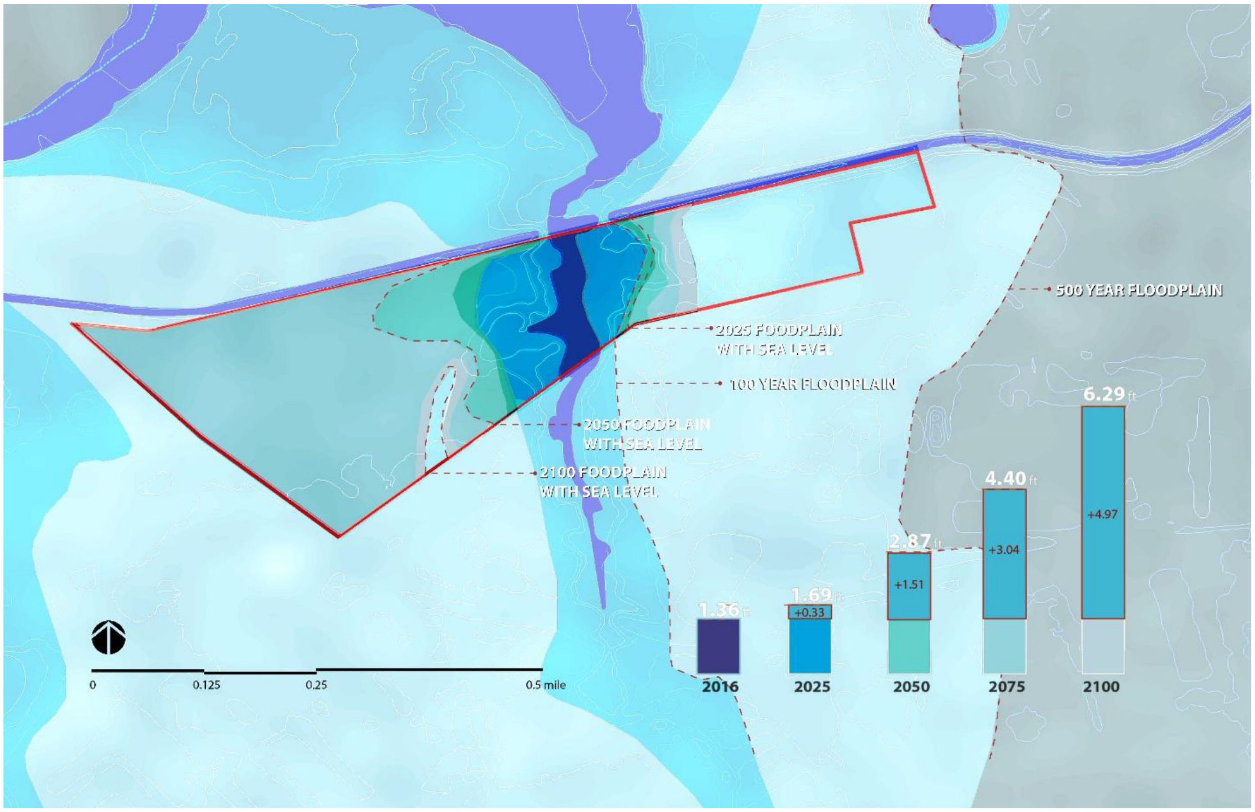

Figure 4.

GIS based Projection of the FEMA 100-year Flood Plain by 2100 at the Site Scale in League City, TX

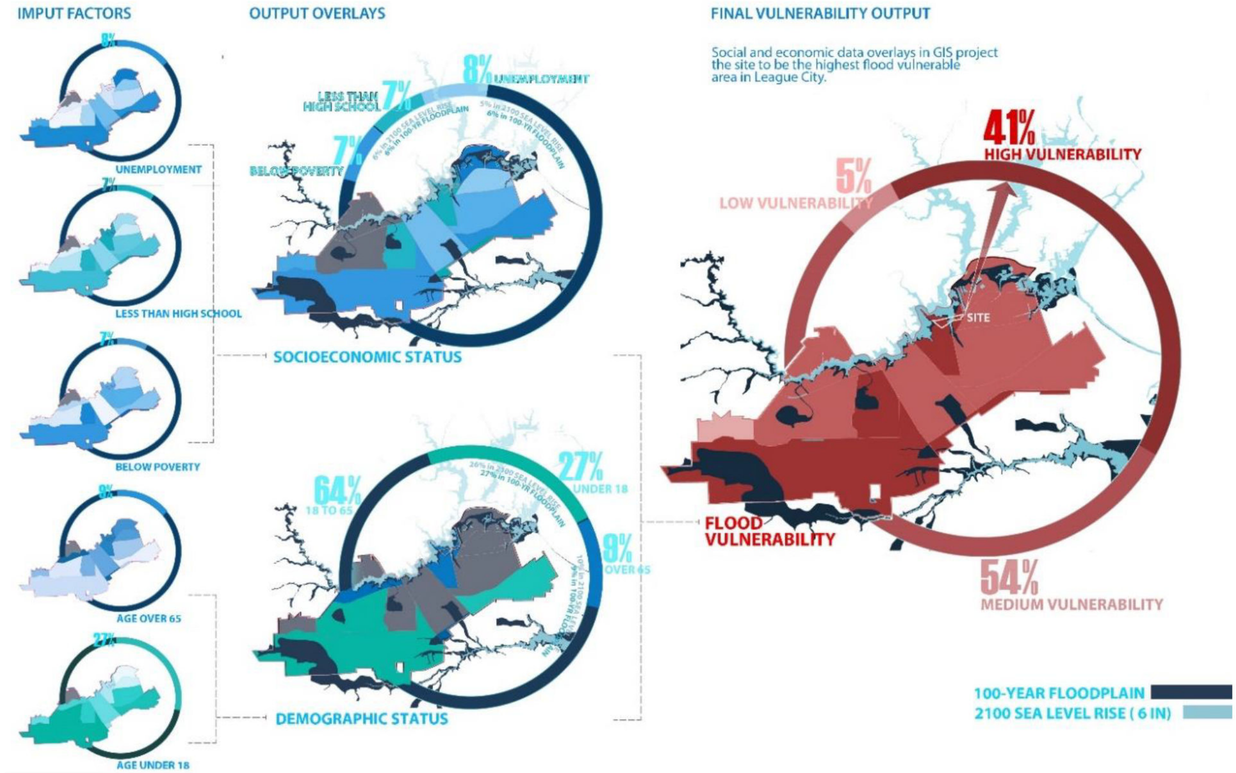

Figure 5.

Hazard Vulnerability Outputs by Census Block in League City, TX

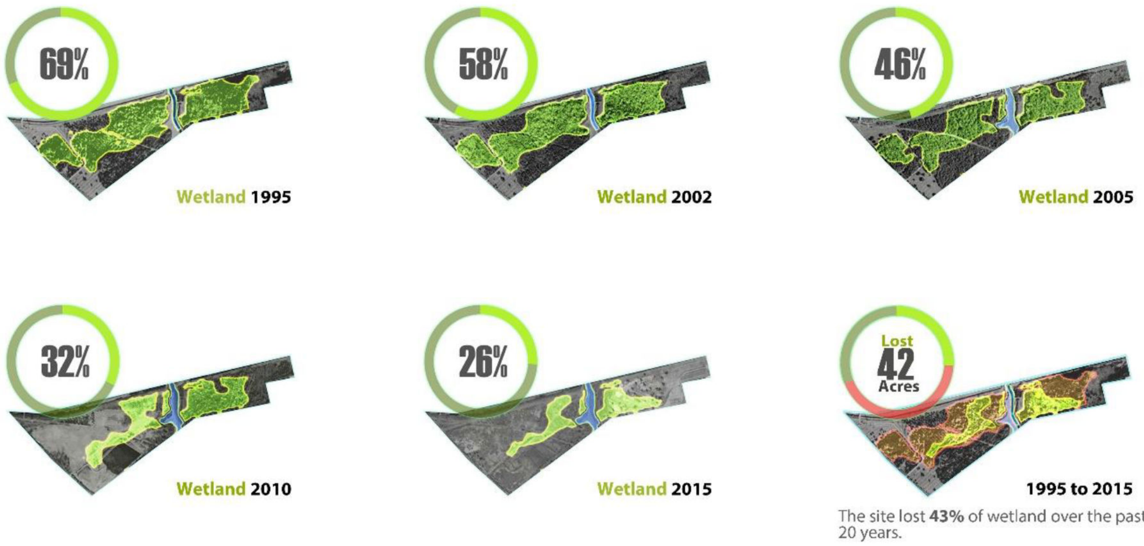

Figure 6.

Wetland loss from 1995–2015 at the Site Scale in League City, TX

Figure 7.
Master Plan and Section Showing Spatial Functions and Flood Protection Mechanisms at the Site Scale in League City, TX

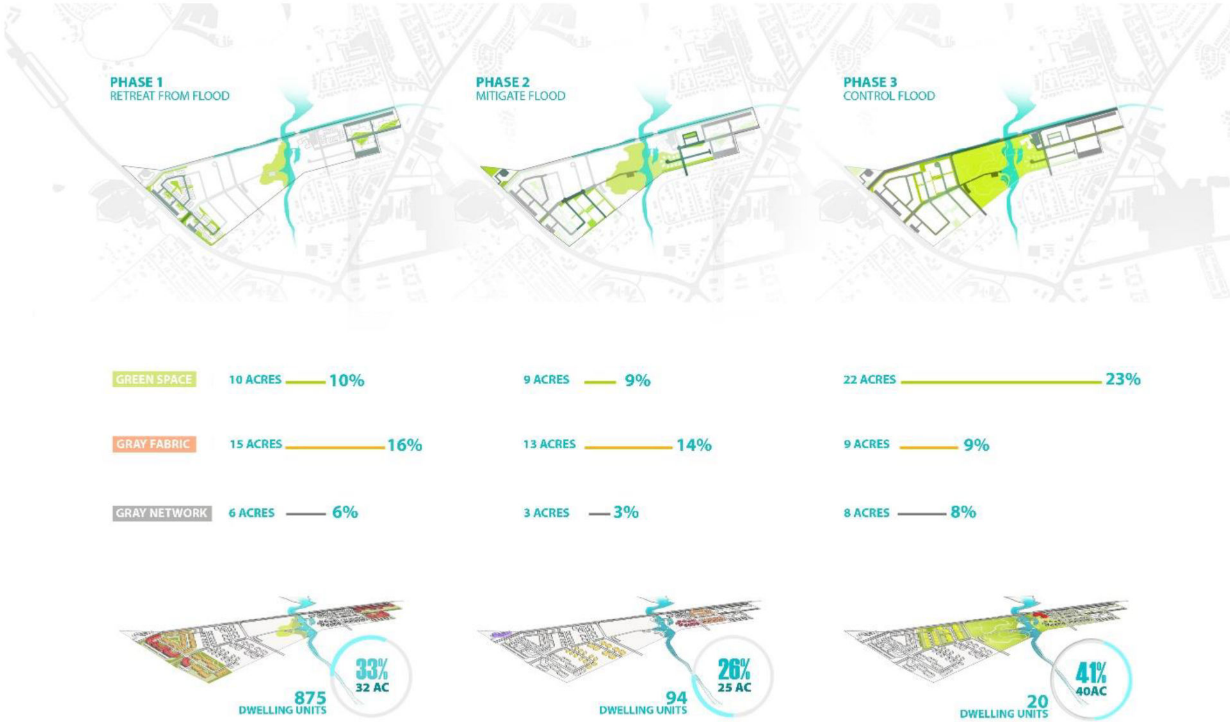

Figure 8.
Phases of Master Plan Implementation at the Site Scale in League City, TX

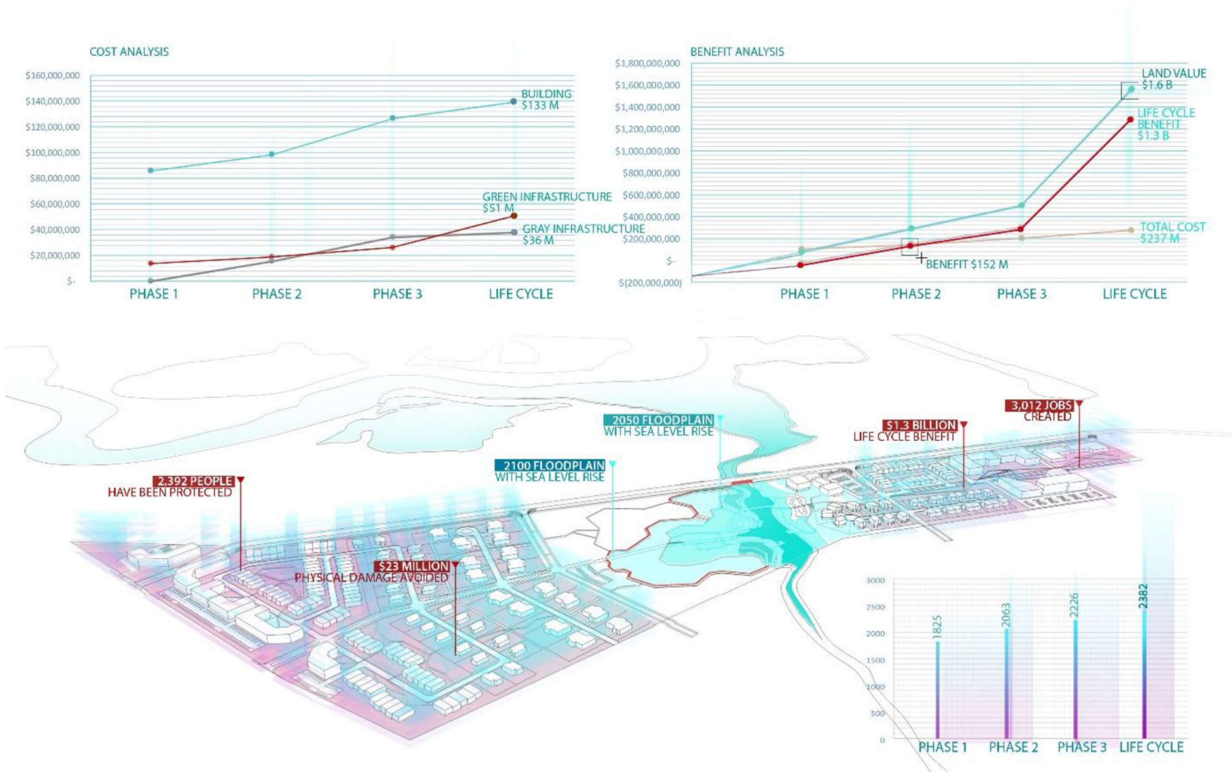

Figure 9.

Design Impact Outputs from the National Green Values™ Calculator at the Site Scale in League City, TX

Table 1.

Geodesign Process Utilized

Model (Steinitz, 2012)	Model Parameters (Steinitz, 2012)	Problem(s)	Task	Scale(s)	Scenarios	Tool	Tool Description
Representation	How should the study area be described?	Flood Hazards/ Disasters	Inventory/ Analysis	Region;Municipal;Site	2015	GIS Mappings	A collection and analysis of the study area's existing GIS database and determination of what information is needed (Schuurman, 2004)
Process	How does the study area operate?	Sea Level Rise	Flood Plain Projection	Municipal; Site	2025; 2050; 2075;2100	Vertical buffer	A zone around a map feature measured in units of distance in a three-dimensional plane (Saeed et al., 2011)
Evaluation	Is the current study area working well?	Ineffective Policy	Plan Evaluation	Municipal; District	2016	Resilience Scorecard	A policy evaluation scoring mechanism designed to enable the development of a local disaster risk reduction strategy (Berke, 2015)
Change	How might the study area be altered?	Flood-Threatened Populations	Hazard Vulnerability Projection	Municipal; Site	2015	Weighted raster overlay	A technique for combining multiple rasters by applying a common measurement scale of values to each raster, weighting each according to its importance, and adding them together to create an integrated analysis (Newman et al., 2017)
Impact	What differences might the changes cause?	Flood Attenuation and Economic Costs	Design Impact Projection	Site	2100	National Green Values™ Calculator	A tool for comparing the performance, costs, and benefits of Green Infrastructure compared to conventional stormwater practices (Jayasooriya & Ng, 2014)
Decision	How should the study area be changed?	Flooding and Sea Level Rise	Phased Master Planning	Site	2017; 2027; 2037; 2047	Digital Workflow	An orchestrated and repeatable pattern of digital design tools and processes that transform materials, provide services, or process information (Katsianis et al., 2018)

Table 2.

US Census 2010 Variable Definitions and Suitability Classifications used for Vulnerability Output

Factor	Variable	Census Level	Description	GIS Weighting Score
Socioeconomic Status	Percent individuals below poverty	Block Group	Individuals below poverty=“under .50” +”.50 to .74” + “.75 to .99.” Percent of persons below federally defined poverty line, a threshold that varies by the size and age composition of the household. Denominator is total population where poverty status is checked.	Below Poverty Level = 5 Above Poverty Level = 1
	Per capita income in 2010	Block Group	Mean income computed for every person in census block group. (In <DollarYear> inflation adjusted dollars)	Income Classified into Quantiles Lowest = 5; Highest = 1
Household Composition	Percent persons 65 years of age or older	Block Group	Senior populations have been shown to be more vulnerable to floods	65 Years or Older = 5 17 Years or younger = 5 18–64 = 1
	Percent persons 17 years of age or younger	Block Group	Younger populations have been shown to be more vulnerable to floods	
Race	Percent Minority	Block Group	Total of the following: “black or African American alone” + “American Indian and Alaska Native alone” + “Asian alone” + “Native Hawaiian and other Pacific Islander alone” + “some other race alone” + “two or more races” + “Hispanic or Latino - white alone.”	Percent Minority Classified into Quantiles Lowest = 1; Highest = 5
Educational Obtainment	Less than High School Diploma	Block Group	Percent of persons 25 years of age and older, with less than a 12th grade education (including individuals with 12 grades but no diploma).	No HS Diploma = 5 HS Diploma or Above = 1
	High School Diploma or Higher	Block Group		
Improvement Value	No Improvement Value	Block Group	Parcels with no structure on them	Improvement Value Classified into Quantiles
	Quantiles of High to Low Values	Block Group	Parcels with a building or structure built	Lowest = 5; Highest = 1