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Identifying the Vulnerabilities of Working Coasts Supporting Critical Energy Infrastructure

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Abstract: The U.S. Gulf of Mexico (GOM) is an excellent example of a working coast that supports a considerable degree of critical energy infrastructure across several sectors (crude oil, natural gas, electric power, petrochemicals) and functionalities (production, processing/refining, transmission, distribution). The coastal communities of the GOM form a highly productive and complicated human, physical, and natural environment that interacts in ways that are unlike anywhere else around the globe. This paper formulates a Coastal Infrastructure Vulnerability Index (CIVI) that characterizes interactions between energy assets and the physical and human aspects of GOM communities to identify and prioritize, using a multi-dimensional index, coastal vulnerability. The CIVI leads to results that are significantly different than traditional methods and serves as an alternative, and potentially more useful tool for coastal planning and policy, particularly in those areas characterized by very high infrastructure concentrations.

Keywords: coastal vulnerability; coastal infrastructure vulnerability index; coastal Louisiana; Gulf of Mexico; climate change

1. Introduction

The northern Gulf coast is one of the world's most unique, complex, productive and threatened ecosystems, comprised of wetlands, swamps, and barrier islands that developed in response to the delta-building process of the Mississippi River system over the past 7000 years [1]. It is also home to and supports a large number of energy infrastructure facilities that are of both regional and national importance across several sectors. Unfortunately, this dynamic region has experienced drastic land loss of approximately 1900 mi^2 since at least the 1930s [2]. The years 1985 to 2010, on average, show a wetland loss rate of 16.6 mi^2/year, and this loss is anticipated to continue for the next several decades [3].

This land loss has resulted in increased environmental, economic, and social vulnerabilities, which have been compounded by multiple disasters, including hurricanes, river floods, and the 2010 Deepwater Horizon oil spill. For instance, Hurricane Katrina resulted in at least $105 billion in direct property damages [4], and an estimated reactionary spending of more than $250 billion [5]. These extreme disasters have motivated several researchers to pursue studies aimed at comprehensively understanding and predicting landscape change and the aforementioned vulnerabilities of the northern Gulf coast ecosystems and human communities. Attaining this goal requires increased knowledge and analysis of the implications of such changes in the natural and human-made components of the region for hurricane impact or climate susceptibility.

Research conducted over the past two decades has utilized new empirical tools for measuring the vulnerabilities of coastal communities to sea level rise among other coastal risks. The early literature in this area dates to the 1990s with the work of Gornitz *et al.* [6,7] and Shaw *et al.* [8]. These studies utilize objective multi-variate index number approaches that measure potential coastal vulnerabilities in summary form. These index-based approaches, referred to more commonly in the literature as a coastal vulnerability index (CVI), incorporate a variety of geo-physical information to characterize coastal area weaknesses. This type of empirical work has been expanded over the past two decades to include a variety of other geo-physical considerations including, but not limited to that offered by Theiler *et al.* [9,10], Boruff *et al.* [11], Pendelton *et al.* [12], and Kunte *et al.* [13]. These methods have been applied to a number of region-specific case studies around the world as summarized by Kunte *et al.* [13], as well as Bosello *et al.* [14].

The coastal vulnerability literature also recognizes that coastal vulnerabilities are not a function of a coastal area's physical characteristics alone, but also includes a host of important socio-economic considerations. Wu *et al.* [15], for instance, incorporate social and demographic factors in an index-based coastal vulnerability measure. Cutter *et al.* [16] and Boruff *et al.* [11] also make contributions to this approach by including a wide range of socio-economic and demographic information including population, age, race, per capita income, and housing values, to name a few of the numerous variables included in their respective index-based approaches. Indices using these combined physical and socio-economic variables expand the CVI approach into what is commonly referred to as a Coastal Economic Vulnerability Index (CEVI) given the additional socio-economic information. Taramelli *et al.* [17] summarize some of the leading literature associated with location-specific CEVI case studies conducted over the past two decades. Much of this research, as it increases in scope and multidimensional complexity, utilizes geographic information systems (GIS) to manage the considerable breath of its various components.

While a number of more contemporaneous CEVI studies have explored the role of housing and commercial stocks on coastal community vulnerabilities, few isolate the role that important and often critical infrastructure plays on coastal vulnerabilities. Johnston *et al.* [18] develop a CEVI-based approach that includes an analysis of the role of critical transportation infrastructure on coastal vulnerabilities that itself is comprised of a number of objective and subjective measures of transportation infrastructure, such as road type/size (by types of traffic served), failure probability, and the social, health, safety, and environmental impacts of transportation infrastructure failure in coastal areas.

Only one study, Thatcher *et al.* [19], examines the role that a limited set of critical energy infrastructure plays on coastal vulnerabilities. The study is unique in that the socio-economic component of the CEVI includes not only a set of socio-economic variables (population, housing values, *etc.*), but also the economic replacement values for a limited set of critical energy infrastructure including petroleum refineries, natural gas processing facilities, and electric generation facilities located on the coastal Gulf of Mexico (GOM) region. The Thatcher study, however, is not without a few analytic challenges.

This study attempts to compensate for these challenges by developing a type of CEVI that (1) includes a full range of critical energy infrastructure occupying coastal areas; (2) includes a more parsimonious set of socio-economic variables that limits inadvertent over-weighting of variables; and (3) measures critical energy infrastructure in terms of its observation-specific physical energy capacities, not a generalized set of economic replacement values.

2. Study Area: A Working Coast of Critical Infrastructure

The study area includes the statutorily-defined coastal zone of Louisiana (Louisiana Revised Statutes 49:214.24) spanning 14,587 square miles with 397 miles of coastline. This region is well-recognized as having one of the highest concentrations of energy infrastructure in the U.S., if not the world (Figure 1).

Unfortunately, this area also represents one of the most vulnerable coastal areas of the U.S. and around the world. Louisiana itself is threaded with a large number of canals and levees designed to govern the forces of nature. These canals and levees, while providing significant benefits, are not without costs. For instance, the levees constructed to hold back the mighty flood waters of the Mississippi River have contributed to more than a 60% decrease in sediment discharge from an estimated 400 million metric tons per year that was previously distributed across a broad coastal plain nourishing and maintaining the entire lower delta region for centuries [20].

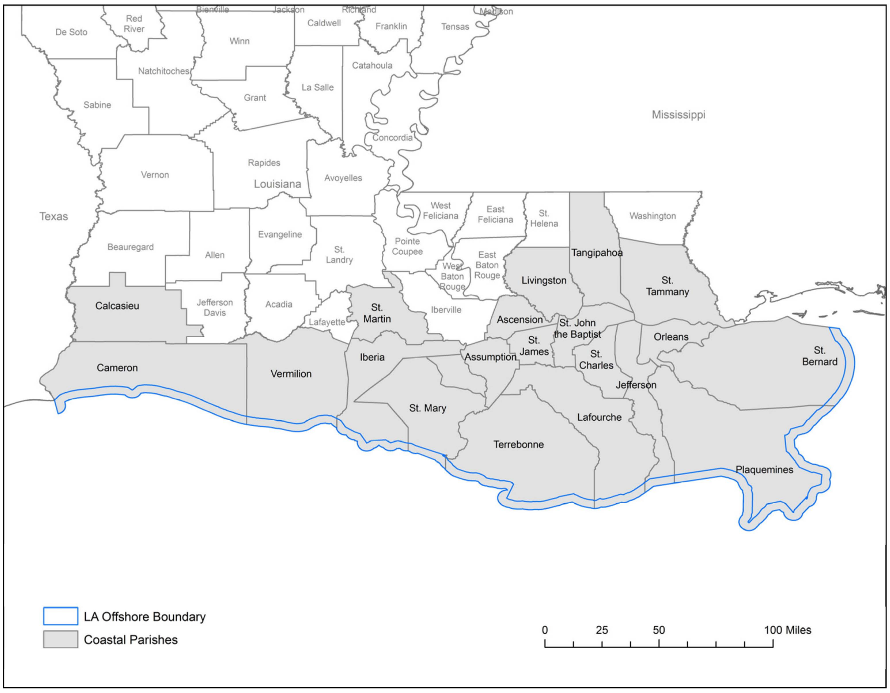


Figure 1. Study area: 20 coastal parishes in Louisiana.

The region also has over 10,000 miles of canals and other man-made waterways that have been dredged over the past century to facilitate various forms of commerce, in particular the exploration and production of crude oil and natural gas [21]. These canals are thought to have contributed, in large part, to a variety of geological and environmental challenges that include localized subsidence. The canals have also facilitated the intrusion of salt water that kills freshwater plants and marshes, leading to soil erosion and even more land loss.

In the middle of this relatively vulnerable coastal area sits the most concentrated set of critical energy infrastructure known in the world. This infrastructure goes beyond simple oil and gas wells, and the pipelines interconnecting these wells to domestic and international markets, and includes: natural gas processing facilities; petroleum refineries; natural gas liquids fractionators; petrochemical plants; natural gas storage facilities; liquefied natural gas (LNG) import/export terminals; electric power plants; petroleum storage facilities; offshore supply bases and heliports; and platform fabrication yards.

Most importantly, Louisiana is home to one of the highest concentrations of natural gas, crude oil, refined product, and petrochemical product pipeline networks in the world. Figure 2 shows the U.S. natural gas pipeline system. If this system can be thought of as the circulatory system of U.S. natural gas supplies, then the pipelines passing through Louisiana represent the critical aorta of that important circulatory system.

Louisiana has a sparsely populated coastal area relative to other coastal states along the GOM. For instance, Louisiana averages about 41 persons per square kilometer (km^2) compared with Florida, which has 137 persons/km^2. The population density along Louisiana's coast ranges from a relatively densely-populated areas in Orleans Parish (New Orleans) at 858 persons/km^2 to a very sparse

14 persons/km^2 in Cameron Parish in Southwestern Louisiana, which represents the lowest population density of any coastal parish or county along the GOM (2010 Census, U.S. Census Bureau).

Thus, the concentration of critical energy infrastructure should be as important a component in the development of any CEVI as other socio-economic variables like population, per capital income, housing stock, and other comparable variables. Energy infrastructure, furthermore, is important to not only the economic vulnerabilities of the coastal region of Louisiana alone, but also that of the U.S. The concentration of a wide range of energy infrastructure along the coastal areas of Louisiana is shown in the various panels included in Figure 3.

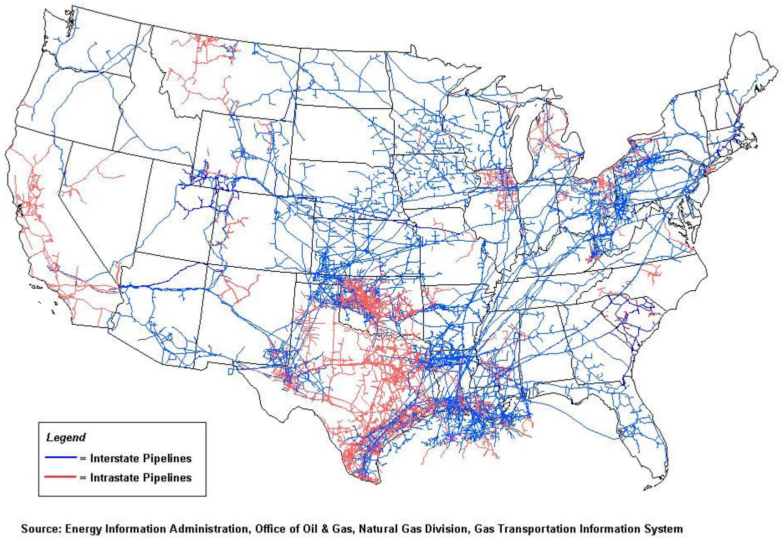


Figure 2. U.S. natural gas pipeline network (Energy Information Administration [22]).

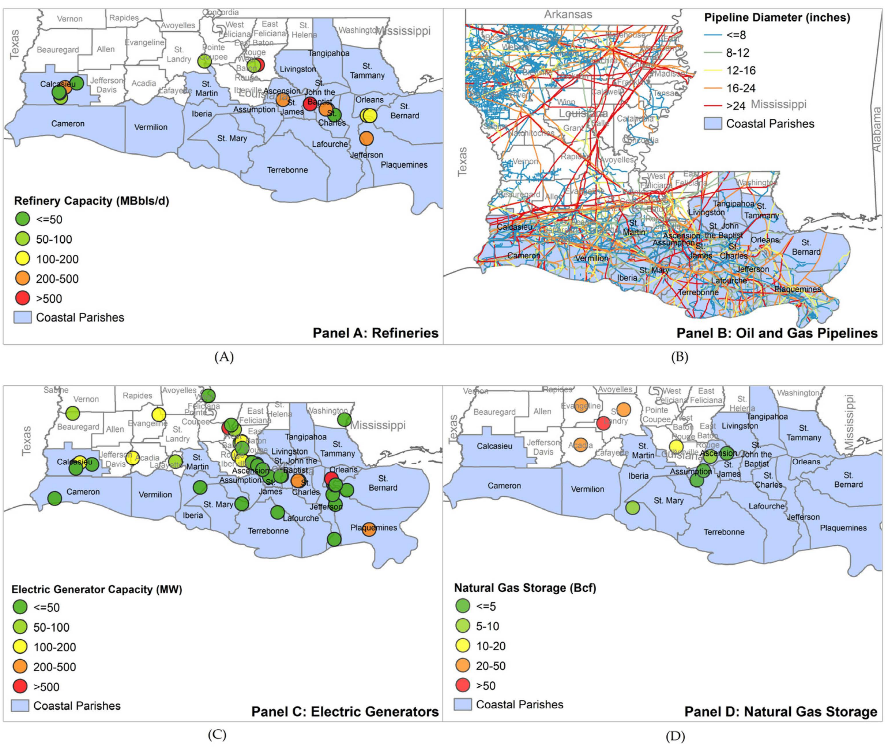


Figure 3. *Cont.*

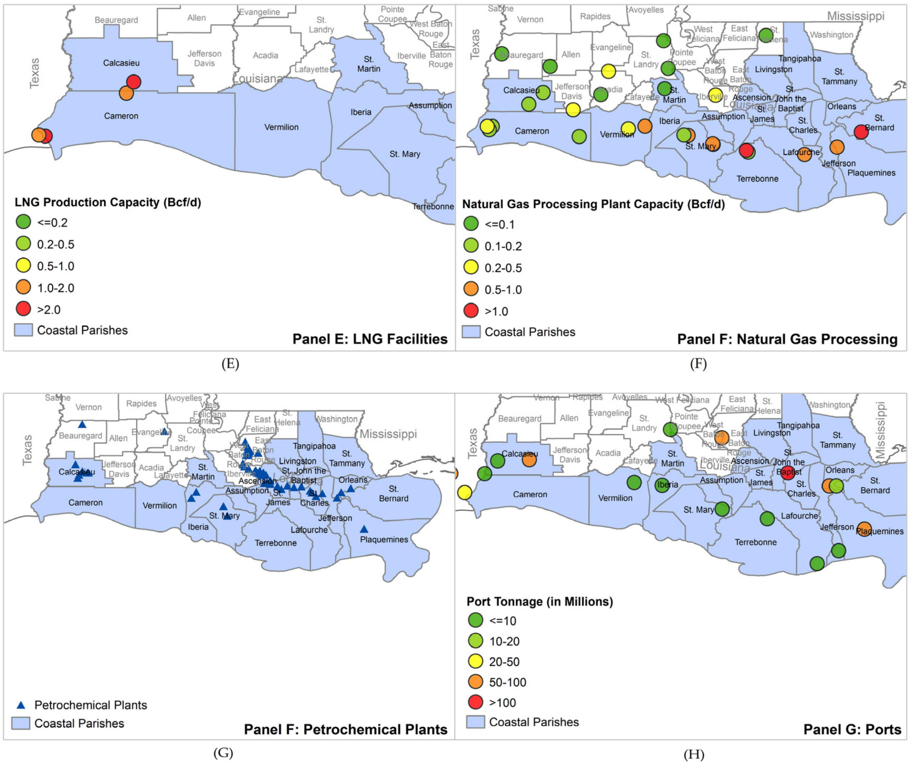


Figure 3. Critical energy infrastructure located in coastal Louisiana: (**A**) Refineries; (**B**) Oil and gas pipelines; (**C**) Electric generators; (**D**) Natural gas storage; (**E**) LNG facilities; (**F**) Natural gas processing plants; (**G**) Petrochemical plants; and (**H**) Ports.

This study uses information at the census block level as defined by the U.S. Bureau of the Census. A census block is the smallest geographical unit used by the Census Bureau for tabulation of 100-percent data. Census blocks are grouped into block groups, which are further grouped into census tracts. Census blocks are important demographic/geographic delineations that facilitate the development of relatively consistent and stable statistical analyses. Each parish is represented by a different number of census blocks with a total of 88,162 blocks across the 20 coastal parishes as shown in Table 1.

Table 1. Twenty coastal parishes in the study area and the count of constituent census blocks.

Parish	Census Blocks
Ascension	2711
Assumption	1315
Calcasieu	5561
Cameron	1651
Iberia	2935
Jefferson	10,454
Lafourche	4397
Livingston	2929
Orleans	13,932
Plaquemines	3843
St. Bernard	3537
St. Charles	2890
St. James	1671
St. John the Baptist	1891

Table 1. *Cont.*

Parish	Census Blocks
St. Martin	2539
St. Mary	4427
St. Tammany	10,141
Tangipahoa	3501
Terrebonne	4460
Vermilion	3377
Total	88,162

3. Methods and Data

This research utilizes a modification of the CEVI approach by combining physical variables reflecting coastal processes and geological conditions, socio-economic variables, and critical energy infrastructure variables. Physical and energy infrastructure information was matched to the socio-economic data collected at the census block level. Collectively, this multi-dimensional data, once standardized, can be referred to as a "Coastal Infrastructure Vulnerability Index" (or CIVI) and differs from a typical CEVI since the index formulation is based upon a third component comprised of a broad set of energy infrastructure capacities. This component of the index is measured in capacity terms for each infrastructure type not in economic or geo-physical information terms like the traditional formulations included in a CVI or CEVI. Instead, each individual type of infrastructure is measured in terms of its capability to produce, transport, or process energy.

The approach utilized in this study differs significantly from prior-related work by Thatcher *et al.* [19] who use an economic approach that measures infrastructure intensity as the replacement cost for a typical facility. Thus, each refinery effectively has the same unit value, and is assumed to be economically and operationally homogeneous, in the CEVI. The only way in which a geographic area becomes more vulnerable in the Thatcher study is through a larger number of refineries since the infrastructure measure is simply the product of the count data (number of refineries) and the dollar value to replace a refinery of a typical size. This is a biased measure for two reasons. First, the Thatcher study will bias outcomes to infrastructure numbers, not size: more refineries lead to greater vulnerability than larger refineries. Thus, in the Thatcher study, two refineries of 250,000 barrels per day (Bbls/d) of capacity have greater weight than one large refinery of 500,000 Bbls/d. Second, the economic replacement value used in the analysis is based upon a typical (or average) refinery that very likely does not match the individual refineries observed at the local level. This is not just an error relegated to refineries in the prior study, but the other two energy infrastructure variables that are also included in the Thatcher analysis as well. This study avoids both of these problems by using individual measures of capacity for each and every infrastructure type in each and every coastal location.

Each set of variables included in the CIVI (physical, socio-economic, infrastructure) is included as a map layer in a GIS with the spatial extent of the critical energy infrastructure variables being defined by the census blocks of the 20 coastal parishes. ArcGIS 10.2 software (Environmental Systems Research Institute; Redlands, CA, USA) was used for all geospatial data processing. Because the physical, socio-economic and infrastructure variables are derived using different measurement scales, each variable is standardized in order to facilitate comparability and aggregation. The standardization approach for each set of variables is discussed in greater detail in Section 3.4. Each of the variables included in the final CIVI are combined using linear aggregation, defined as the sum of standardized variables, resulting in a single CIVI value for each census block and parish-level aggregates. No weights were applied to any variable or standardized series.

The data layers and sources for all three components of the CIVI are provided in Table 2 and the following subsections discuss each individual component in greater detail.

Table 2. Data layers and sources for infrastructure, physical and socio-economic variables included in the Coastal Infrastructure Vulnerability Index (CIVI) for coastal Louisiana.

Layer	Source
Physical Variables	
Regional Elevation	Coastal Relief Model (CRM), National Oceanic and Atmospheric Administration (NOAA)
Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Storm Surge	NOAA SLOSH model for the New Orleans basin
Vegetation Types	U.S. Geological Survey
Land Loss Areas	U.S. Geological Survey
Socio-Economic Variables	
Commercial Buildings	FEMA HAZUS Multi-hazard loss estimation methodology version 2.2, 2015
Population Density	U.S. Census Bureau
Energy Infrastructure Variables	
Natural Gas Processing Plants	U.S. Energy Information Administration (EIA-757, Natural Gas Processing Plant Survey)
Petrochemical Facilities	Manufacturing and Industrial Plant Database, IHS and Center for Energy Studies, Louisiana State University
Natural Gas Storage	Natural Gas Underground Storage facilities map layer from EIA (EIA-191, 2014)
Refineries	Petroleum refinery map layer; EIA-820 refinery capacity report (2015)
Electric Generators	Form EIA-860 detailed data (2013)
Pipelines	Center for Energy Studies, Louisiana State University (LSU)
Ports	United States Army Corps of Engineers (USACE) Navigation Data Center
LNG Plants	EIA, Federal Energy Regulatory Commission, and U.S. DOT, 2013

3.1. Physical CIVI Variables

The physical variables included in the CIVI reflect a number of dynamic coastal factors that define both past and future trends of the region's physical characteristics. The variables included are: (1) historical land loss (1932 and 2010); (2) percent area under marsh or swamp or open water; (3) mean regional elevation; and (4) potential storm surge values generated using the SLOSH models from NOAA.

3.1.1. Historical Land Loss

Historical land loss in coastal Louisiana for the period 1932–2010 is derived from the Louisiana Department of Natural Resources. Percent land loss per each census block is calculated by spatially intersecting these blocks with land loss areas.

3.1.2. Land Cover and Vegetation Types

Vegetation data is obtained for the year 2013 from the digital data compiled by United States Geological Survey (USGS), Louisiana State University (LSU) and from Louisiana Department of Wildlife and Fisheries. Vegetation layers were intersected with census block layers to determine the percentage of marsh, swamp or open water present in each census block. No weighting scheme is applied to the vegetation types and the proportion of census block classified as one of the marsh or swamp vegetation types is used in determining their relative vulnerability.

3.1.3. Regional Elevation

Regional elevation on a census block basis was calculated from 30-m resolution NOAA National Geophyiscal Data Center's (NGDC) 3 arc-second U.S. CRM (2015). Average elevation is calculated for each census block using the source raster data.

3.1.4. SLOSH Storm Surge

The Category 3 hurricane storm surge impact zone was developed via the National Hurricane Center's SLOSH model from the NOAA Coastal Services Center for the New Orleans Basin, which covers the entire coastal Louisiana except a small portion of the Cameron parish in Southwest Louisiana bordering Texas. The nearest storm surge value is assigned to these census blocks that are outside the New Orleans Basin area. SLOSH models determine inundation zones for storm surge via a series of hundreds of hypothetical hurricanes in each category with various forward wind speeds, landfall directions, and landfall locations. At the end of each model run, an envelope of water is generated, reflecting the maximum surge height obtained by each grid cell for a given category of storm. The Category 3 SLOSH output represents the potential surge inundation under current sea level conditions.

3.2. Socio-Economic CIVI Variables

The CIVI also includes a limited set of socio-economic factors including localized population estimates and commercial buildings values. The socio-economic variables are intentionally limited in order to minimize what appears to be an inadvertent bias towards over-weighting socio-economic considerations in the prior literature. For instance, some of the prior literature in the CEVI area includes a wide range of socio-economic variables including population, residential housing density, per capita income, income, and a host of other variables. The problem with expanding these socio-economic variables is that they are highly correlated and, in effect, reflect measurements of the same characteristics, particularly from a dynamic perspective. A linear aggregation of such information will only serve to over-weight the socio-economic component without providing any new, incremental information. Only those socio-economic variables that are estimated to provide meaningful incremental information, through the use of correlation analysis, are included in the final CIVI.

3.2.1. Population Density

Human population density is estimated from block-level population data for the year 2010, which is the finest-scale demographic data available from the U.S. Census Bureau.

3.2.2. Commercial Buildings

Commercial building data is obtained from the HAZUS database developed by the U.S. Federal Emergency Management Agency (FEMA). Replacement values are calculated at the census block level for typical commercial buildings and are not unique or specific to a particular commercial building or building type.

3.3. Critical Energy and Other Infrastructure Layers

Critical infrastructure is defined as "those physical and cyber-based systems essential to the minimum operations of the economy and government. They include, but are not limited to, telecommunications, energy, banking and finance, transportation, water systems, and emergency services, both governmental and private" [23]. This article only focuses on facilities related to oil and gas industry as the critical infrastructure to demonstrate index-based vulnerability assessment. These critical facilities transform a raw energy resource into useable forms, and their geographic configuration can influence the distribution and local severity of impacts associated with events that strike a single region—such as the hurricanes Katrina and Rita.

The critical energy infrastructure variables utilized in the CIVI are relatively comprehensive in coverage and include: (1) the aggregate pipeline capabilities per square mile (total pipe diameter times line segment length); (2) LNG import and export terminals; (3) electric generation facilities; (4) natural gas processing plants; (5) natural gas storage facilities; (6) refineries; (7) petrochemical plants; and (8) ports/service bases. The location for each type of infrastructure, on a unit or observation-specific basis, is identified for each coastal parish and census block. Again, each individual unique infrastructure unit, and its associated capacity, is identified in this research such as the individual pipeline segment, individual refinery, individual gas processing station, *etc.*

The impact of any individual infrastructure type or unit, was assumed to not be limited to just its specific point location. Most all energy infrastructure along the GOM has impacts that stretch a broad geographic area. Employees often commute long distances to work at particular plants or refineries, supply-chain relationships with vendors and subcontractors often span a broad geographic area, and there are a variety of other commercial and institutional relationships that can expand the definition of that infrastructure's relevant "community". Thus, the spatial "reach" of each critical energy infrastructure unit was estimated by the use of a kernel density surface using a radius of 50 km and a cell size of 500 m^2. These cells were then aggregated and averaged across each census block. If a census block is smaller than the cell size, the nearest cell value is assigned to the census block.

3.3.1. Oil and Gas Pipeline Volume

All active pipelines are intersected with the census block layers from each coastal parish to determine the aggregate pipeline capabilities per census block area. Pipelines included in the analysis vary by diameter and by segment length. Pipeline diameters can be thought of as an indicator or proxy for the volumetric/throughput capabilities for each line segment (assuming relatively typical level of compression for that pipe diameter type). Pipeline segments range from 1 inch to 48 inches in diameter. A cumulative pipeline capability measure for each census block c_j is given by Equation (1).

$$c_j = \sum_{i=1}^{n} \pi r^2{}_i l_i \tag{1}$$

where r_i is the radius and l_i the length of pipeline segment i.

3.3.2. Crude Oil Refineries

Data on crude oil refinery locations and their individual distillation capacities is obtained from the U.S. Department of Energy, Energy Information Administration (EIA). There are 19 operating refineries in the state of Louisiana, three of which are located outside the study area. Refining capacity as measured in thousand barrels of distillation capacity per day (MBbls/d).

3.3.3. Electric Generation Facilities

A list of electric generator facilities, along with their nameplate capacity as measured in megawatts (MW), is obtained from the Form EIA-860 data at the generator-level for each in-service generator greater than 1 MW.

3.3.4. Petrochemical Facilities

Petrochemical layer is created using the shapefile that is created as part of an earlier work at the Center for Energy Studies and original data from the Manufacturing and Industrial Plant Database published by IHS Energy. Since petrochemical plants are used to manufacture a wide range of products, and their capacity may not equate across multiple plant types, only the spatial distribution of these facilities is used in the analysis.

3.3.5. Natural Gas Processing Facilities

Natural gas processing facility data is also compiled from the EIA Natural Gas Processing Plant Survey (Form EIA-757) reported in terms of processing facility capacity, as measured in billion cubic feet per day (Bcf/d).

3.3.6. LNG Terminals

LNG import and export terminal data is obtained from the data compiled by EIA, Federal Energy Regulatory Commission (FERC), and U.S. Dept. of Transportation (USDOT) and is reported in terms of maximum throughput capacity, as measured in billion cubic feet per day (Bcf/d).

3.3.7. Natural Gas Storage Facilities

Natural gas storage facility data is obtained from the EIA and reported in the EIA Monthly Underground Gas Storage Report (Form EIA-191). Capacity information for these facilities is reported in terms of billion cubic feet (Bcf) of storage capabilities.

3.3.8. Port Facilities

Port facility data is obtained from the United States Army Corps of Engineers' Navigation Data Center. Total capacity is measured as total maximum freight tonnage that can be handled by each individual port.

3.4. Data Standardization

Table 2 highlights the fact that the data utilized to develop the CIVI comes from a variety of sources and is measured in differing forms of capacity (stock and flow as well as liquid, weight, and gas). Each of the variables, therefore, are assigned a standardized score within its own infrastructure type and then summed in order to develop (1) an aggregate measure for each component of the CIVI (*i.e.*, physical, socio-economic, infrastructure) and (2) an overall composite CIVI measure.

Each census block for every variable is assigned a risk score ranging from 1 to 5 in the order of increasing vulnerability based on the variable mean and standard deviation (SD). A value that is less than 1.5 SD below the mean is given a score of 1; a value between 1.5 and 0.5 SD below the mean is given a score of 2. Likewise, values ranging between >-0.5 SD and $\leqslant 0.5$ SD from the mean is scored 3; 0.5 SD to 1.5 SD above the mean is 4, and; greater than 1.5 SD from the mean is scored 5. The infrastructure sub-index is calculated using the simple mean of the standardized kernel density values of the seven energy infrastructure variables as well as pipeline volume density given by Equation (2).

$$((a+b+c+d+e+f+g+h)/8) \tag{2}$$

where a = kernel density of electric generators; b = kernel density of natural gas storage plants; c = kernel density of natural gas processing facilities; d = kernel density of liquefied natural gas plants; e = kernel density of refineries; f = kernel density of petrochemical plants; g = kernel density of ports; and, h = pipeline volume/mi^2.

Using the same criteria as above, each census block is assigned a risk value ranging from 1 to 5 for both physical and socioeconomic variables. Physical sub-index is calculated using the formula given by Equation (3).

$$((a+b+c+d)/4) \tag{3}$$

where a = mean regional elevation; b = SLOSH storm surge; c = historical land loss; and, d = vegetation type.

Likewise, socioeconomic sub-index is calculated from the average of population density and commercial building values. These variables provide insight into locating areas of relatively greater potential impact from disaster events within coastal Louisiana. For calculating the composite CIVI, the average of the above 14 energy, physical and socioeconomic variables is used. For calculating parish-level vulnerability, an average of the CIVI values based on the number of census blocks that fall under each parish are used for both sub-index and composite CIVI. It may also be noted that the coastal zone boundary encompasses 20 coastal parishes of Louisiana, not all parishes are included in the CZB in their entirety. Infrastructure sub-index for each census block is calculated from the average of the eight variable scores.

4. Results and Discussion

Figure 4 is comprised of four different panels. Figure 4A (Panel A) examines the energy infrastructure component of the CIVI alone. The chart shows the highest concentration of energy infrastructure vulnerability to be along the Mississippi River (between Baton Rouge and New Orleans) and in the southwestern region of Louisiana (the Lake Charles metropolitan area). This should come as no surprise given that the concentration of the largest types of energy infrastructure in Louisiana (*i.e.*, refineries, petrochemical facilities and power plants) are located in this area of the state. Interestingly, the results of this individual component of the CIVI suggests that energy infrastructure vulnerabilities are likely not directly along the coastal areas of Louisiana, but instead are in the low-lying areas along the river corridor and adjacent to the coast. This method is effective in that it highlights areas of coastal Louisiana where the impacts of energy disruption may be the greatest in the immediate aftermath of a hurricane event.

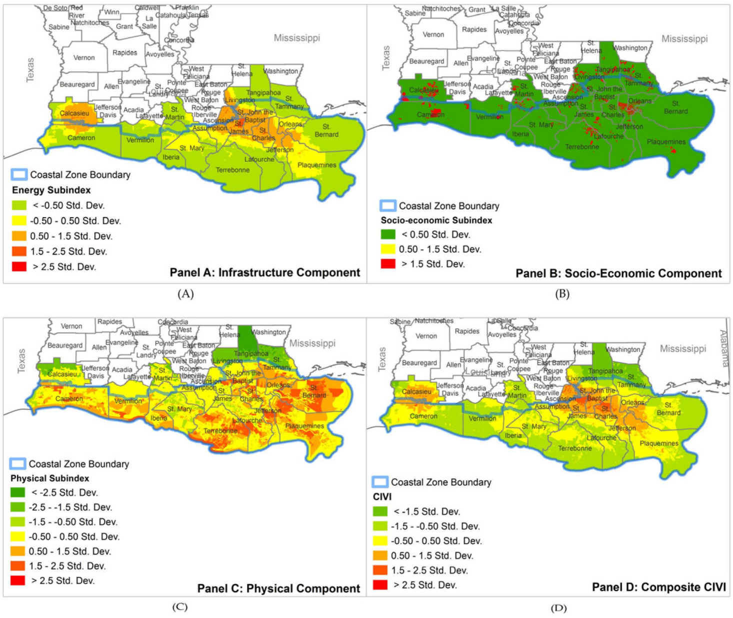


Figure 4. Louisiana-based CIVI. Results are categorized in terms of standard deviations from the mean component score value across all census blocks. Higher values represent higher infrastructure vulnerability measures whereas lower values represent lower infrastructure vulnerability measures. (**A**) Infrastructure component; (**B**) Socio-economic component; (**C**) Physical component; (**D**) Composite CIVI.

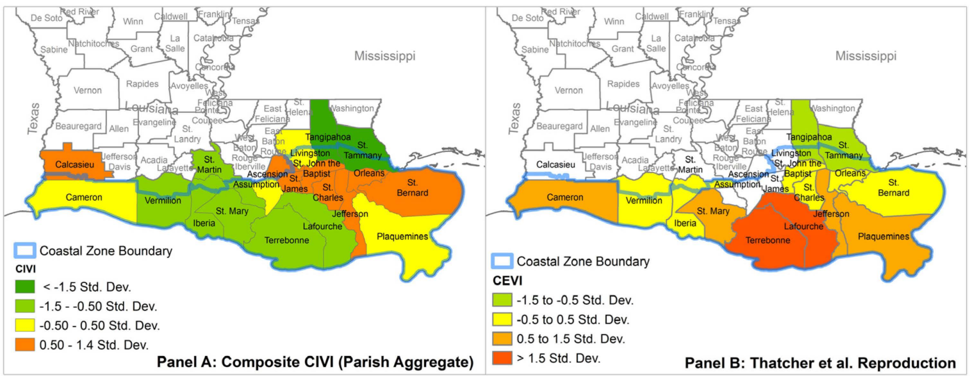
Figure 4B (Panel B) provides the socio-economic component of the CIVI which is driven primarily by population and commercial building structures. The highest values of the index are located primarily in the larger urban areas of the state. The socio-economic component of the index differs from the infrastructure component since many of the larger concentrations of energy infrastructure are located in more sparsely populated areas of the state. The one exception to this result is associated with the southwestern part of the state (Lake Charles) which is estimated to have relatively high infrastructure and socio-economic vulnerability indices.

Figure 4C (Panel C) also provides the results from the physical component of the CIVI. This component shows the very (physical) vulnerable areas of the state are primarily located directly in coastal areas particularly in the central region of coastal Louisiana. The southeastern corner of coastal Louisiana also shows very high physical vulnerabilities, as seen in the aftermath of Hurricane Katrina in 2005, when these areas were inundated by storm surge and flooding. Physical vulnerabilities are not relegated to those areas along the GOM coast alone but also include those communities located along the Mississippi River and the backside of Lake Pontchartrain and Lake Maurepas.

Figure 4D (Panel D) provides the composite, or aggregate estimated CIVI for Louisiana that is the linear combination of the three sub-component indices discussed earlier. One of the highest areas of composite vulnerability, as measured by the CIVI, is in the Lake Charles area. This is an area, as shown earlier, that has very high energy infrastructure vulnerabilities, high socio-economic vulnerabilities, and relatively high physical vulnerabilities.

The CIVI presented in Figure 4 (Panel D) also shows that the central area along the River corridor between Baton Rouge and New Orleans are exceptionally vulnerable coastal areas. The CIVI estimates very high vulnerability values for this area given its (a) high concentrations of very large energy infrastructure and (b) very high physical vulnerabilities. The results of the CIVI show that the combined physical, socio-economic and infrastructure characteristics of this region makes it a very vulnerable coastal area. Understandably, the socio-economic component of the CIVI is less variable compared to the physical and infrastructure components, both showing a greater degree of variability.

The integration of these parameters makes this study much more comprehensive. This is reflected in the significant difference in the results between this study (Figure 4) and the Thatcher *et al.* [19] CEVI study that found (a) relatively high coastal vulnerabilities in the central coastal areas near Terrebonne Bay (Port Fourchon) and (b) relatively low vulnerabilities along the Mississippi River corridor. The CIVI values presented here shows that, while the Port Fourchon area does have relatively significant physical vulnerabilities, its energy infrastructure and socio-economic vulnerabilities are relatively low. A simple examination of Figure 3 above confirms this finding. While Terrebonne and Lafourche parishes have relatively high concentration of pipelines (Panel B) and ports (Panel H), those are the only types of energy infrastructure in that area. A comparison of the current CIVI approach to the CEVI, aggregated to the parish level, is provided in Figure 5.



(A) (B)

Figure 5. Comparison of CIVI results to the CEVI results of Thatcher *et al.* [19] (Parish level aggregation). (**A**) Composite CIVI (Parish aggregation); (**B**) Thatcher *et al.* reproduction.

However, it may be noted that because of the interdependent nature of this critical energy infrastructure across the region, a facility determined to be vulnerable from one sector may have cascading effects on other dependent facilities from the same or other sectors. Hence, although the initial assessment of vulnerability and CIVI index may highlight certain portions of the region as being more vulnerable than others, interdependency of these variables make the system complex, and thus ascertaining the effects of, say, a hurricane or other natural disaster is more complicated than identifying these regions. In this paper, although Lafourche Parish is determined to be one of the less vulnerable areas because of its limited density of critical infrastructure, it may still indirectly affect other areas that are dependent on facilities located in that parish. Several different models were studied in past research dealing with interdependent infrastructure [24–26]; however, most studies were based on a single non-interacting infrastructure type. A much more complex network framework is needed to understand the interdependencies in the critical energy infrastructure locations, and any further discussion of this framework is outside the scope of this paper.

5. Conclusions

Climate change is thought to likely impact coastal communities either through (1) sea level rise or (2) increased storm surges created by an increase in the frequency and intensity of tropical activity [27]. Even without these ominous threats, many coastal areas, like Louisiana, continue to face a host of coastal challenges, like coastal erosion and subsidence, which will defy the people, business and industry operating in the coastal zone. These threats will also expose a set of critical energy infrastructure that has been, and continues to be, responsible for a large part of the U.S. energy production, storage, transportation, and processing/refining. A compromised infrastructure in turn could result in a range of undesirable ancillary affects.

Locations like the coastal areas of the GOM, including Louisiana, will likely need additional coastal vulnerability tools that explicitly include such considerations. This study provides an approach for developing such tools through the use of a CIVI. Care must be given, however, in developing such tools to ensure that the correct scope of the critical infrastructure under consideration is included, and that the methods and measures by which these infrastructure considerations are included in the index number calculation are appropriate and meaningful.

Past research has shown that future wetland loss will cost Louisiana much more than historical wetland because wetlands have provided a buffer against hurricane and storm events, and the cost of wetland loss increases sharply as the wetland buffer becomes smaller [28]. A further assessment of the dynamics as well as the economic impact of both natural and human systems is warranted for understanding the underlying resilience mechanisms in the face of future storms and sea level rise.

The implementation of the Louisiana Coastal Master Plan is expected to decrease potential damages from storm surge, and realizing its plans is projected to result in no net loss of land after 20 years and an annual net gain of land after 30 years [29]. This Master Plan includes an array of projects for protecting and restoring the fragile ecosystem through barrier island restoration and sediment diversion, to name a few. Correspondingly, the existing knowledge of future climate change and its implications for the energy sector generally captures the relevant hazards and their implications, but equally important is the adaptive responses that can be implemented by the energy industry.

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