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# Life cycle assessment of green–grey coastal flood protection infrastructure: a case study from New Orleans

**Rahaf Hasan**[1], **Lauren McPhillips**[2,3], **Gordon Warn**[2] **and Melissa Bilec**[1,*]

[1] Department of Civil and Environmental Engineering, Mascaro Center for Sustainable Innovation, Swanson School of Engineering, University of Pittsburgh, Pittsburgh, PA, United States of America
[2] Department of Civil and Environmental Engineering, Penn State University, University Park, PA, United States of America
[3] Department of Agricultural and Biological Engineering, Penn State University, University Park, PA, United States of America
[*] Author to whom any correspondence should be addressed.

**E-mail:** mbilec@pitt.edu

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Supplementary material for this article is available online

## Abstract

The study compared the life cycle environmental impacts of three coastal flood management strategies: grey infrastructure (levee), green–grey infrastructure (levee and oyster reef), and a do-nothing scenario, considering the flood damage of a single flooding event in the absence of protection infrastructure. A case study was adopted from a New Orleans, Louisiana residential area to facilitate the comparison. Hazus software, design guidelines, reports, existing projects, and literature were utilized as foreground data for modelling materials. A process-based life cycle assessment was used to assess environmental impacts. The life cycle environmental impacts included global warming, ozone depletion, acidification, eutrophication, smog formation, resource depletion, ecotoxicity, and various human health effects. The ecoinvent database was used for the selected life cycle unit processes. The mean results show green–grey infrastructure as the most promising strategy across most impact categories, reducing 47% of the greenhouse gas (GHG) emissions compared to the do-nothing strategy. Compared to grey infrastructure, green–grey infrastructure mitigates 13%–15% of the environmental impacts while providing equivalent flood protection. A flooding event with a 100-year recurrence interval in the study area is estimated at 34 million kg of $CO_2$ equivalent per kilometre of shoreline, while grey and green–grey infrastructure mitigating such flooding is estimated to be 21 and 18 million kg, respectively. This study reinforced that coastal flooding environmental impacts are primarily caused by rebuilding damaged houses, especially concrete and structural timber replacement, accounting for 90% of GHG emissions, with only 10% associated with flood debris waste treatment. The asphalt cover of the levee was identified as the primary contributor to environmental impacts in grey infrastructure, accounting for over 75% of GHG emissions during construction. We found that there is an important interplay between grey and green infrastructure and optimizing their designs can offer solutions to sustainable coastal flood protection.

## 1. Introduction

Floods are among the costliest natural disasters globally (Brand *et al* 2021), with long-lasting effects on society, the environment, the economy, and infrastructure (Gall *et al* 2011, Kirezci *et al* 2020). The vulnerability of coastal regions to flooding is further increased by rising sea levels, primarily attributed to the escalating levels of anthropogenic greenhouse gases (GHG) released into the atmosphere, contributing to climate change (Mikhaylov *et al* 2020). Projections suggest that, by the end of the century, over 4% of the world's population will face the risk of coastal flooding (Kirezci *et al* 2020), posing a threat to the lives of millions of people and critical infrastructure.

Construction of flood protection infrastructure can mitigate these impacts. However, this may entail initial economic and environmental costs. Building such infrastructure may also lead to increased GHG emissions, resulting in higher sea levels and increased flooding risks in coastal communities in the future. To ensure climate change adaptation measures are sustainable, their impacts on society, the economy, and the environment should be evaluated (Hopkins 2014, Zuluaga *et al* 2021). Nonetheless, the complexity of the interconnections between social, natural, and built environments (Chester and Allenby 2022), combined with the uncertainty associated with flood risk assessments, makes selecting an adequate defensive system not straightforward (Alves *et al* 2018).

Coastal flooding prevention strategies typically rely on grey infrastructure such as seawalls, levees, and embankments (European Environment Agency 2017, Xian *et al* 2018). However, these solutions can be resource-intensive, expensive, require ongoing maintenance, and negatively impact ecosystems and the physical environment (Zischg *et al* 2018). In recent years, research has focused on nature-based solutions that can enhance the resilience of coastlines in a sustainable manner (Santoro *et al* 2019). These green, ecological solutions utilize naturally occurring components such as coral and shellfish reefs, salt marshes, wetlands, mangroves, or dunes to protect coastal regions from flood damage and erosion (Sutton-Grier *et al* 2015).

Oyster reefs, for example, can act as a natural offshore wave break, absorbing wave energy, and attenuating wave magnitude (Wiberg *et al* 2019, Hynes *et al* 2022). These green adaptive measures are effective in coastal flood defense (Dong *et al* 2017), with additional advantages of lower initial and maintenance costs (Pontee *et al* 2016), reduced carbon dioxide emissions (Depietri and McPhearson 2017), enhanced water quality (Cheong *et al* 2013, Sutton-Grier *et al* 2018), and improved natural wildlife habitat (Gobetti *et al* 2021). Moreover, in contrast to 'grey' infrastructure, such as seawalls and levees, that require continuous heightening as sea levels rise, green infrastructure can have the ability to self-adapt to sea level rise and changing environmental conditions. For example, oyster reefs can continue to grow vertically as sea levels rise, thus maintaining their protective function against storm surges and wave damage (Ridge *et al* 2015). These eco-friendly techniques can supplement the conventional grey infrastructure forming a 'hybrid' coastal flood prevention system (Chen *et al* 2021).

Despite the numerous studies advocating for a shift toward greener flood protection infrastructure, such as green–grey hybrid and green infrastructure (Chen *et al* 2021, Gobetti *et al* 2021, Sohn *et al* 2021, Lashof and Neuberger 2023), there remains a significant research gap in the comparative analysis of the life cycle environmental impacts of grey, hybrid, and green flood protection infrastructure. While there is an extensive body of literature on the economic cost of coastal flood damage (Pistrika and Jonkman 2010, Pistrika *et al* 2014) and flood protection infrastructure (Jonkman *et al* 2013, Aerts 2018), minimal attention has been given to quantifying the environmental impacts of coastal flooding and flood protection infrastructure from a life cycle perspective (Hennequin *et al* 2018, 2019). Thus, a critical gap exists in understanding the environmental impact of coastal flooding and flood protection infrastructure, highlighting the need for further research in this area.

A widely utilized systematic approach for assessing the environmental impact of products or systems throughout their life cycles is life cycle assessment (LCA), including stages from raw material acquisition and production to use and end-of-life. LCA is a quantitative approach often conducted to compare the environmental alternatives (Pasciucco *et al* 2023) or identify 'hot spots' in a system, thereby highlighting opportunities for improvement (Castellani *et al* 2017). Widely employed across diverse sectors to aid decision-making, LCA standards are established in International Organization for Standardization (ISO) standards 14040 and 14044 (ISO 2006a, 2006b). The LCA process involves four main steps: goal and scope definition, life cycle inventory (LCI), impact assessment (LCIA), and interpretation of results. The goal and scope step entails defining the study's scope and system boundary. The LCI step involves collecting and compiling data to inventory the system's inputs and outputs. LCIA first classifies the environmental emissions and resources into impact categories, then the emissions and resources are multiplied by characterization factors for the relevant impact categories. Finally, in interpreting results, the findings are translated into meaningful insights to promote sustainable, informed decision-making (ISO 2006a, 2006b).

While, to the authors' knowledge, no studies have employed LCA to compare grey and green coastal flood protection infrastructure, relevant research has explored such comparisons in other contexts. Additionally, the authors did not find an LCA on oyster reefs. For instance, using a case study from Bronx, New York, De Sousa *et al* (2012) conducted an LCA comparing one green to two grey combined sewer overflow control strategies scaled to reduce overflows equivalently. Another relevant example is the work of Petit-Boix *et al* (2017b), who conducted a consequential LCA in the context of urban flood management, examining the life cycle environmental impact and the environmental payback of stormwater management practices using a case study from a Brazilian neighbourhood, accounting for the avoided flood damage to cars and sidewalks. Another influential example to our work is the study by Hennequin *et al* (2018), where the authors conducted an LCA to compare the life cycle environmental impacts of constructing a coastal flood protection infrastructure, a dike, to repairing flooded houses in the absence of such protection. The study also modelled flood damage but assumed a single building type and design. Hennequin *et al* (2018) adeptly integrated risk assessment with LCA using three case studies from Denmark. The study concluded that constructing flood protection infrastructure, specifically dikes, is environmentally preferable in densely populated urban areas with a high flood risk.

In this study, we presented a novel approach that compared the life cycle environmental impacts of three scenarios related to coastal flooding and its mitigation: grey infrastructure represented by a levee; a green–grey hybrid infrastructure system consisting of double line defense- a levee, and a constructed oyster reef; and a baseline scenario with no flood infrastructure. This study aimed to quantify the life cycle environmental impacts of grey and green–grey coastal flood protection infrastructure through a case study. The primary objectives were to highlight the environmental impacts of providing flood protection infrastructure and assess nature-based solutions for coastal flood protection in light of recent advancements in our understanding of their performance.

## 2. Method

### 2.1. Goal and scope

This LCA aimed to investigate the life cycle environmental impacts of several coastal flooding control strategies to facilitate eco-efficient flood-prevention planning. The core findings of this study can help shift the flood protection approach from mitigative to preventive by identifying flood protection infrastructure that not only protects against flooding in the short term but also minimizes harmful environmental impacts to avoid future climate change threats. More specifically, this LCA study examined the environmental impacts of three strategies: do nothing, grey infrastructure, and green–grey infrastructure. However, conducting such a comparison necessitates the selection of a specific area to serve as a case study, providing an example with distinct geographic characteristics and flood level. In this paper, a case study from New Orleans, Louisiana, was selected, as detailed in (section 2.3).

The ‘do-nothing’ scenario included flood damage from a single flood event and was introduced to investigate whether grey or green–grey flood protection infrastructure can environmentally payback the environmental damage related to its construction, determining the number of events required for such compensation. The grey flood protection infrastructure investigated in this study was a levee which serves as a protective barrier rather than a preventive measure, protecting an area from a given flood event (e.g. 100 year event). While levees do not decrease the probability of these floods occurring, they are intended to protect against major damage in a designated area (CIRIA 2013), (European Environment Agency 2017). The green–grey hybrid infrastructure consisted of an oyster bed serving as the first line of defense, absorbing the shock and reducing the wave height and a smaller levee is intended to provide protection against the water reaching the city shore. The study was designed to ensure that both the grey infrastructure (levee) and green–grey infrastructure (oyster bed and smaller levee) achieve the same functionality, allowing for functional unit comparability. A fully green infrastructure solution was deemed inadequate and thus not considered in the presented analysis due to the inability to provide an equivalent level of coastal flooding protection compared to grey and hybrid strategies, based on reported wave attenuation levels in the literature and water levels in the study area.

Figure 1 illustrates a flowchart of the methodology followed in this study, starting from study area selection and flood hazard scenario specification (section 2.3), followed by examining the three strategies: the do nothing (section 2.4), the grey infrastructure (section 2.5), and the green–grey infrastructure (section 2.6), followed by the LCI (section 2.7), and the LCIA (section 2.8), and finally the results comparison, interpretation, and analysis.

### 2.2. Functional unit and system boundary

The primary purpose of coastal flood protection infrastructure is to manage floods in a coastal area, ultimately reducing or preventing adverse impacts on people and infrastructure. To facilitate a comparison of alternative flood mitigation strategies, we defined the functional unit as flood management of a residential coastal area in New Orleans, Louisiana, with an area of 20.7 $km^2$ and a shoreline length of 8.9 km, based on the base flood elevation (BFE) in the region. Specifically, we used the flood elevation level aligned with the 100 year floodplain, which corresponds to a one percent probability of experiencing a base flood in any given year. The typical lifespan of a levee ranges from 50 to 100 years (Diermanse *et al* 2010, Tromp 2014). Some studies specify the service life of a levee at 100 years (Tung and Mays 1981, Hui *et al* 2016). Theoretically, oyster reefs are expected to grow and strengthen over time, continuously reducing wave heights with a self-sustaining potential. In a study by Ridge *et al* (2015), it was observed that the age of reefs can extend up to 100 years. In our study, both the levee and the oyster reef are assumed to have a lifespan of a 100 years.

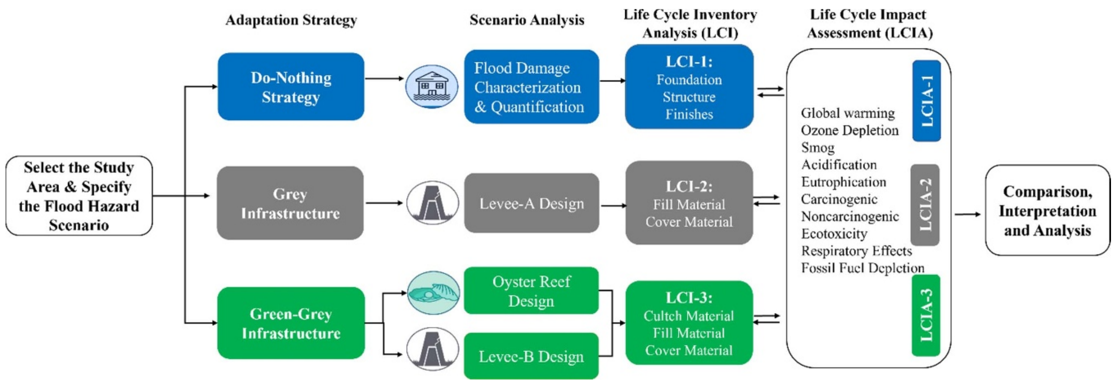


**Figure 1.** Flowchart of the LCA methodology used to compare multiple flood protection scenarios.

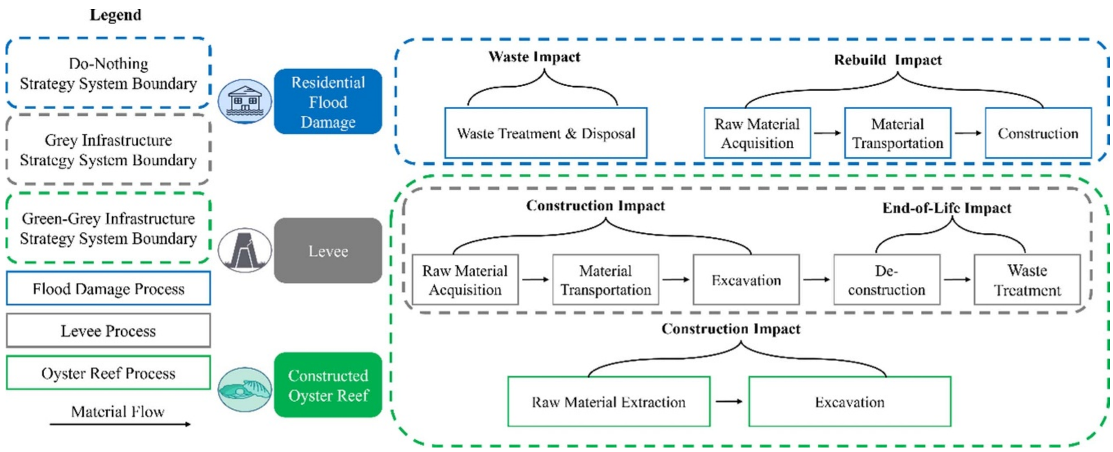


**Figure 2.** System boundary for the life cycle assessment of do-nothing strategy, grey infrastructure strategy, and green–grey infrastructure strategy.

The system boundary was cradle-to-grave, accounting for the environmental impacts resulting from the extraction, construction, and waste treatment for each of the three alternatives, *as appropriate*, see figure 2. For example, in the case of the do-nothing strategy, the waste treatment of structural flood debris after a single flooding event, including the collection, transportation, sorting, and disposal or recycling, was considered the 'waste impact'. In contrast, modelling the same debris material on the cradle-to-gate level, accounting for the extraction of raw materials, manufacturing, and transportation to the construction site, was considered as the 'rebuild impact', representing the impact of replacing the damaged material with new material.

Similarly, the 'construction impact' of the grey infrastructure strategy accounted for the extraction, manufacturing, and transportation of the levee material as well as the excavation work. In contrast, the 'end-of-life impact' accounted for the excavation, handling, and treatment of the levee material at the end of its useful life. The maintenance phase of the grey flood protection infrastructure was excluded because the impact is negligible (Hennequin *et al* 2018). Additionally, the system boundary of the grey-green infrastructure strategy accounted for the construction of the levee and the construction impact of the oyster reef. Similar to the grey infrastructure, the maintenance of green flood protection infrastructure was assumed to be negligible compared to the initial impact during construction. Notably, the LCA of the constructed oyster reef was performed without considering end-of-life impacts since the infrastructure is designed to blend in with the environment. It was assumed that the oyster bed remains viable over the lifetime considered in the study.

### 2.3. Study area selection and flood hazard scenario specification

New Orleans, situated at the edge of the Gulf of Mexico, is a significant coastal city flanked by Lake Pontchartrain to the north and traversed by the Mississippi River through its centre. The city and its suburbs, largely below sea level, experienced tragic consequences during Hurricane Katrina in 2005—a catastrophic event that resulted in massive economic damage and human suffering in Louisiana. Over 204 000 homes

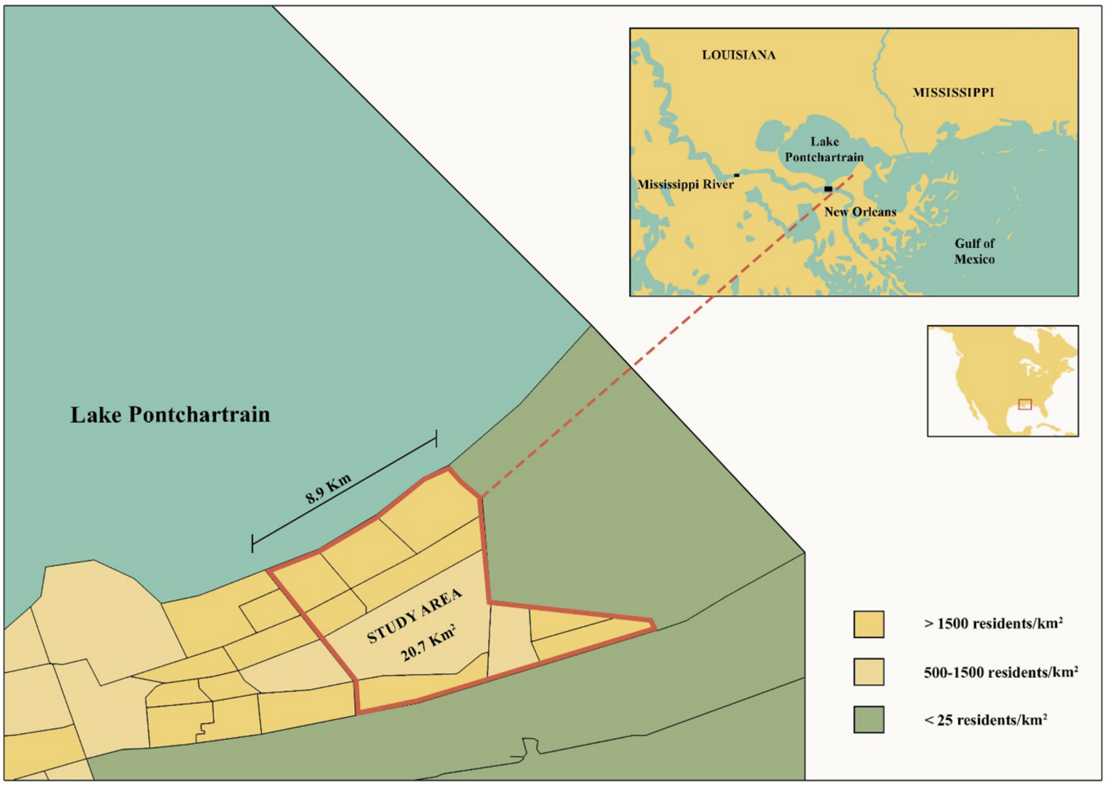


**Figure 3.** Study area in the New Orleans, Louisiana region, highlighted in red with tan polygons representing census tracts.

were left uninhabitable or destroyed (Pistrika and Jonkman 2010), and the state witnessed more than 1100 fatalities, with the majority occurring in New Orleans (Kates *et al* 2007, Jonkman *et al* 2009). New Orleans was chosen as the study area for several reasons. Firstly, the area is a suitable habitat for oyster reefs and there are ongoing efforts to restore oyster reefs in the area. Secondly, reports were available characterizing the potential flood damage based on flood depth in the area, especially after the recovery efforts from Hurricane Katrina (U.S. Army Corps of Engineers 2006). Lastly, the availability of specific levee construction guidelines in the area made modelling the levee more viable (Dijkman 2007). Therefore, New Orleans was an ideal location to study the potential benefits of oyster reef restoration in mitigating the impacts of coastal flooding while improving ecosystem health.

The study area was established using Hazus 5.1, a geographic information system based software developed by the US Federal Emergency Management Agency (FEMA) to estimate the economic and physical potential losses of flood events to aid the development of flood mitigation strategies (FEMA 2022). Hazus allows users to create a study region based on the census block, tract, or county level (FEMA 2022). The region of interest was selected from the Orleans Parish area to comprise a residential area adjacent to Lake Pontchartrain, a brackish estuary along the Northshore of New Orleans, Louisiana. The study area was established based on several factors aiming for a straight shoreline with the closest resemblance to a rectangular configuration, aligning the flood-protected area with potential flood-affected zones. However, Hazus limitations restrict direct area selection; instead, we must choose from census tracts, as shown in figure 3. Considering the non-alignment of census tract borders vertically, our area selection required careful consideration. While the chosen census tracts on the western side aligned vertically, the eastern side formed a polygon shape. However, the eastern area, adjacent to marshes that exhibit a lower population density compared to the study area, suggesting minimal flood damage in the unanalysed entrapped area within the study region. The study area was established with an 8.9 km long coastline and 10 census tracts consisting primarily of residential housing (∼95%), with an estimated 10 907 buildings and a total of 30 071 residents, according to the Hazus Inventory.

The study area is located in New Orleans East Polder (Pistrika and Jonkman 2010), also called the East Bank or Eastside of New Orleans. It is a coastal urban area and predominantly a Black community, with most residents falling within the working-age bracket (Brinkhoff 2023). Enclosed by levees and situated in the Orleans Levee District's East Subbasin, the study area is part of the New Orleans East Bank Levee System, spanning approximately 176 miles and covering four parishes (U.S. Army Corps of Engineers 2023). The

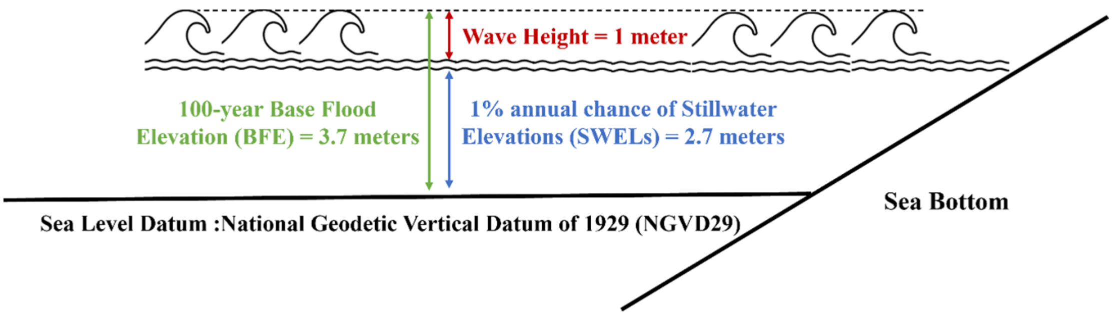


**Figure 4.** Basic coastal characteristics and assumptions in the study area.

city's levees, established since 1980, undergo continuous upgrades, redesigns, and realignments (Dijkman 2007), particularly after Hurricane Katrina when over half of the levees protecting Greater New Orleans were breached or destroyed due to insufficient height, misguided elevation references, and other construction deficiencies (Van Heerden *et al* 2007). Consequently, improvements have been made to the design of the levee system to protect against a 100 year hurricane (Miller *et al* 2015).

Establishing the parameters to estimate the coastal hydrodynamics, such as wave heights and sea level, was a critical step in this study as they served as the basis for all three scenarios under investigation. These parameters were determined using equation (1) adopted from FEMA (2006) and were used for flood damage quantification in the case of the 'do-nothing scenario' and for the design of levees and wave attenuation estimation in the case of the grey–green scenario with respect to the oyster bed design. As per FEMA floodplain mapping, the Orleans Parish area has been categorized as a VE zone, coastal high hazard area, with a 100 year BFE of 3.7 m (FEMA 2006). A zone VE is characterized by the potential for extensive damage caused by waves and fast-moving water during the 1-percent-annual chance flood, where expected wave heights are three feet or higher; hence a wave height of 1 m was assumed in the area (FEMA 2021). Figure 4 illustrates the 1-percent annual chance of Stillwater Elevations (SWELs), the wave height considered in this study,

$$\text{BFE} = 100 \text{ year SWEL} + \text{wave height}. \quad (1)$$

### 2.4. Do-nothing scenario: flood damage characterization & quantification

The quantification of flood damage resulting from a single flood event in the case of the do-nothing scenario served as a baseline, enabling the assessment of environmental benefits and payback associated with flood protection infrastructure in the absence of preventive measures. Hazus 5.1 was employed to obtain a quantitative structural damage estimate based on the study region's coastal flood depth and geographic characteristics. A Level-1 analysis was conducted by building the study region, selecting the shoreline, and inputting the 100 year flood level to estimate the potential impacts of coastal flooding. More specifically, Hazus generated deterministic results specifying the amount of debris material attributed to finishes, foundations, and structural waste, based on the study region's building stock and foundation type (FEMA 2022).

A number of assumptions were required to achieve a more comprehensive analysis of the debris material. For example, Hazus estimates the structural debris and identifies the material as wood and brick; however, it does not provide a breakdown ratio, and the same limitation applies to the finishes and foundation materials. To address this issue, Hazus offers information regarding the number and type of affected buildings associated with the expected damage level in the region. This information was utilized to estimate and allocate the structural debris material into wood and bricks, employing a weighted average of the ratio of buildings impacted by each type and the damage level.

To further investigate the allocation of foundation material into the concrete slab, block, and steel rebar, we utilized data on the prevalence of residential building types in the Orleans Parish area of Louisiana. The U.S. Census Bureau's 2019 American Community Survey indicated that single-family houses are the most common type of residential building, followed by multi-family apartment buildings and duplexes, with ratios of 58% and 30%, respectively (U.S. Census Bureau 2019). These house types typically use a slab-on-grade foundation comprising a concrete slab poured directly onto the ground and reinforced with steel bars. Finally, the partitioning of the foundation material into concrete and steel rebar was based on a 110 kg reinforcement rate per $m^3$ of concrete (Thanh 2016, One Click LCA 2021).

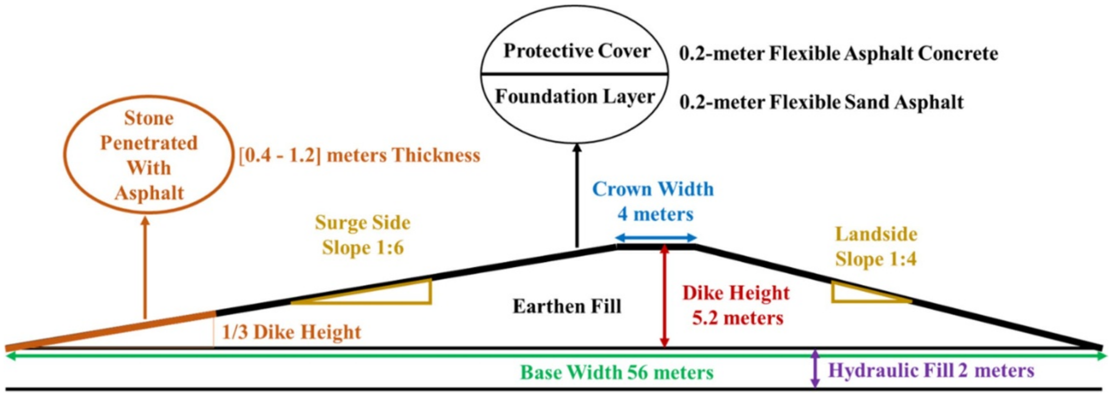


**Figure 5.** Cross-sectional view of the designed Levee-A based on flood elevation, following guidelines in Dijkman (2007).

For finished materials, we based our analysis on a U.S. Army Corps of Engineers (USACE) report providing tables of flood depth and economic damage based on typical residences in the study area (USACE 2006). Based on the flood elevation in the study area, the cost for drywall, insulation, and flooring materials was obtained assuming a one-story on-slab structure and a short-duration storm of fresh and saltwater. The cost was then adjusted for inflation using the consumer price index between 2006 and 2022 (U.S. Bureau of Labor Statistics 2023). We assumed the drywall, insulation, and flooring materials to be gypsum, cellulose insulation, and hardwood, respectively. The average unit cost ($) per unit area, typical thicknesses, and densities of the materials were used to establish a mass ratio to break down the finish material damage into gypsum, cellulose insulation, and hardwood caused by coastal flooding with a specific flood elevation.

### 2.5. Scenario 2: grey infrastructure—Levee A

The first flood protection scenario examined in this study is a grey infrastructure option, specifically the construction of a new levee. The technical design of the levee was primarily adopted from Dijkman (2007) which is based on the state of storm surge and waves in Louisiana's coastline, and which is also aligned with the minimum design requirements reported in Ganiron Jr (2017). Figure 5 presents a cross-sectional view of the designed levee for the grey infrastructure scenario (referred to as 'Levee A') based on regional flood elevation and guidelines (Dijkman 2007). The surge side slope and the inner slope of the levee were selected as 1:6 and 1:4, respectively, to ensure the cost-effectiveness of wave energy dissipation and the stability of the soil in the specific region (Dijkman 2007). Given the proximity of houses and the levee in the Lake Pontchartrain area, a safety freeboard of 2.5 m above the expected surge level is recommended to ensure adequate flood protection for events that occur with a frequency ranging from 1/50 to 1/100 000 per year (Dijkman 2007). Levee A height was determined as a summation of the 100 year BFE and the safety freeboard in the area.

### 2.6. Scenario 3: grey–green (smaller Levee B with oyster bed)

For the green–grey infrastructure scenario to achieve the same flood protection level as the grey alternative, Levee-B is a smaller levee that is constructed along with the oyster bed. The design of Levee-B followed the same guidelines as Levee-A, with a lower elevation based on the reduction in wave height achieved by the construction of the oyster reef. Levee B height was determined using equation (2),

$$\text{Levee B height} = \text{Levee A height} - (\text{oyster reef wave attenuation} \times \text{wave height}). \quad (2)$$

For oysters to reproduce and grow, their larvae must attach to a solid structure with voids to set and develop into spats. In their natural habitat, larvae settle on rocks or existing oysters. When this does not occur naturally, humans can intervene by providing a three-dimensional bed with crevices for oyster larvae to attach, grow, and reproduce, mimicking natural reefs. These oyster reefs are called 'constructed' or 'artificial' oyster reefs. Potential materials for creating these beds are crushed concrete, limestone, or oyster baskets. The placement of the bed material is a practice known as 'cultch planting,' a proven habitat improvement technique followed by the Louisiana Department of Wildlife and Fisheries (LDWF) since 1917 (LDWF 2022).

Designing a constructed oyster reef involves selecting a suitable location, choosing the cultch material, and determining the dimensions of the reef. Our study adopted the oyster bed design from the cultch plant oyster restoration project in Louisiana project. The project used limestone as a cultch material, placed at 200 tons per acre planting density in the targeted areas to promote increased oyster abundance and spawning stocks (Louisiana Trustee Implementation Group 2020). The same material and planting density was chosen and adapted to the area based on the study site. Constructed oyster reefs can vary in length from small patches to continuous structures spanning kilometres depending on project goals and available space (Baggett *et al* 2014). For this study, we assumed that the limestone will be placed in a continuous line along the study area shoreline (8.9 km) to form a solid reef structure that is parallel to the levee. The width of the reef was set to 4 m based on the average width of three oyster reef projects conducted in Louisiana (Morris *et al* 2021).

Morris *et al* (2021) explored the wave attenuation capacity of oyster reef living shorelines as coastal protection infrastructure in a spatially large-scale study along the Atlantic and Gulf coastlines. The authors compared wave attenuation data from 15 distinct projects with control where no reefs were present across various environments and reef types. Morris *et al* (2021) found that oyster reefs can reduce wave height by 68% when inundated for less than half of the flooding time. However, the study concluded that achieving this level of wave attenuation is ecologically undesirable as it hinders the reef's ability to establish a self-sustaining oyster population. The wave attenuation achieved by the oyster reefs was integrated with Levee-B height per equation (2) to establish a green–grey flood defense system that provided equivalent flood protection to the conventional grey infrastructure.

### 2.7. LCI

A process-based LCA approach was employed to assess the life cycle environmental impacts of the three scenarios by modelling the inputs and outputs of each life cycle stage. The basic building element of a process-based LCA is referred to as a 'unit process,' it represents one part of the product's life cycle for which inputs and outputs are quantified (ISO 2006a ). These unit processes are linked together to model the life cycle of a particular scenario as defined in the system boundary of the study (Frischknecht and Rebitzer 2005, Yang *et al* 2017). Table 1 presents the unit processes used to model the structural flood damage, levee, and constructed oyster reef throughout the life cycle phases. An example of a unit process used in this study is 'waste-reinforced concrete', which refers to collecting, processing, and transporting one kilogram of reinforced concrete after the end-of-life stage.

The foreground data for quantifying each strategy's input and output materials were collected from literature, design guidelines, and existing projects and by using Hazus 5.1 and its respective datasets. The parameters and assumptions used for each scenario are detailed in the previous sections 2.4–2.6. The ecoinvent database, accessed through SimaPro, provided various construction material unit processes as background data. While the quantities of the materials of the three scenarios were held fixed, uncertainty in the background data was addressed through 1000 Monte Carlo simulations. The foreground information (e.g. material quantities) and aggregate LCIA results for Levees A and B and the oyster reef bed are available in *supplementary material 1*.

### 2.8. LCIA

The LCIA method used in this study is the Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.1 (TRACI 2.1 V1.07/US 2008). TRACI, developed by the environmental protection agency in 2002 specifically for North America, was chosen due to its geographic relevance. TRACI is a 'midpoint' LCIA approach, focusing on characterizing midpoint impacts like global warming potential (GWP) and eutrophication potential rather than the endpoint damages resulting from these impacts, such as sea level rise and marine life damage, respectively (Sharaai *et al* 2010). Using specific characterization factors, TRACI estimates the potential impact for each substance or emission based on their concentration through a Monte Carlo analysis, ultimately generating a probability distribution for each impact category. These characterization factors represent the potential environmental impact for each substance per unit, developed based on considerations of impact pathways, equivalency factors from epidemiology and toxicology, and fate and transport mechanisms (Bare 2002).

The TRACI method comprises 10 impact categories: GWP, ozone depletion, acidification, eutrophication, smog formation, resource depletion, ecotoxicity, and human health impacts (respiratory effects, carcinogens, and non-carcinogens) (Bare 2002). All these categories are evaluated in this study, with a focus on GWP for the three scenarios: the do-nothing scenario, grey infrastructure, and grey–green infrastructure. The following are definitions of each impact category along with its corresponding unit, as per Bare (2002).

**Table 1.** Unit processes corresponding to each life cycle phase for the scenario components.

| | Life cycle phase | Unit process | Unit | Category |
|---|---|---|---|---|
| Structural flood damage | Waste impact | Waste reinforced concrete {RoW}[a]\| market for waste reinforced concrete \| Cut-off[b], U[c] | kg | Waste treatment-construction waste |
| | | Waste building wood, chrome preserved {RoW}\| market for \| Cut-off, U | kg | Waste treatment-wood |
| | | Waste brick {RoW}\| market for waste brick \| Cut-off, U | kg | Waste treatment-construction waste |
| | | Waste fibreboard {RoW}\| market for waste fibreboard \| Cut-off, U | kg | Waste treatment-construction waste |
| | | Waste gypsum {RoW}\| market for waste gypsum \| Cut-off, U | kg | Waste treatment-construction waste |
| | Rebuild impact | Concrete slab {RoW}\| market for concrete slab \| Cut-off, U | $m^3$ | Material-construction-concrete |
| | | Reinforcing steel {GLO}[d]\| market for \| Cut-off, U | kg | Material-metals-ferro |
| | | Structural timber {RoW}\| market for structural timber \| Cut-off, U | $m^3$ | Material—wood-products |
| | | Clay brick {GLO}\| market for \| Cut-off, U | kg | Material-construction-bricks |
| | | Sawnwood, hardwood, raw {GLO}\| market for \| Cut-off, U | $m^3$ | Material-wood-products |
| | | Gypsum fibreboard {GLO}\| market for \| Cut-off, U | kg | Material—construction-covering |
| | | Cellulose fibre {RoW}\| market for cellulose fibre \| Cut-off, U | kg | Material-construction-insulation |
| Levee | Construction impact | Excavation, hydraulic digger {GLO}\| market for \| Cut-off, U | $m^3$ | Transport-building equipment |
| | | Clay {RoW}\| market for clay \| Cut-off, U | kg | Material-construction-mineral |
| | | Sand {RoW}\| market for sand \| Cut-off, U | kg | Material-construction-mineral |
| | | Mastic asphalt {GLO}\| market for \| Cut-off, U | kg | Material-construction-covering |
| | Waste impact | Excavation, hydraulic digger {GLO}\| market for \| Cut-off, U | $m^3$ | Transport-building equipment |
| | | Waste concrete {RoW}\| market for waste concrete \| Cut-off, U | kg | Waste treatment—construction waste |
| Oyster reef | Construction impact | Limestone, crushed, washed {RoW}\| market for limestone, crushed, washed \| Cut-off, U | kg | Material-construction-mineral |
| | | Excavation, hydraulic digger {GLO}\| market for \| Cut-off, U | $m^3$ | Transport-building equipment |

[a] {RoW}: Rest-of-World geography; indicating that the unit process applies to the rest of the world, excluding regions explicitly defined for each respective unit process.
[b] Cut-off: Denotes that material and energy flows of low environmental significance associated with the unit process were excluded.
[c] U: Stands for Unit Process.
[d] {GLO}: Global geography; indicating that the unit process applies on a global scale.

- GWP estimates the potential climate change impacts caused by heat-trapping GHG emissions such as $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$). It is expressed in kilograms of $CO_2$ equivalent.
- Eutrophication refers to the fertilization of surface waters by scarce nutrients like phosphorus or nitrogen, leading to excessive growth of aquatic plants. This imbalance can cause ecosystem disruption, oxygen depletion, changes in biodiversity, and other impacts. It is expressed in kilograms of nitrogen (N) equivalent.
- Acidification estimates the potential to cause dry or wet acid deposition, including acid rain. Emissions like sulfur dioxide ($SO_2$) or nitrogen oxides ($NO_x$) have the potential to cause acidification. Acidification can

lead to damage to property and ecosystems, affecting aquatic life, soil, and plants. It is expressed in kilograms of $SO_2$ equivalent.

- Ozone depletion assesses the potential to destroy protective ozone (O3) in the stratosphere caused by emissions like chlorofluorocarbons (CFC), hydroCFC, and carbon tetrachloride ($CCl_4$). Ozone depletion can lead to endpoint damage such as crops and marine life damage. It is expressed in kilograms of CFC-11 equivalent.
- Smog assesses the potential of a substance to contribute to the formation of ground-level ozone and photochemical smog. Smog can lead to endpoint damages such as human mortality, asthma effects, and plant effects. It is expressed in kilograms of O3 equivalent, representing the amount of ozone formed.
- Ecotoxicity assesses the potential of a chemical to cause ecological harm expressed in Comparative Toxic Units for Ecosystems (CTUe).
- Fossil fuel depletion assesses the potential of a substance or activity to reduce the availability of energy fossil fuel supplies. It is expressed in megajoules of surplus energy (MJ surplus).
- Human health—respiratory effects assesses the potential to generate particulate matter less than 2.5 $\mu$m, which has respiratory effects. It is expressed in kilograms of PM2.5 equivalent.
- Human health—carcinogenic assesses the potential of a substance to cause human cancer impacts, expressed in comparative toxic units for human health (CTUh).
- Human health—non-carcinogenic assesses the potential of a substance to cause human noncancer effects, expressed in CTUh.

## 3. Results

In this section, the scenario analysis results (section 3.1) are presented first, including the overall life cycle environmental impacts of three scenarios: the do-nothing scenario, grey infrastructure (levee only), and the integration of grey and green infrastructure (smaller levee and constructed oyster reef). The following sections present a detailed breakdown of the environmental impacts of the structural flood damage in (section 3.2), the levees in (section 3.3), and the constructed oyster reef in (section 3.4).

### 3.1. Scenario analysis

Our results showed that green–grey infrastructure scenario is the most promising strategy across most impact categories. Figure 6 presents the environmental impacts among the three scenarios and their respective 95% confidence intervals. The results showed that, under the do-nothing baseline strategy, a single flooding event exhibits the highest mean environmental impacts in all categories except for fossil fuel depletion and ozone depletion. Implementing grey flood infrastructure demonstrated a significant reduction as compared to the flood damage, ranging from 25% to 96%, in the environmental impacts of climate change, water quality, human health, ecotoxicity, and smog. Additionally, the results depicted in figure 6 indicate that green–grey infrastructure mitigates 13%–15% of the environmental impacts compared to grey infrastructure, showcasing its potential as a more sustainable flood protection solution.

Our results showed that green–grey infrastructure reduced the environmental impacts and achieved $CO_2$ equivalent emission reductions compared to the do-nothing and grey infrastructure scenarios while providing equivalent flood protection to grey infrastructure. The results in figure 6 indicate that, for GWP, the do-nothing scenario yielded a mean of 306 million kg $CO_2$ eq per flood event where damage is avoided, the grey infrastructure scenario resulted in a mean of 189 million kg $CO_2$ eq, and the green–grey infrastructure scenario had a mean footprint of 163 million kg $CO_2$ eq for the entire study area, translating to emissions of 34, 21, and 18 million kg per kilometre of shoreline, respectively. Thus, implementing grey infrastructure for flood protection could reduce GHG emissions by 38% compared to the emissions resulting from structural damage in the event of flooding. Furthermore, integrating green infrastructure with grey infrastructure could achieve an additional 13% reduction in emissions compared to solely grey infrastructure. This combination resulted in a total emissions reduction of 47% compared to the flood damage scenario.

### 3.2. Structural flood damage impact

The do-nothing strategy can result in significant material debris, leading to additional environmental impacts during rebuilding. This study assessed the potential structural damage caused by a single coastal flooding event in the study area without flood protection infrastructure. A detailed breakdown of building components and material types is provided in figure 7. According to the Hazus model, the estimated total debris generated by flooding was 867 238 tons, with finishes accounting for 22%, structures accounting for

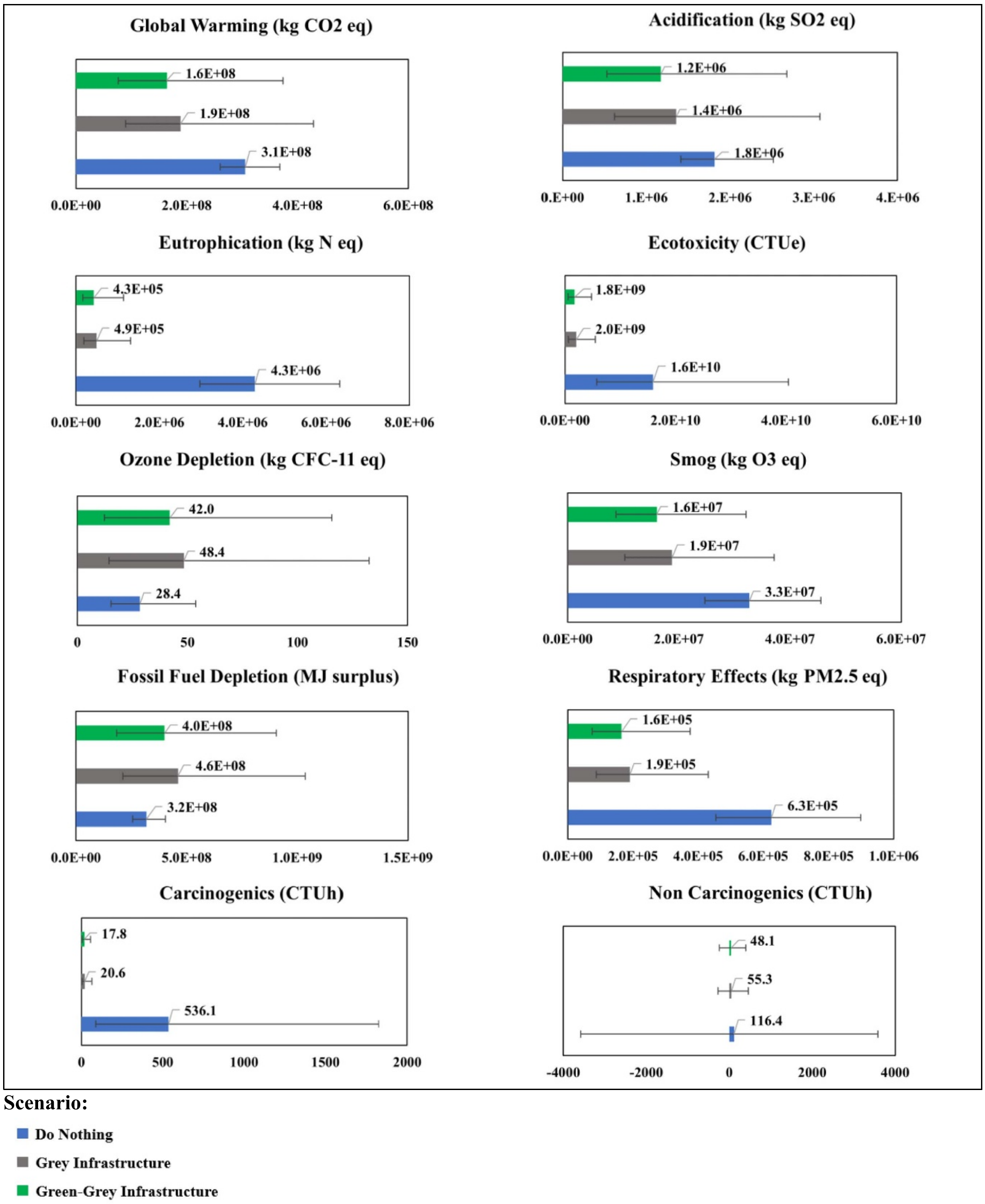


**Figure 6.** Scenario comparison of the life cycle environmental impacts.

43%, and foundations accounting for 35% of the total by weight. Further analysis of the debris material revealed that 80% of the 'finishes' debris material comprises insulation fibres, and 20% of gypsum material used for drywall. The structure material debris consisted of 90% wood and 10% bricks, based on the types of damaged buildings estimated by Hazus. Lastly, the results indicate that 96% of the foundation material debris is generated from the concrete slab and 4% from the reinforcement steel (figure 7).

Rebuilding damaged structures was the primary cause of most flood damage environmental impacts, mainly due to replacing structural timber and reinforcing steel with new materials. Figure 8 presents a breakdown of the environmental impacts associated with the flood damage, based on the life cycle stage: 'rebuild impact' and 'waste impact'. Figure 8 demonstrates that most structural flood damage impacts originate from rebuilding damaged structures, except for carcinogens, eutrophication and ecotoxicity. Specifically, the waste impact dominates the rebuild impact, constituting 84%, 79% and 70% of the carcinogens, eutrophication and ecotoxicity impacts, respectively. Furthermore, the rebuilding impact

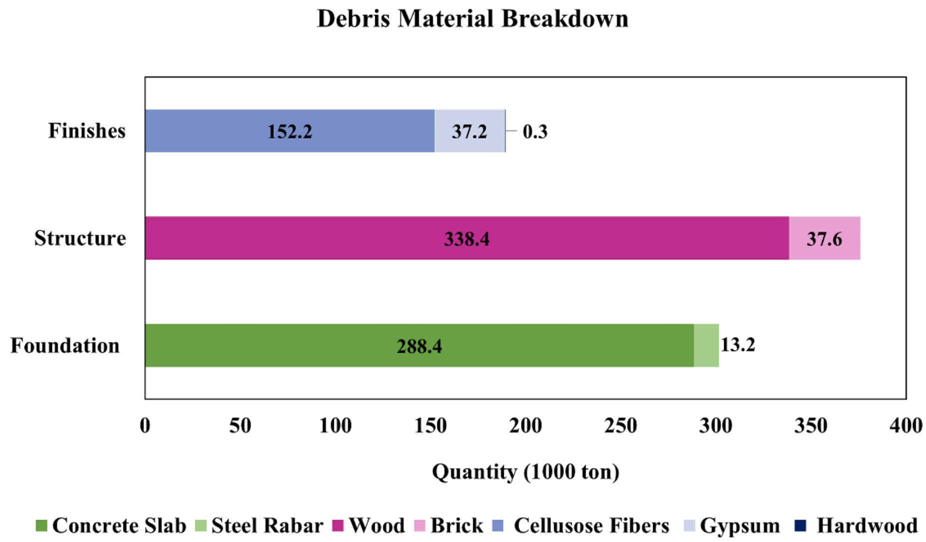


**Figure 7.** Structural flood damage breakdown based on the building components and the material type in metric tons, as presented for the do-nothing flooding scenario.

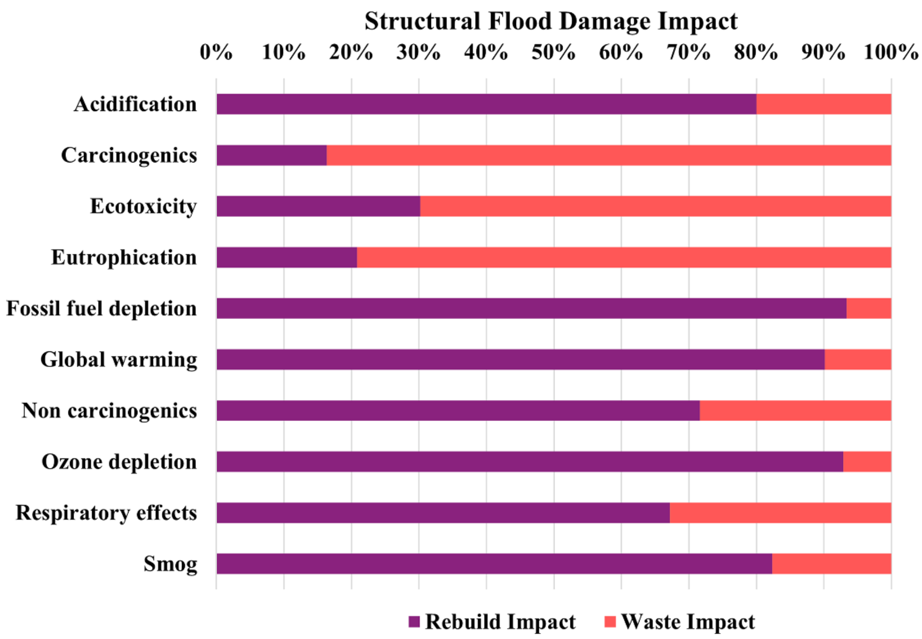


**Figure 8.** Breakdown of environmental impacts of the do-nothing flooding scenario based on the life cycle stage

significantly contributes to the GWP, accounting for 90% of the total impact, while waste impacts contribute only 10%.

A further breakdown of the environmental impacts of the rebuilding and waste impacts based on the construction material is available in *(supplementary material 2: detailed breakdown of environmental impacts)*. Figure S2.1 shows that structural timber and concrete were the primary contributors to the rebuild impact whereas the wood and fibreboard were the major contributors to waste environmental impacts.

### 3.3. Levee impact

Reducing the size of the levee by integrating the constructed oyster reef led to reductions in the environmental impact across all categories. It is important to note that Levee-A was designed to provide independent protection against coastal flooding, while Levee-B is a smaller-sized levee incorporated within a green–grey double-line defense strategy along with a constructed oyster reef. Table 2 presents a comparison of the life cycle impacts between Levees A and B, including their respective 95% confidence intervals. The results in table 2 indicate that Levee-A has a comparatively higher impact than Levee-B due to the disparity

**Table 2.** Life cycle environmental impacts of Levee A and Levee B with 95% confidence.

| Interval impact category (Unit) | Levee A | | | Levee B | | |
|---|---|---|---|---|---|---|
| | 2.5% | Mean | 97.5% | 2.5% | Mean | 97.5% |
| Acidification (kg $SO_2$ eq) | $6.2 \times 10^{+5}$ | $1.4 \times 10^{+6}$ | $3.1 \times 10^{+6}$ | $5.3 \times 10^{+5}$ | $1.2 \times 10^{+6}$ | $2.7 \times 10^{+6}$ |
| Carcinogenics (CTUh) | $5.0 \times 10^{0}$ | $2.1 \times 10^{+1}$ | $6.5 \times 10^{+1}$ | $4.3 \times 10^{+0}$ | $1.8 \times 10^{+1}$ | $5.7 \times 10^{+1}$ |
| Ecotoxicity (CTUe) | $6.6 \times 10^{+8}$ | $2.0 \times 10^{+9}$ | $5.5 \times 10^{+9}$ | $5.7 \times 10^{+8}$ | $1.8 \times 10^{+9}$ | $4.8 \times 10^{+9}$ |
| Eutrophication (kg N eq) | $1.9 \times 10^{+5}$ | $4.9 \times 10^{+5}$ | $1.3 \times 10^{+6}$ | $1.6 \times 10^{+5}$ | $4.3 \times 10^{+5}$ | $1.1 \times 10^{+6}$ |
| Fossil fuel depletion (MJ surplus) | $2.1 \times 10^{+8}$ | $4.6 \times 10^{+8}$ | $1.0 \times 10^{+9}$ | $1.8 \times 10^{+8}$ | $4.0 \times 10^{+8}$ | $9.0 \times 10^{+8}$ |
| Global warming (kg $CO_2$ eq) | $9.0 \times 10^{+7}$ | $1.9 \times 10^{+8}$ | $4.3 \times 10^{+8}$ | $7.7 \times 10^{+7}$ | $1.6 \times 10^{+8}$ | $3.7 \times 10^{+8}$ |
| Non carcinogenics (CTUh) | $-2.7 \times 10^{+2}$ | $5.5 \times 10^{+1}$ | $4.6 \times 10^{+2}$ | $-2.4 \times 10^{+2}$ | $4.8 \times 10^{+1}$ | $4.0 \times 10^{+2}$ |
| Ozone depletion (kg CFC-11 eq) | $1.4 \times 10^{+1}$ | $4.8 \times 10^{+1}$ | $1.3 \times 10^{+2}$ | $1.2 \times 10^{+1}$ | $4.2 \times 10^{+1}$ | $1.2 \times 10^{+2}$ |
| Respiratory effects (kg $PM_{2.5}$ eq) | $8.8 \times 10^{+4}$ | $1.9 \times 10^{+5}$ | $4.3 \times 10^{+5}$ | $7.5 \times 10^{+4}$ | $1.6 \times 10^{+5}$ | $3.8 \times 10^{+5}$ |
| Smog (kg $O_3$ eq) | $1.0 \times 10^{+7}$ | $1.9 \times 10^{+7}$ | $3.7 \times 10^{+7}$ | $8.7 \times 10^{+6}$ | $1.6 \times 10^{+7}$ | $3.2 \times 10^{+7}$ |

**Table 3.** Life cycle environmental impacts of the constructed oyster reef with 95% confidence interval.

| Impact category (Unit) | 2.5% | Mean | 97.5% |
|---|---|---|---|
| Acidification (kg $SO_2$ eq) | $8.0 \times 10^{+1}$ | $1.2 \times 10^{+2}$ | $1.7 \times 10^{+2}$ |
| Carcinogenics (CTUh) | $2.6 \times 10^{-5}$ | $8.4 \times 10^{-4}$ | $1.9 \times 10^{-3}$ |
| Ecotoxicity (CTUe) | $4.3 \times 10^{+4}$ | $7.7 \times 10^{+4}$ | $1.3 \times 10^{+5}$ |
| Eutrophication (kg N eq) | $1.1 \times 10^{+1}$ | $1.8 \times 10^{+1}$ | $2.7 \times 10^{+1}$ |
| Fossil fuel depletion (MJ surplus) | $1.2 \times 10^{+4}$ | $1.9 \times 10^{+4}$ | $2.9 \times 10^{+4}$ |
| Global warming (kg $CO_2$ eq) | $7.1 \times 10^{+3}$ | $1.0 \times 10^{+4}$ | $1.5 \times 10^{+4}$ |
| Non carcinogenics (CTUh) | $-7.3 \times 10^{-2}$ | $2.4 \times 10^{-3}$ | $8.0 \times 10^{-2}$ |
| Ozone depletion (kg CFC-11 eq) | $8.7 \times 10^{-4}$ | $2.0 \times 10^{-3}$ | $4.3 \times 10^{-3}$ |
| Respiratory effects (kg $PM_{2.5}$ eq) | $2.9 \times 10^{+1}$ | $4.6 \times 10^{+1}$ | $7.5 \times 10^{+1}$ |
| Smog (kg $O_3$ eq) | $2.0 \times 10^{+3}$ | $3.0 \times 10^{+3}$ | $4.4 \times 10^{+3}$ |

in levee heights established based on the wave attenuation achieved by the oyster bed in the case of green–grey infrastructure. The table demonstrates that reducing the height of the levee leads to a 15%–17% reduction in total environmental impacts across all categories. For example, by decreasing the size of the levee, approximately 16% of the GWP could be mitigated. This corresponds to a mean of 25.5 million kg $CO_2$ eq of GHG emissions for the study area and 2.9 million kg $CO_2$ eq per kilometre of shoreline.

The asphalt protective cover of the levee was responsible for most of the life cycle impacts of both the construction and end-of-life stages across most categories. The environmental impacts of the construction phase and end-of-life phase of the levee, along with their breakdown based on the construction material, can be found in the Supplementary Material. The results in figure S2.2 show that the asphalt concrete layer accounted for most life cycle impacts, with over 75% of GHG emissions occurring in the construction and end-of-life waste treatment phases.

### 3.4. Constructed oyster reef impact

Compared to grey infrastructure, the green infrastructure option (constructed oyster reef) demonstrated significantly lower impacts, primarily attributed to the extraction and production of cultch material, specifically limestone. Table 3 presents the life cycle environmental impacts of the constructed oyster reef, with the corresponding 95% confidence interval. Comparing the environmental impacts of green infrastructure to those of grey infrastructure (shown in table 2) shows that the impacts of green infrastructure are substantially lower. For instance, while the smaller-size levee produced a mean of 189 million kg $CO_2$ eq, the construction of the oyster bed for the oyster reef growth contributed only about 10 272 kg $CO_2$ equivalent for the entire study area, approximately 1154 kg $CO_2$ eq per kilometre of protected shoreline. A breakdown of the environmental impacts of the constructed oyster reef can be found in the Supplementary Material. The results in figure S2.3 show that more than 96% of all impacts are attributed to the extraction and production of limestone used as the cultch material, with over 97% of the global warming impact stemming from this extraction and production process.

## 4. Discussion

### 4.1. Scenario analysis

The study assessed the environmental impacts of coastal flood management strategies. While applied in the context of New Orleans, Louisiana, the framework and observed patterns might be relevant to other regions. The Scenario Analysis results (section 3.1) emphasize the importance of providing flood protection infrastructure in areas prone to coastal flooding, demonstrating that the absence of such infrastructure can lead to significantly higher environmental impacts. While consistent with existing research (Costanza *et al* 2008, Barbier *et al* 2013, Sutton-Grier *et al* 2015, Jongman 2018, Reguero *et al* 2018) that emphasizes the economic benefits of providing flood protection infrastructure, our study brought attention to the environmental perspective, underscoring the importance of incorporating environmental impacts into the decision-making. Policymakers can leverage these findings to develop more sustainable and effective strategies by factoring in environmental costs in decision-making. For instance, our results reveal that the do-nothing, grey, and green–grey strategies resulted in a mean of 34, 21, and 18 million kg $CO_2$ equivalent per kilometre of shoreline, respectively. We recommend integrating the GHG emission reduction costs into the life cycle costing of large-scale flood protection projects in the study area, and in any other region considering coastal flood protection strategies.

The LCA results revealed that incorporating a green–grey flood protection infrastructure only led to a reduction of environmental impacts, ranging between 13%–15% compared to solely employing a grey flood protection infrastructure. This can be attributed to the assumption based on the latest research by Morris *et al* (2021), suggesting that oyster reefs can reduce wave height by approximately 68%. However, in the study area, this reduction translates to a mere 68 cm of decreased levee height. Considering the area's requirement for a high safety board (2.5 m) and the elevated flood levels, the potential reduction achievable remains relatively low. In other coastal regions with different physical and regulatory contexts, nature-based solutions may be able to provide different levels of benefit, hence should be evaluated on a case-by-case basis.

While the do-nothing scenario considered a single flood event, it is important to note that a 100 year flood event may occur multiple times during the lifetime of flood protection infrastructure. Applying the payback period (PP) concept from Petit-Boix *et al* (2017a) allowed us to address the question 'how many events a flood protection system should protect against within its lifetime to become environmentally beneficial for the community?'. The PP, defined as the number of events at which the system repays the environmental damage related to its construction (Petit-Boix *et al* 2017a), offers valuable insights into the system's environmental efficiency. Specifically, assuming that flood protection infrastructure prevents the entirety of flood damage, the PP is determined by dividing the infrastructure's environmental impact by the impact in the do-nothing scenario. For instance, in terms of GWP, the grey infrastructure system pays back for its construction emissions after the first mitigated flooding event (189 million kg $CO_2$ eq/306 million kg $CO_2$ = 0.6 events). Similarly, the green–grey infrastructure features a slightly shorter PP (163 million kg $CO_2$/306 million kg CO2 = 0.5 events), offsetting its emissions after the initial flood event. A single avoided 100 year flood event is sufficient for environmentally paying back the grey or green–grey flood protection infrastructure. As protection extends to more flood events during the lifetime of the infrastructure, the environmental benefits of both grey and green–grey flood protection system amplify.

Finally, it is important to note that while mean impacts typically favour the green–grey infrastructure scenario, followed by the grey infrastructure scenario, and finally the flooding event in the do-nothing scenario for most impact categories, this may not always hold true when considering the upper and lower limits of the 95% confidence interval. Therefore, it is important to understand that while these estimations represent the central tendency, variations in preferences between scenarios may diverge from the mean trends for specific impact categories (refer to figure 6) due to background uncertainties stemming primarily from the selection of inputs, parameters, and model formulations employed in developing the ecoinvent database (Igos *et al* 2019).

### 4.2. Structural flood damage

The potential for generating substantial amounts of structural debris in a relatively small residential area indicates the region's high vulnerability to coastal flooding. These findings not only emphasize the need for flood protection infrastructure but also highlight the importance of enhancing the resilience of buildings in flood-prone areas. This is only considering the environmental impacts, whereas anticipated social impacts related to flooding would likely make the need for flood protection even more apparent.

Furthermore, the results of this study highlight the predominant role of rebuilding in driving environmental impacts, mainly attributed to structural timber and concrete. This can be explained by the prevalence of wood houses and the environmental burden associated with concrete production. These findings call for innovative approaches to explore alternative sustainable building materials, particularly in coastal flood-prone regions. Additionally, the study emphasizes that wood and fibreboard are major contributors to the structural flood waste impact in the study area. This can be attributed to the considerable quantities of structural wood wasted, the most prevalent type of debris, as shown in figure 7, and the common practice of landfilling fibreboards, which leads to chemical leaching and groundwater contamination, intensifying the environmental impacts of waste materials. Therefore, careful management of flooding building material waste is essential for minimizing the adverse effects of floods on the environment.

### 4.3. Levees

The wave attenuation offered by an oyster reef can lower the necessary height of a levee implemented in tandem, in order to achieve a given level of flood protection. This results in a reduction of approximately 15%–17% in environmental impacts across all impact categories, including a 16% decrease in global warming impact. These results indicate that hybrid green–grey solutions can serve as a valuable transition phase towards unlocking the full potential of nature-based systems.

The study revealed that the levee's asphalt protective cover is responsible for most life cycle impacts in most categories, with over 75% of the GHG emissions impacts *(Refer to supplementary material 1 and 2)*. These findings emphasize the need to explore sustainable alternative cover materials to promote sustainable infrastructure design like vegetated cover.

### 4.4. Constructed oyster reef

The minimal environmental impacts of green infrastructure compared to grey infrastructure illustrate the benefit of these solutions in terms of ecological performance and environmental impact. However, the findings suggest that there is room for improvement in the engineering performance of these systems to entirely rely on them as standalone solutions and maximize the range of ecological benefits they offer. It is vital to recognize the numerous co-benefits associated with oyster reefs, including water filtration enhancing the water quality and providing habitat for marine species, which enhances shoreline biodiversity. These localized co-benefits are challenging to measure and capture (Sutton-Grier *et al* 2015), especially within LCA. Therefore, we recommend exploring alternative tools to compare the benefits of these nature-based systems effectively and more comprehensively to the traditional built infrastructure.

Furthermore, the study revealed that over 96% of the impacts could be attributed to the extraction and production of limestone, which serves as the cultch material for the oyster reef *(see supplementary material 1 and 2)*. Exploring alternative materials, such as recycled oyster shells in baskets or crushed concrete, holds the potential for further maximizing the benefits of these infrastructures. By considering these alternatives, we can reduce the environmental footprint and enhance the sustainability of green infrastructure in flood protection.

### 4.5. Limitations & future work

As evident, the limited availability of data on the performance of green infrastructure and hybrid infrastructure in flood protection (Sutton-Grier *et al* 2015) poses a challenge in assessing the full potential of green flood protection infrastructure, specifically within the context of our LCA. Nevertheless, our results serve as proof of concept, demonstrating the ability of nature-based solutions to mitigate life cycle environmental impacts and emphasizing the necessity for further field-based research to comprehend the potential of green infrastructure in wave attenuation fully. The findings also highlight the importance of improving the efficiency of green infrastructure systems in flood protection.

The scenarios in this study were established based on a fixed flood protection criterion, the 100 year BFE. This approach is limited as it does not incorporate a probabilistic estimation of the environmental damage and does not account for the non-stationary nature of climate change. Future research should build on this study by comparing the environmental impacts of green and grey flood protection strategies following a risk-based flood protection approach and incorporating the possible impact of sea level rise under various climate change scenarios and associated uncertainties. The study focused on building-related structural damage. Future research endeavours could broaden the scope by incorporating additional data to assess flood damage to other infrastructure and vehicles. This study relied on a simplified Level 1 Hazus coastal analysis due to limited data, leading to limitations in accuracy and precision. Future studies should incorporate more detailed and comprehensive data. Moreover, the study was limited in its ability to include other types of green infrastructure due to a lack of the necessary data. One process not directly included in the current study is carbon sequestration, which can help to counter the GHG footprint of materials. While it is anticipated that this would be relatively minimal for a constructed oyster reef, other coastal nature-based solutions like mangrove forests or marshes could have significant biological carbon uptake and overall carbon sequestration (Duarte *et al* 2013, Fodrie *et al* 2017). Future research should delve into a more diverse range of green and grey flood protection infrastructure, exploring the life cycle impacts of maintaining these systems (Hasik *et al* 2019).

Additionally, there are opportunities to expand the detail of hydrodynamic impacts of considered strategies. This study focused primarily on assessing the engineering performance of flood protection infrastructure based on wave attenuation. Our assumptions were based on review of rates of wave attenuation documented in existing published research. Future research could incorporate a more detailed assessment of wave attenuation based on modelling of the case study system, and potentially incorporate a greater range of uncertainty in assumed wave attenuation. Additional performance measures could also be considered, such as wave energy dissipation (Ghiasian *et al* 2019, 2021), to assess the benefits of green flood protection infrastructure.

Overall, the study demonstrated an approach integrating Hazus with LCA to assess the life cycle environmental impacts of flooding and flood protection infrastructure in a specific location. Despite the site-specific results, the approach can be replicated in future studies, extending its application to different geographical areas. We also recommend exploring other green and grey flood protection infrastructure, considering various damage types, and incorporating future climate change scenarios. While this study quantifies the environmental impacts associated with each flood protection strategy, it is crucial to consider their practical implications in decision-making by accounting for the stochastic nature of hazard occurrences and associated damages.

## 5. Conclusions

In conclusion, our study assessed the environmental impact of three coastal flood management scenarios in a New Orleans residential area: a baseline scenario, representing the flood damage resulting from a single flooding event with no flood protection infrastructure, grey infrastructure (levee), green–grey infrastructure (double line defense-smaller levee and constructed oyster reef). We used a process-based LCA approach and evaluated the environmental impact of each strategy using the ecoinvent database accessed through SimaPro. Hazus software was employed to model the structural flood-induced damage. The following are the main findings of the study:

Scenario analysis:

- A single flooding event under the do-nothing baseline strategy exhibited higher environmental impacts than providing grey or green–grey flood protection infrastructure in all categories except for fossil fuel depletion and ozone depletion.
- The green–grey hybrid flood protection strategy demonstrated the most promising outcomes, reducing environmental impacts by 13%–15% compared to grey infrastructure.
- A single flooding incident could result in a mean of 34 million kg of $CO_2$ eq per kilometre of flooded shoreline. In contrast, implementing grey and green–grey flood protection infrastructure was estimated to release 21 and 18 million kg $CO_2$ eq per kilometre of protected shoreline.
- Implementing grey infrastructure as a coastal flood protection measure reduced GHG emissions by 38% compared to the emissions during a single flooding incident.
- Implementing a green–grey protection strategy resulted in an additional 13% reduction in emissions compared to using only grey infrastructure, achieving a total reduction of 47% compared to flooding under the do-nothing scenario.
- A single avoided flood event is sufficient for environmentally paying back the flood protection system. As protection extends to more flood events, the environmental benefits of both grey and green–grey flood protection infrastructure amplify.

Structural flood damage:

- The study emphasized that the rebuilding process of damaged residential houses significantly contributes to most environmental impact categories, particularly GHG emissions. In the case study, 90% of emissions resulted from replacing damaged structural elements and only 10% were associated with the waste treatment of the flood debris waste.
- The results showed that structural timber and concrete were the primary contributors to the environmental impact associated with the rebuilding process, and wood and fibreboard were the main contributors to the flood debris waste impact.

Levees:

- By accounting for the wave attenuation achieved through a constructed oyster reef, the height of the levee could be reduced, resulting in a decrease of 15%–17% in the total environmental impacts across all categories. Additionally, reducing the size of the levee led to a reduction of approximately 16% in GWP.
- The asphalt protective cover of the levee was identified as the primary contributor to life cycle impacts in most categories. Over 75% of the GHG emissions associated with the levee were attributed to the protective asphalt layer during the construction and end-of-life phases.

Constructed oyster reef:

- The impacts of the constructed oyster reef were significantly lower than those of the levees. The oyster reef construction only resulted in a mean of 1154 kg $CO_2$ equivalent per kilometre of shoreline.
- The results highlighted that the extraction and production of limestone contributed to the majority of impacts associated with the constructed oyster bed, accounting for over 96% in all impacted categories and 97% of the global warming impact.

Overall, the findings of our study highlight the potential benefits of integrating nature-based solutions with grey infrastructure for coastal flood protection. These green–grey strategies can be implemented as a transitional approach towards adopting green infrastructure as an independent solution until further research unlocks the wide-ranging benefits of green solutions in coastal flood protection. We recommend that policymakers consider the environmental impacts when making policy decisions, especially the GWP, to both ensure the protection of the coastal communities in the short term while also aiming to reduce the impact of climate change in the long run.

## Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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## Conflict of interest

The authors declare no conflict of interest.

## ORCID iDs

Rahaf Hasan https://orcid.org/0000-0002-3876-4976
Lauren McPhillips https://orcid.org/0000-0002-4990-7979
Melissa Bilec https://orcid.org/0000-0002-6101-6263

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