Functional post-disaster damage assessment in urban setting with remote sensing

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ABSTRACT

Functions in the urban setting had already been extensively studied in several research fields, such as urban planning and social sciences. As demonstrated in this research, there were distinct definitions for urban functions depending on the author and aim of the research. Post-disaster functional damage, however, had not been studied in depth, allowing a gap of knowledge between disciplines.

Therefore, the primary aim of this research was to fill the knowledge gap, contributing with a broad analysis of post-disaster functional damage. A comprehensive conceptual framework was developed to provide guidance to future studies related to functional damage. Also, a list of proxies was established to explore the proxies that could be used to as indicators to assess functional damage through remote sensing. Some of these proxies were assessed in more depth through a case study.

The study case selected for this research was the flooding caused in the Greater New Orleans by the hurricane Katrina, 2005. The assessed area consisted of three polder: Central polder, East Orleans polder and St. Bernard polder. This disaster had a major impact in various sectors of the city and it was followed by numerous studies in different research field. In order to assess the functional damage caused in the road network, the number of connected nodes was considered before and after the event for each polder. This enabled an overview of the disruption in accessibility within the polders. However, as the network layout was characterized by grade-separated highways, it was seen that possibily not all the nodes within the flood extent were blocked by water. Three sections of the Interstate highway (I-10) were considered as examples to analyze some of the proxies, such as the proxy of an observable cluster of cars that could indicate that the highway is blocked.

The facilities selected for a further analysis were the acute care hospitals in the area. Their accessibility was related to three main flood variables: flood presence, duration, and depth. These three variables were obtained in four different dates following the disaster. The proxy of presence/absence of vehicles was analyzed in the Tulane Hospital's parking lot and also in the adjacent streets in eight images, three of them before the disaster. This proxy was assessed as an indicator of functional damage to Tulane Hospital.

This thesis demonstrates that there is a promising path to be followed toward assessing post-disaster functional damage utilizing remote sensing data. It is shown that currently, remote sensing data could be used in combination with other data sources. Thus, this study can be used as a base to be built upon and applied toward more research in the post-disaster functional damage field.

Keywords: post-disaster functional damage, remote sensing, proxies, Katrina.

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1. INTRODUCTION

1.1. Justification

Functional networks are essential elements within urban settings, as they enable people to freely move around a city for goods and services (Galderisi, 2010). The study of cities has been the primary focus of different researches, such as in urban planning and social sciences field, which have already identified the importance of spatial elements to facilitate the characterization of urban and suburban systems (Cowen & Jensen, 1998). In addition, architects have also dedicated studies into analyzing the urban form and the functioning of the built environment (Evans, 2008; Knox, 2010). Oliveira (2016) has indicated the intrinsic relationship between the urban form and its physical attributes, demonstrating how important the built environment is to the integration and functionality of a city.

As the urban setting is a complex system of interdependencies, its functions can be severely disrupted when a disaster strikes. It can cause severe damage even beyond the physical environment and impact the system as a whole (Vespignani, 2010). Damage is defined as the harm inflicted on a community or its assets and is not restricted to the physical environment (Galderisi & Ceudech, 2013). Also, it can reflect on the partial or complete interruption of services, directly disturbing functions within a system. Galderisi and Ceudech (2013) suggested that the structures' physical and functional characteristics can also have an effect on the disaster aftermath, as their damage can reach beyond the city's boundaries.

The consequences to a disaster-stricken metropolitan area can be considerably more complex than in nonurban regions, due to the concentration of people and interconnectivity of sectors (Menoni, 2001). Some worldwide known disasters have shown the vulnerability present in an interconnected system. The Great Hanshin-Awaji (Kobe) earthquake that hit Japan in 1995, exemplifies this. The earthquake took almost 6,500 lives and severely damaged infrastructures, such as buildings, hospitals and roads, including the maritime Port of Kobe (Chang, 2000; United Nations, 1995). There was a wide-spread damage, causing great difficulty for people to access different sectors in the city and critical infrastructures, such as hospitals (Ukai, 1997). The author also indicated that the physical damage was only one of the contributors to the loss of efficiency on the transportation network system. Obstructed roads caused by heavy traffic congestions were also partly responsible for the inefficient transport of patients. Medical staff was also reduced, as the majority lost their means of transport (Ukai, 1997). This event is a significant lesson of how much the damage to the built environment can influence the functionality of critical infrastructures and sectors of a city directly.

Although physical damage has been the main focus of post-disaster research assessment, not much attention has been given to the assessment of functional damage. Some authors have already identified the importance of the link between the infrastructural damage and its (damaged) functionality within a system (Bono & Gutierrez, 2011; Galderisi & Ceudech, 2013; Menoni et al., 2016). However the multiple facets of functional damage assessment make it a complex issue to be addressed. Therefore, this subject has not been extensively studied yet. As functions are intrinsically related to physical attributes, there is the potential of Remote Sensing (RS) to provide further understanding of how the functionality of an area is affected by a disaster.

Joyce et al. (2009) reviewed the multiple aspects where remote sensing can help filling information gaps during all phases of the disaster management cycle. Images have established their value, as they provide quick information with the coverage of vast areas that would otherwise be unreachable. Essentially, all types

of sensor and platforms have been used for many decades to identify, characterize, and quantify structural damage (Kerle, 2015).

Making use of integrating geospatial technologies, Blaschke et al. (2011) developed a comprehensive overview of technologies and techniques that can be used to understand urban systems using remote sensing. The authors also mentioned that although remote sensing can be considered as an essential source to mapping urban systems, used alone it is not sufficient and more data sources might be required. The study developed by Aubrecht et al. (2009) utilized several technologies available to characterize the urban land use and the correspondent sectors. Integrating RS, Geographical Information Systems (GIS) and socioeconomic data resulted in a high accurate model of the urban land use functions. Recently, Zhou et al. (2016) analysed spatial patterns under the context of urban expansion. They quantified the expansion dividing the city into rings in order to analyse the patterns of four different categories, commercial, residential, industrial land and public service.

However, to assess the damage caused to functions, or *abnormal* circumstances, it is necessary first to determine what is considered *normal* to each particular urban setting. Different disciplines have already explored this field. For example, in 1970, Goddard identified the city cabs movement patterns, correlating them to the location of activities and services in London. Over forty years later, a similar study was carried out by Manley (2014), also tracking the flow of minicabs within the road network. The author not only focused on the origin-destination flow but also on the route choices in order to correlate them to London's sectorial functions. Manley showed that monitoring the commonly used road networks can indicate regions that are similar in functionalities. This demonstrates interdependencies that could serve as indicators to shared functional relations. Zhou et al. (2015) also showed that the use of transportation network could act as an indicator for patterns. They analysed intersection nodes and related them to network locations that are critical to functions in Wuhan, China.

Galderisi and Ceudech (2010) developed an important research regarding functional damage assessment. The loss of efficiency of different sectors of Naples urban system after the earthquake in 1980 was the main scope of their research. They measured the reduction in efficiency in the health care system by evaluating the number of injured people, the hospitals capacity and their accessibility, for instance. Also, land use has been widely used to characterize functionalities. In 1959, Guttenberg had already understood the importance of relating the land use with the activities performed. Over a decade later, Simonsen (1974) also focused on the patterns of daily activities, using a Danish town as a study case. Although both studies previously mentioned did not utilize remote sensing as an assessment tool, they represent some of the precursor developments in the area.

Even though there have been advances in characterizing urban functions, analyses assessing the level of inefficiency that urban systems can display after a disaster are scarce. Equally important are the studies addressing the potential vulnerability of certain functions in a system (e.g. Cirianni et al., 2012; Massabò et al., 2013; Taubenböck, Roth, & Dech, 2006). The scope of this research falls within the response phase of the disaster management cycle, i.e. when the damage and needs assessments are carried out (Figure 1). The following phase of the cycle, recovery, can also benefit greatly from a functional damage assessment. Here, it can be implemented towards both an effective and efficient recovery, giving priority to areas that were vital to the systems' functionality prior to the disaster.



Figure 1. The disaster management cycle, emphasizing the response phase, during which the damage assessment is carried out. Adapted from Faculty of Geo-Information and Earth Observation - ITC (2015).

The link between the physical damage and the disruption of related functions is apparent and frequent (Galderisi & Ceudech, 2013). For instance, the number of casualties can increase, and lasting disruptions in the economy can be induced when critical road networks fail to perform their function due to physical damages (Galderisi, 2010). As a result, the functional disturbance and its link to physical damage should not be overlooked.

Measuring functional damage can be directly linked to the assessment of the physical damage (Galderisi & Ceudech, 2013). Also to be considered is the level of efficiency that was being achieved before the disaster. The efficiency is related to the characteristics of each studied element.

The social impact to affected communities is also relevant. However, it falls outside the scope of this study. This research focuses on functional damage assessment, evaluating it at three different levels. At a first level, a comprehensive analysis of post-disaster functional damage, including types and characteristics is presented. Then, functional damage is examined in more detail, concentrating on how it can be detected and assessed through proxies using remote sensing. And finally, some of the previously indicated proxies are tested in order to assess the functional damage to an urban setting.

1.2. Research problem

There have been extensive studies in the social science and urban planning fields using remote sensing to characterize normal activities through proxies, such as using vehicles' routes to connect sectors in the city (Manley, 2014) or the buildings' characteristics (Aubrecht et al., 2009). Yet, very few have attempted to assess the inefficiency of a system up to the same level during post-disaster circumstances.

After a disaster event, there is a high demand for information, along with pressure from policy makers and non-governmental agencies, to understand the extent of the damage. However, the focus of post-disaster damage assessment has been given extensive attention to assessing structural damage and partially neglecting functional ones (Galderisi & Ceudech, 2013). As physical damage is directly linked to the corresponding functionality, it is essential that the disrupted functions are also assessed to the same level, given their importance.

Therefore, this research intends to fill the knowledge gap that persists among disciplines regarding postdisaster urban functional damage. A comprehensive understanding of the issue is presented, introducing the main concepts and how they are linked. Moving towards a deeper analysis, functional damage characteristics and correlated proxies are analysed in more detail. Along with the proxies, forms of assessment are discussed and the post-disaster inefficiency of a city's sector is addressed. The premise is that through recognizing the pre-disaster level of functionality as a reference point, it is possible to define what is non-functioning, or inefficient in comparison.

1.3. Objectives and research questions

1.3.1. General objective

To characterize the functionality of elements in the urban setting scenario under normal circumstances by utilizing proxies derived from remote sensing, for the purpose of identifying disrupted or non-functions under post-disaster circumstances.

1.3.2. Specific objectives and research questions

- To identify and characterize different types of damage that can occur.
 - Are there different types of functional damage?
 - Can they be identified and characterized?
- To develop a comprehensive conceptual framework of functional damage.
 - How to translate potential and observable indicators of functionality disruption into a comprehensive conceptual framework, so that the framework can be repeated?
- To develop a list of potential proxies that can identify and characterize functional damage using remote sensing.
 - Is the absence of normal functions sufficient to detect damage?
 - 0 Which indicators can be used to identify functional damage?
- To evaluate if selected potential proxies can be used to identify and characterize post-disaster functional damage through remote sensing.
 - o Are more data needed to assess functional damage, beyond RS data?

1.4. Thesis outline

This research is divided into seven chapters. A concise outline explaining the content of each chapter is given below.

Chapter 1

The research context and motivation for this research is introduced in the first chapter. Section 1.3 presents the research objectives and questions.

Chapter 2

The second chapter shows the conceptualization regarding post-disaster functional damage and related concepts. The focus is given to the overall understanding of functions under normal circumstances and under a post-disaster scenario. Accessibility and the related concepts are also presented in this chapter. The concept of the use of proxies is introduced and illustrated through literature. Section 2.5 shows and describes the conceptual framework regarding functional and systemic damage that was developed during this research. The literature found regarding the functional post-disaster assessment that is carried out in the field is explained in section 2.6. This chapter addresses the following research objectives based on information obtained through the analysis of the relevant literature: to identify and characterize different

types of damage that can occur; to develop a comprehensive conceptual framework of functional damage and to develop a list of potential proxies that can identify and characterize functional damage using remote sensing.

Chapter 3

This chapter illustrates the study case: the subsequent flooding in Greater New Orleans after the hurricane Katrina in 2005. A description of the study area and a brief overview of the disaster is illustrated. Focus is given to the acute care hospitals and corresponding connected nodes located in the study area.

Chapter 4

Chapter four describes the methodology applied to assess the selected proxies: the connected nodes in the road network in relation to the flood extent, depth, and duration for each polder; the connected nodes in the hospitals' surrounding area also in relation to the flood extent, depth and, duration; the road disrupted by the presence of water using remote sensing imagery and finally, the presence and absence of cars in the parking lot of Tulane Hospital and adjacent streets.

Chapter 5

This chapter illustrates and analyses the results obtained through the applied methodology for each of the proxies assessed. This chapter also addresses the following research objective: if potential proxies can be used to identify and characterize post-disaster functional damage.

Chapter 6

A comprehensive discussion is presented in this chapter, including a critical analysis of the data used, results obtained, and limitations. The flood depth surrounding the acute care hospitals is also discussed. Furthermore, an overview of network analysis regarding functional damage is presented in section 6.2. Section 6.3 draws a link between vulnerability, functional damage, and recovery.

Chapter 7

Chapter seven summarizes the main conclusion and findings during this research. It also elaborates recommendations for future work.

2. UNDERSTANDING POST-DISASTER FUNCTIONAL DAMAGE IN URBAN SPACE

Although physical damage has been extensively studied, functional damage has not been deeply explored yet. The analysis of different study domains, such as urban planning and disaster management, is crucial to conceptualize how damage to functions is perceived and what this actually comprises. This chapter aims not only to demonstrate how the concepts of functions under normal conditions and damage are correlated to post-disaster functional damage but also to show a comprehensive analysis of post-disaster functional damage is examined in more detail, concentrating on how it can be potentially detected through proxies. For this, section 2.1 illustrates the relation between the urban system and functions, including different authors' definitions of functions. The following section, 2.2, demonstrates the difference between functional and systemic damage, while 2.3 presents a central key to a functional urban system as seen in literature, accessibility. The use of proxies and the conceptual framework developed after analyzing the literature are shown in sections 2.4 and 2.5, respectively. This chapter closes with a summary.

2.1. Urban System and Functions

Urban systems can be separated into different land uses that are commonly connected to correspond land cover. Bare soil, for example, could be representing a dirt road, agricultural field or a recreational area. Essentially, land cover represents the natural aspect of the land, while land use represents how the urban landscape is used (LaGro, 2005). Land use can also be described as representing the land functions that change according to the level of human interaction (Food and Agriculture Organization of the United Nations (FAO), 2009).

As a result, land use can be classified into different levels, and each of them offers different challenges. Guttenberg (1959) generated a comprehensive and detailed classification for the use of land. The author began the classification from the overall development of the land to building type and use, as the building type can present consequences to the use. Analyzing land use in more details, Guttenberg (1959) considered the economic aspects and the main activity characteristics as well, relating traffic volume and area of influence to the activity.

Recent studies have addressed the issue of characterizing the functional aspect of land use, classifying it as landscape functions (e.g. Verburg et al., 2009; Willemen, Verburg, Hein, & van Mensvoort, 2008). Willemen et al. (2008) defined it as "the capacity of a landscape to provide goods and services for society." According to this definition, both land cover and land use not only contribute but also influence the landscape functions in an urban setting, as can be seen in Figure 2.



Figure 2. Interaction between land use, land cover and land functions. Retrieved from Verburg, van de Steeg, Veldkamp, & Willemen (2009).

Development and employment opportunities have led more than half of the world's population to live in urbanized centers (United Nations, 2014). Modern commodities, assets, and critical infrastructures are concentrated in urban environments. As a result, urban settings present a group of layers, with different elements in each, where most interactions take place (Van de Voorde, Jacquet, & Canters, 2011). The infrastructure layer interconnected with the social component fuel the economic aspect of an urban center (Bettencourt & West, 2010). Therefore, urban environments represent a living system, where the existing sectors are not only interconnected by physical attributes, but also interdependent and people can move freely (Blanchard & Volchenkov, 2009).

Although scholars have described functionality and functions in different ways, it appears that to some extent, a functional system refers to its interactions, interconnections, and interdependencies (e.g. Manley, 2014; Shen & Karimi, 2016; Li, Shen, & Hao, 2016). However, it does not always seem to be the case. In contrast, functionality may also refer to the activity or use that a certain physical structure performs when related to a single building activity and land use (e.g. Aubrecht et al., 2009). In this case, interconnections and interdependencies can only be evaluated when assessing more than one single building and its function.

Therefore, land use functions can also represent the use of the land. In contrast, the functional aspect of the land can also correspond to the operational side of it (i.e., if it is in operation), for instance, a physically damaged or inaccessible industry. Although it would still be classified as an industry according to the land use, it may not be in operation (functional). Aubrecht et al. (2009) presented an approach integrating socioeconomic data and spatial tools that resulted in a highly accurate model of the urban land use functions. Although they used highly accurate data, theirs is a good example of integrating several tools to characterize the city's functions.

As demonstrated, the definitions for function can vary per author also depending on the focus of the research. To illustrate the contrasting concepts, Table 1 exemplifies some of the main definitions of 'functions' and 'functional' separated per author, found in literature and cited in this chapter.

Author	Definition
Guttenberg (1959) Function is related to the economic function that a facility perf	
	distinction is made between function and activity.
Willemen et al. (2008)	Similar definition between authors. They characterize based on the relation
Verburg et al. (2009)	between functionality, the land use and the "goods and services" provided.

Table 1. Definitions of 'function' among authors.

Aubrecht et al. (2009)	They characterized the land use as a functional dynamic model, e.g. as the	
	building use: residential, mixed, garage, public use and commercial.	
Manley (2014)	Characterized "functional urban regions", i.e. zones within an area that are	
	interconnected, functioning together.	
Li et al. (2016)	Characterized urban functions according to the land use type, e.g. residentia	
	commercial, among others	

There is also a dynamic component related to functions that are important in urban systems. Some activities are more dynamic, fluctuating throughout the day, such as traffic flow connecting different regions (Manley, 2014). However, some functions are represented in a more static way, such as land use or road networks, taking longer to fluctuate in comparison. It is important to emphasize that functions can also depend on the region's characteristics and the scale that is being assessed (de Groot & Hein, 2007; Wallace & Wallace, 2008). Different element can demonstrate different characteristics before and after an event and both scenarios should be considered. If the element assessed presents seasonal characteristics, for example, that could depend on the region as well, the relevant characteristics should be considered during the assessment.

Bretagnolle, Pumain and Vacchiani-Marcuzzo (2009) demonstrated that the analysis of functional urban systems could be approached from different perspectives: from the micro, meso or macro level. The smallest scale the authors proposed consists of single infrastructures and individual people (micro level) that together form the urban system itself, geographically defined by its boundaries (meso level). When there is an interaction between cities, the "system of cities" is formed, constituting the macro level of analysis (Bretagnolle et al., 2009).

Cities¹ are complex systems that result from interactions and processes can determine and change the shape and purpose of the physical environment (Cavallaro et al., 2014). Therefore, efficient networks are fundamental to guarantee a continuous functional interaction among sectors, (Wallace & Wallace, 2008), which if interrupted might decrease the functionality of all the interconnected links. Although communication, electricity and water supply are also vital lifelines in the system, the transportation network differs due to its accessibility to people, enabling the mobility of goods and services (Cirianni et al., 2012).

2.2. Functional and systemic post-disaster damage

Literature indicates that the United States military has already been assessing functional damage to targets since the World War II (Rauch, 2002). This assessment is performed during the cycle named Battle Damage Assessment (BDA) cycle, formerly known as bomb damage assessment. The BDA cycle is composed of three phases. The physical damage is initially assessed during phase one, while on the second phase, the operational level of the target is determined (i.e., functional damage assessment) (U.S. Air Force, 1998). During the last phase, the information from previous phases is combined in order to assess the target's overall system (Rauch, 2002). In this context, the functional damage assessment is estimated in order to determined how much has the operational level of the target decreased, if existent (U.S. Joint Forces Command, 2004). In addition, part of the military functional damage assessment is estimating the time that the target would take to recover from the effects (U.S. Joint Forces Command, 2004).

In academia, although functions have been used in many studies, literature regarding functional damage is scarce. One of the earliest publications found dates back to 1977, in which Haas, Kates, and Bowden (1977) indicated that the reconstruction phase could benefit greatly if problems regarding functions and areas were recognized soon. Galderisi represents one of the authors that has so far conceptualized it in recent studies (Galderisi, 2010; Galderisi & Ceudech, 2010, 2013). The authors separate indirect damage into functional and systematic (Galderisi & Ceudech, 2013), understanding as functional damage "any loss of efficiency or functioning affecting an element as a consequence of physical damage." However, functional damage does

¹ For this research, cities are considered as complex urban systems.

not always seem to be derived solely from physical damage. Functional damage can also be seen as an abnormal circumstance, as referred to in this document. Additionally, the same authors introduced systemic damage, which indicates a "loss of efficiency or functioning as a result of the damage to other elements" (Galderisi & Ceudech, 2013), i.e. disturbance to other elements due to their interdependencies. This correlated damage was also referred to as a cascading effect by the authors. Galderisi and Ceudech (2013) also characterized functional and systemic damage according to the scale and time they occur. As functional damage is directly related to physical damage, it occurs in the short and immediate term after a disaster, influencing local to urban scale (Galderisi & Ceudech, 2013). Systemic damages then follow functional ones, taking place on a larger scale and often for an extended period, as they involve complexes of interrelated functional damage (Figure 3).



Figure 3. The pyramid presents the type of damage, scale and temporal influence of the event. Retrieved from Galderisi and Ceudech (2013).

The authors indicated that the boundaries between the damage type (physical, functional and systemic) and correlated time and scale are uncertain, as they happen as a consequence of the other damage (i.e., as a domino effect). However, they did not characterize what they considered as a short, medium or long term. In 2010, the same authors considered functional damages as up to the first week after the 1980 earthquake in Naples. Their research followed the premise that functional crises depend on the difference between supply and demand of certain activities and services, such as healthcare, for instance. They characterized it according to newspaper articles from 1980, identifying proxies that could cause inefficiency in services, such as traffic jams and obstruction in roads, as seen in Figure 4.

Pescaroli and Alexander (2016) studied the chain of effects that damaged networks can trigger after a disaster. They also indicated that the level of interdependencies is directly related to the level of damages that it initiates, i.e. the more the interdependencies in a network, the higher will be the collateral damage. In contrast to Galderisi and Ceudech (2013), systemic damage is also perceived as being damage to the overall system, and not only as a cascading effect (Menoni et al., 2016). Throughout the literature, both definitions are perceived as valid, as cascading effects can also damage the urban system. As they are not mutually exclusive, building upon the definition of Galderisi and Ceudech (2013), it is coherent to define systemic damage as any loss of efficiency or functioning of one or more functional elements as a result of the simultaneous damage to other functional elements or as a cascading effect.



Figure 4. Functional damage after the 1980 earthquake in Naples, Italy, as determined by Galderisi and Ceudech (2010). Bottom right graph: the x and y-axes represent the time after the earthquake and the score attribution, respectively. The curve shows the total functional damage (original: *damo funzionale*, free translation).

A significant example of global systematic damage was seen in 2010 with the volcanic eruption of Evjafjallajökull in Iceland, causing an unexpected interruption in the European aviation, which resulted in a worldwide disruption (Pescaroli & Alexander, 2016). Another demonstration the effect of systemic damages, the Tohoku Earthquake in 2011 that resulted in the Fukushima meltdown and an energy crisis in Japan (Pescaroli & Kelman, 2016). Both examples had unique worldwide repercussion, demonstrating the interdependencies of systems. However, systemic damage does not only happen at the global scale, but it can also be seen on a regional scale. Exemplifying it, there is the 1995 Kobe earthquake that damaged not only the structure at Kobe Port but also the roads connecting to it. Even after 20 years, the port has not been able to recover its full operational status (DuPont & Nov, 2015), which could also be attributed to the redistribution of trades to competitor ports, indicating that perhaps even if the port is repaired, there could still be a residual systemic damage. As demonstrated, the systemic damage is very complex to assess, as all related interconnections should be considered. These studies mainly analyzed the outcome of systemic damages, indicating that systemic damage is the result of numerous functional damages, either through a cascading effect or not, disturbing part of or the whole system. Apparently, there has been a growing interest in exploring cascading effects triggered by disaster events, as seen in the studies by Pescaroli and Alexander (2016) and Xie et al. (2014). However, assessing the functional damages that eventually contributes to widespread systemic damage has not been the focus of many types of research.

2.3. Accessibility as Key to a Functional Urban System

Identifying an infrastructure's critical features and how they are interconnected to other elements is one of the main steps for functional damage assessment (U.S. Joint Forces Command, 2004). Reggiani et al. (2015) identified that connectivity plays an important role in creating and maintaining the link between spatially distant points. Along with accessibility, connectivity is also performed by the network system in an urban setting (Reggiani et al., 2015).

According to Geurs and Ritsema van Eck (2001), accessibility can be defined in different ways. Litman (2010), for instance, defines it as the "ability to reach desired goods, services, activities and destinations." However, to choose a proper definition, it is necessary to consider the research purpose (Geurs & Ritsema van Eck, 2001), which enables a more suitable definition. As this study addresses functional damage assessment, it is more appropriate to refer to accessibility as a measurement of the level of efficiency of certain activities, i.e. lack of accessibility can compromise the efficiency of an element in the system.

A few elements integrate accessibility. On one hand, there is the physical component, connecting elements and zones in the urban space through the transportation network infrastructure; on the other hand, the transportation network has a purpose (i.e., its functional component) (Zhou, Y. et al., 2015). As presented in Figure 5, accessibility can also be broken down into four other components: individual, temporal, spatial, and transportation elements (Geurs, 2006; Geurs & Ritsema van Eck, 2001). Figure 5 also shows the relationships between all the components and accessibility, demonstrating direct and indirect interactions. The individual component reflects the social aspect of the area to be studied, including age, gender and income, whereas the temporal element indicates the constraints that the availability of services may impose. During this research, the focus is given to the transportation and spatial components of accessibility, as they respectively represent travel time (distance) and land-use, i.e. the spatial distribution of services.



Figure 5. Components that integrate accessibility and their relationship (Geurs & Ritsema van Eck, 2001).

To link people, goods and services, accessibility and an efficient transportation network are crucial. Therefore, any disruption or physical damage can cause inefficiency to any of the interconnected systems, limiting even basic functional structures, such as hospitals for instance (Bono & Gutierrez, 2011). Bono and Gutierrez (2011) studied the overall accessibility in the city of Port of Prince, Haiti. They evaluated the effects that structural, physical damage had on the roads network system, decreasing the accessibility to different sectors of the city.

During the Kobe earthquake, in 1995, Ukai (1997) reported that the wide-spread damage on the transportation system not only disrupted the access to hospitals by ambulances but also decreased the number of staff members in hospitals, as they also could not access the facilities. Recognizing the importance of the transportation network, several studies were dedicated to understand its vulnerability (Berdica, 2002; Menoni, Pergalani, Boni, & Petrini, 2007) and resilience (Gu, 2015). Furthermore, Mattsson and Jenelius (2015) provided a comprehensive analysis of recent studies regarding vulnerability and

resilience of not only road networks, but also railway transports, among others. Although the studies represent a small portion of the available researches regarding transportation networks, they serve as examples of the focus given to the important role these networks have in the urban accessibility and connectivity.

2.3.1. Network analysis for accessibility

There are several methods to perform road network analysis. This section focuses on studies that assessed accessibility through the analysis of the network, prioritizing post-disaster studies.

Using a hypothetical flood in Maryland as a study case, Sohn (2006) assessed the importance of the highway system prioritizing its links. They quantified the effects on the network through two main elements, traffic flow and distance. Attributing a score to Maryland's accessibility, they were able to calculate the percentage of loss in access after the flood. Sohn (2006) also indicated that assessing the flood depth would have characterized the level of disruption in accessibility, which was not addressed in the study.

Also studying flood accessibility damages in the transportation network system, Bil et al. (2015) developed a comprehensive review of six major disasters that occurred in the Czech Republic between 1997 and 2010. The authors used a few indicators to calculate and compare the accessibility before and after the events. One of the indicators was each segment's length and correspondent linking nodes. The length of the network was also one of the elements used by Chang and Nojima (2001) to evaluate the transportation system and the accessibility after the Kobe earthquake.

Some studies also used the number of nodes as an indicator of accessibility, as shown in Bono and Gutierrez (2011). They analyzed the city of Port of Prince overall accessibility after the 2010 earthquake. Along the same line, studies have also used accessibility indexes to compare pre and post-disaster scenarios (e.g. Chang & Nojima, 2001; Sohn, 2006).

2.4. The use of proxies

Although there is limited literature using proxies to assess functional post-disaster damage, proxies have been commonly used along with remote sensing analysis. This section aims to characterize some of the proxies that could potentially also be used to assess the functional damage. In addition, this section addresses the research objective to develop a list of potential proxies that can identify and characterize functional damage using remote sensing.

In the military context, after the initial physical damage assessment, the military estimates the degree in which the target's operations have been effected, i.e. to what level the target is still in operation (Rauch, 2002). In order to determine that, they gather not only satellite and aerial imagery but also communication signals and information from a person at the scene (U.S. Air Force, 1998).

Physical proxies obtained through remote sensing are widely used to characterize and assess the urban environment in the civilian context. Cowen and Jensen (1998) and Maktav et al. (2005) described the urban landscape according to its physical attributes, as it is composed of objects with different materials, also showing heterogeneity in their spatial arrangement. The examples of proxies that could potentially indicate functional damage are organized in Table 2 andTable 3. The first table presents a list of proxies for the build-up environment, while the following table shows a list of proxies for social and economic functional damage. The proxies were divided into these three sections to demonstrate toward which category the proxy could be better implemented.

Using physical proxies, Ebert, Kerle, and Stein (2009) assessed urban social vulnerability using high resolution imagery. Some of the physical proxies used included building height and derived number of floors, which was used to characterize commercial development. Combined with detailed land use information, Aubrecht et al. (2009) also used building height as a proxy to calculate volume and estimate

the number of people per building. Building infrastructural damage can be assessed not only by their difference in height and shape pre- and post-disaster but also by texture and spectral signature (Bevington et al., 2015). Texture and spectral signature are one of the proxies that Blaschke et al. (2011) cited in a comprehensive review of current methods to interpret urban landscapes using geospatial techniques. Buildings' shapes and density have also been used to characterize urban recovery (e.g. Costa Vieira, 2014).

The connectivity among regions has also been the theme of study to characterize zones that are interconnected within a city. The study by Manley (2014) tracked the movement of minicabs within the road network in London to assess the connectivity among different regions. It showed that the regions that are used together demonstrated a shared interdependency that could serve as an indicator of a shared functional status. Therefore, for a society to function, it needs interaction. Gao, Liu, Wang, and Ma (2013) evaluated the community patters that were hidden in the geo-located telecommunication network of all phone-interaction in a city in China and compared these with their spatial movement during one week. They explored the spatial interaction patterns between different regions and how they are divided, contextualizing the geographical context behind the boundaries. Both studies are very interesting in the context of characterizing the connecting flow patterns, under daily (normal) circumstances and using it as a proxy to assess functional communities. As roads can be monitored by remote sensing tools under normal circumstances (Gomez, 2002; Schnebele, Tanyu, Cervone, & Waters, 2015), if the flow were physically interrupted due to a disaster event, as Bono and Gutierrez (2011) evaluated after the earthquake in Port of Prince for example, the community would not interact as it normally would, disturbing its functionality.

Bono and Gutierrez (2011) used the difference between the number of nodes connecting roads and their length before and after the disaster. These proxies were utilized to characterize the impact that network transportation structural damage had to the accessibility of Port of Prince. In order to quantify the nodes, they evaluated not only the physical interruptions on the road but also the disruptions close to the road, creating a "debris buffer zone". Kermanshah and Derrible (2016) also used the number of nodes and their links to characterize how the roads network in New York and Chicago would perform under a theoretical scenario of an extreme flood.

Galderisi and Ceudech (2010) studied the possible disruption of urban systems' functionality in Naples after the 1980 earthquake. The research focused on functions in the context of coping capacity and resilience. They followed the premise that a functional crisis depends on the difference between supply and demand of certain activities and services. Firstly, they evaluated the urban system component that was defined as the accessibility of people to emergency collection points. This was assessed by characterizing the size of open public spaces remaining and relating it to their influence area and capacity. The assessment related to healthcare system's efficiency was determined by two elements. One of them was the hospital's accessibility to emergency vehicles that was estimated through traffic jams. Another element was the number of casualties that a hospital could hold. The last component assessed during the study was the efficiency reduction in the residential system. They considered the number of inhabitable buildings in order to estimate the number of homeless people. Some of the proxies described in Table 2 andTable 3 could not be linked directly to an author or research, corresponding to the outcome after analyzing the literature. These proxies are marked with asterisks in the following tables.

Table 2. List of potential proxies that could be used to characterize functional damage in the built-up environment.

Parent proxy	Supporting proxy	Feature	Reference
Built-up environment			
Means of transportation		Public transportation: absolute number and desired route	***

Roads and transportation		Changes in pedestrian access (e.g. sidewalks)	***	
	Presence/absence/ movement of vehicles	Cluster of vehicles on roads (e.g. possible traffic jam)	Galderisi and Ceudech, 2010	
		Traffic flow	Goddard, 1970; Manley, 2014	
		Traffic density	Hinz et al., 2008	
	Change in road network	Number of connecting nodes	Bono &	
		Road blockage	Gutierrez, 2011;	
		Road destruction	Kermanshah and	
		Road obstruction (partial)		
		Road width	Gu, 2015; Wang et al., 2015	
		Road length		
Buildings	Physical characteristics	Building size	Aubrecht et al.,	
		Building height	2009; Costa Vieira, 2014	
		Building shape		
		Building density		
		Presence/absence of vehicles in the infrastructure's premises (e.g. in parking lots)	Rathfon, 2010	
		Heat detection	Costa Vieira, 2014	

Night lights have been widely used as a proxy in researches. Under the economic aspect, studies were developed using the intensity of night lights as a proxy for quality of life (Tsouvala, 2015), wealth (Ahlerup et al. 2016; Deville et al., 2014) and to map economic activity (Doll et al. 2006). Assessing the impact of hurricanes in the Caribbean Islands, Bertinelli and Strobl (2013) combined wind speed models and night lights as proxies. Also identifying affected areas, Gillespie et al. (2014) used night lights combined with household surveys to assess economic changes and recovery. As shown, night lights have been used in several fields of study, but they were seldom used alone. In most studies, they were used in combination with other proxies, such as socioeconomic data, in order to give support to their analysis.

It is important to consider that every sector in the urban system works differently, and consequently present different observable characteristics. A functional maritime port, for example, shows the presence and transit of cargo ships, along with the presence of containers, cranes, and heavy vehicles. Industries that have a chimney in their infrastructure, such as power stations, present observable smoke or water vapour from cooling towers when they are in operation, the same way that residential homes in certain areas emanate heat from the heating system that can be seen in thermal imagery (e.g. Costa Vieira, 2014).

Table 3. List of potential proxies that could be used to characterize economic and social functional damage.

Parent proxy	Supporting proxy	Feature	Reference
Economic			
	City's economic zone	Change in night time light intensity	Gillespie et al., 2014

Economic activity		Change in the accessibility to the city's economic zone	***
	Industries	Physical damage to industrial buildings	***
		Presence/absence of industries' unique feature (e.g. working chimneys)	***
		Presence/absence of heavy vehicles	***
	Port activity	Presence/absence of vessels	***
		Presence/absence of (heavy) vehicles	
Social			
Displaced	Estimate number of	Damage to residences	Feng et al., 2013
people	affected people	Damage to commercial buildings	-
		Casualties	_
		Presence of tent camps	***
		Presence of observable temporary shelters	***

2.5. Conceptual framework

This section aims to illustrate how all concepts related to functional damage are interconnected, as shown in Figure 6. This section also addresses the research objective of developing a comprehensive conceptual framework based upon reflection of the literature regarding this study.

After disaster strikes, the first noticeable effect is related to all physical damage. Physically induced damage can be separated into structural damage, comprising buildings and critical facilities, and environmental damage (Meyer et al., 2013). The environmental aspects that could be directly harmed by physically induced damage are primarily parks, forests and green spaces. The other categories under the environmental section, like the biodiversity, could be indirectly impacted (Van Westen, 2013).

The indirect effects of the disaster event is more difficult to see and evaluate (National Research Council Staff, 1999). Resources and the ecosystem are among the environmental aspects that are indirectly affected. In addition, the social composition of the disaster-stricken zone can also suffer consequences. The social composition can be altered, modifying the social interaction in a community (Meyer et al., 2013). Losses in the economy can also be a direct result of damaged infrastructure that will need repair, which is usually estimated after the disaster and also used to seek for post-disaster relief funds. The event can also have a negative influence in the economical setting, which is sometimes difficult to estimate due to the unknown extent of the loss (Meyer et al., 2013). The decrease in business and trading activities along with a reduction in profits are a few examples that reflect some of the economic issues that an area could suffer from (National Research Council Staff, 1999).

It is also important to consider that the effect of disasters are not scale-limited, nor limited by geographical boundaries. This way, an event can also influence distant areas, sometimes positively increasing the economic growth, but also negatively affecting it. An area outside the disaster-stricken zone could also, to some extent, indirectly suffer the impact from the event (Pescaroli & Alexander, 2016).

According to Galderisi and Ceudech (2010, 2013), the functional damage is not only the result of physically induced damages not only to infrastructures themselves, but is also caused by interdependencies in the system (Menoni et al., 2007). For example, due to a road blockage (physical damage), there may be no access

to an intact facility. This means that there could be a functional damage to the facility as it may not be able to perform to the same level as previously. However, the literature indicates that functional damage is not a result only limited to physical damage. Decrease in population can also be an effect of the disaster, which could generate a decrease in the workforce and consequently a functional damage in the system. For instance, a hospital with reduced staff because of the disaster may not operate to the same standards as before the event (e.g. Ukai, 1997).

Although physical damage is not the only element to considered regarding functional damage, it is still an important element of the system. Physical damage to the water distribution system could influence the performance of industries, for example. The interdependencies in the system should be considered in functional damage, as different elements can influence each other, such as road networks influencing the infrastructure activity and vice-versa (Menoni et al., 2007). Lifelines, like electricity and water systems, could influence the performance of an activity and/or on the road network system.

After a disaster, functional damages could last for a long time, exceeding the response phase. When that is the case, along with the increase of damaged elements, it could lead to systemic damage (Galderisi & Ceudech, 2013). This means that when one or more functional elements from the same sector are damaged, it could lead to a systemic damage in a related sector. Due to the system's interdependencies, it could also lead to disruptions to another sector. As a result, systemic damage can occur on a bigger scale than functional damage (Galderisi, 2010).

2.6. In-situ Post-disaster Functional Damage Assessment

There have not been many guidelines and frameworks found in the literature that analyse the impact of a disaster, considering all the elements that could be indirectly affected. The most relevant analysis found was the Damage and Loss Assessment Methodology (DaLa) developed by the Economic Commission for Latin America and the Caribbean (ECLAC). The DaLa methodology is considered part of the Post-Disaster Needs Assessment (PDNA), which identifies the recovery priorities, assessing not only the physical and economic effects but also the impact in the community involved (The World Bank, 2011).

The DaLa methodology differentiates between disaster loss and damage. Disaster loss is defined by DaLa as the economic flow changes, potentially lasting longer than damage. Disaster damage, on the other hand, takes place directly after or during the event, affecting the physical assets in the area. The DaLa methodology offers a framework that can be used as a tool to analyse the damage and losses caused by the disaster. The main element in this methodology that was found to be different than others is that it analyses the overall indirect losses related to the event, such as the flow of income and services, highlighting the possible effects on the economy (De Groeve, Poljansek, & Ehrlich, 2013).

2.7. Summary

This chapter presented several definitions for functions under normal circumstances. Although functions are defined differently when considered through different aspects, this research focuses on the definition of functional damage. The definition which was found not to be directly derived from the definitions seen for urban functions. For the definition of urban functions, there were no references toward the efficiency, whereas for functional damage, there were. As a starting point of analysis, this research considers the definition of functional damage to be the same as that defined by Galderisi and Ceudech (2013) as follows: "any loss of efficiency or functioning affecting an element as a consequence of physical damage."





3. CASE STUDY: 2005 FLOOD AFTER HURRICANE KATRINA IN GREATER NEW ORLEANS, USA

This chapter describes the study case: the flooding disaster that occurred after hurricane Karina in Greater New Orleans, USA. The first section of the chapter illustrates the area of the study case and all the relevant polders that were used for the assessment of the connecting nodes during this research. The subsequent section briefly presents an overview of the disaster and the impact over the area, including the breaches that occurred in the flood protection.

3.1. Study area

For this research, it was important to select a study case that could fulfil the following criteria:

- 1) Location an urban area that had been hit by a major disaster.
- 2) Information a great volume of multi-disciplinary studies developed after the disaster and potential of data availability.

The study case area is located in the state of Louisiana, southeast of the United States of America (USA). The analysed area is composed by the three main polders, or so-called bowls, two in Orleans Parish² (Central and New Orleans East polder) and one in St. Bernard Parish (St. Bernard polder) (Pistrika & Jonkman, 2010). Figure 7 illustrates the study area and the three polders. These three polders have approximately half of their areas below the sea level and consequently integrate the areas that were most affected by the consequential flooding after hurricane Katrina (Boyd, 2010).



Figure 7. Image of the area of the study case emphasizing the three polders that constitute the study area.

Although the state's capital is Baton Rouge, its largest city is New Orleans, with a population of approximately 485,000 before Katrina, in 2000 (Plyer, 2016). After Katrina's impact, the population was estimated to have decreased to nearly 230,000 (Plyer, 2016). Articles recently published indicated that New Orleans has not yet fully recovered from the impact in 2005 (Fussell, 2015; Li et al., 2016; Ward, Leitner, & Pine, 2010).

3.2. Overview of the the disaster and its impact

Hurricane Katrina passed at the east portion of New Orleans on the 29th of August of 2005 (Fussell, 2015). Prior to landfall, the mayor had declared a state of emergency, requesting for evacuation, which started on the 26th of August (Boyd, 2010). Although the majority of the population evacuated, many remained in their houses or simply did not have the means to leave. The Mercedes-Benz Superdome, a sports venue, was then opened to serve as a last-resort shelter.

Greater New Orleans had a flood protection system in place consisting of levees and floodwalls. The hurricane's passage caused a high storm surge that breached through the flood protection system, inundating nearly 80% of the urban area (Boyd, 2010). There were breaches in several locations along the study area, as illustrated in Figure 8. This figure also shows the breaches in more detail for each location (on the right hand side). The storm surge overtopped the floodwalls and breached the levees along both sides of the Industrial Canal and the Intracoastal Waterway. The flood protection at the London Avenue Canal and 17th Street Canal also failed, flooding the Central polder and the New Orleans East polder. In addition, storm surge coming through the Lake Borgne breached the flood protection around St. Bernard polder, flooding St. Bernard area (Nelson, 2012).



Figure 8. The left image shows the flood protection and the location of the breaches in the study area. On the right, it is shown the correspondent letter for each of the breaches in more detail. Adapted from Kent (2005).

By the time the Greater New Orleans area was flooded, the most common means of communications, such as television and telephone, had gone down (Freudenburg, Gramling, Laska, & Erikson, 2012). Electric power distribution had also been lost, leaving the only designated shelter, the Superdome, in the dark. By the 30th of August, the Superdome was surrounded by water and conditions inside it were then deteriorating. In addition, trucks with supplies did not have access to the city due to the flooding (Freudenburg et al., 2012). People had then occupied the Convention Centre as a shelter, without the government's knowledge. In an effort to contain the water coming in, the U.S. Army Corps of Engineering (USACE) dropped sandbags over the 17th Street Canal, but these were carried off by the water flowing in and the action was unsuccessful (U.S. House of Representatives, 2006). They were only able to keep the waters at bay around the 1st of September. However, it required several more days to repair the pumping system and start pumping the water out. Essentially, after Katrina, the situation was described as chaotic in New Orleans (Arendt & Hess, 2006).

In Orleans parish, the highest flood depth examined by FEMA reached approximately 6 m (Federal Emergency Management Agency, 2006). Thus, the flood extent and depth imposed a barrier for the emergency agencies to fully respond to the disaster as the accessibility to all sectors of the city was problematic (Freudenburg et al., 2012). Some facilities, such as the acute care hospitals that were still open during the disaster, had to evacuate due to the lack of electricity and subsequent fuel for the generators, for example (Arendt & Hess, 2006).

There were discrepancies regarding when the flooding in New Orleans had finished. The Dartmouth Flood Observatory (University of Colorado) listed that the flood had ended on the 19th of September. However, NBC News released a news article on the 2nd of October describing that the pumping in New Orleans was nearly completed. According to the article, there were still isolated portions of flood. In addition, USACE was still pumping the water out from the Lower Ninth Ward, which was reported to be the last area to be completely dry (NBC News, 2005).

4. METHODOLOGY

This chapter illustrates the methodology used to characterize functional damage in Orleans parish after the Hurricane Katrina and subsequent flood in 2005. This section aims to address the following research objectives: to evaluate if selected potential proxies can be used to identify and characterize post-disaster functional damage through remote sensing. This chapter also addresses the methodology used for the third level of the approach of this research, i.e. to assess proxies.

The methodology is separated into two main sections in order to fulfil the aforementioned objectives. As per definition, indication of loss of efficiency to any element of the system could be characterized as functional damage. Considering this, the first part, 4.2, consists of the methodology used to characterize the change in the area's accessibility, analyzing how it was before the disaster as a parameter to be compared with while evaluating after the event. The second part contains the methodology applied to analyse to what extent proxies observed through remote sensing could be used to characterize functional damage. It is important to emphasize the significance of characterizing how the analysed area was before the disaster, as different areas can potentially show different functional characteristics.

Some proxies that could potentially be used to assess functional damage in Orleans parishes are presented in Table 4. The table also shows the questions that the proxies could address as outputs. The proxies that were chosen to be assessed during this study are shown in bold. Although the proxies for economic and social functional damage are included in Table 4, they are considered to be outside the scope of this research.

Proxy	Feature	Potential output			
Built-up environmer	Built-up environment				
Means of transportation	Public transportation: absolute number of vehicles, for example, and desired route	Is the same amount of public transportation able to serve the sectors of the city at the same efficiency as before the disaster? Are the main desired routes being served?			
	Changes in pedestrian access (e.g. sidewalks)	Are there abnormal changes in pedestrians' access to the destination?			
Presence/absence of vehicles	Cluster of vehicles on roads (e.g. possible traffic jam)	Is there an abnormal traffic congestion detected possibly decreasing the efficiency of transportation?			
	Traffic flow	Is there an abnormal change in traffic flow and/or $% \left({{\left {{{\rm{A}}} \right } \right _{\rm{A}}}} \right)$			
	Traffic density	density to a specific sector?			
Change in road network	Number of connected nodes	Were there changes in the road network that could disturb its functionality? Could it			
	Road blockage	disturb accessibility to facilities or services resulting in less efficiency? Have the disaster's characteristics been considered?			
	Road obstruction (partial)				
	Road destruction				
	Road width				
	Road length				
	Building size				

Table 4. List of proxies that could be assessed and the potential output.

Physical characteristics	Building height Building shape Building density	Was the building damaged? Could the building's main functionality be affected by the change in the building's characteristics?
	Presence/absence of vehicles in the studied infrastructure's premises (e.g. in parking lots)	Is there an abnormal change in the presence/absence of cars in the parking lot that could indicate loss or disturbed functionality?
	Heat detection	Are there abnormal changes in detected heat? Changes could characterize a facility that is inefficient or non-operational.
Economic		
City's economic zone	Change in night time light intensity	Are there significant changes in night time light intensity seen in different sectors before and after the event?
	Change in the accessibility to the city's economic zone (e.g. industries)	Was the main accessibility to the city's economic zone disturbed? Is there a possible loss in efficiency?
Industries	Physical damage to commercial buildings	Is there physical damage to commercial buildings? What is the level of damage? Could it still be operational? Could it affect the economy?
	Presence/absence of industries' unique feature (e.g. working chimneys)	E.g. is there an indication of working chimneys, presence/absence of smoke? Was there a significant difference between pre and post disaster?
	Presence/absence of heavy vehicles	Is there presence/absence of heavy vehicles in the industry? Was there a significant difference between pre and post disaster?
Maritime port activity	Presence/absence of vessels and containers	Is there presence/absence of vessels in port? Are there containers and/or indication of containers being moved? Are there vessels sailing through? If applicable, is there enough bridge clearance? Are there significant differences between pre and post disaster?
Social		
Number of affected people	Damage to residences and buildings Casualties Presence of camps and temporary shelters	How many people was affected? Could the number of affected people disturb the local community setting? Has the workforce significantly changed? Could the change in the workforce disturb the economy flow?

4.1. General approach

For this study, proxies in the built-up environment were chosen. The first proxy in the built-up environment is related to the road network. The features used for this analysis is the change in the connecting nodes that are considered as caused by road blockage and partial obstruction during this research. The change in connecting nodes is seen as an indicator of efficiency decrease in the system, which is considered to be functional damage in this study.

In order to explore proxies that are observable through remote sensing, the other proxy selected in the builtup environment is related to the infrastructure's physical characteristics. The feature analysed is the presence/absence of vehicles in the studied infrastructure's premises, e.g. in parking lots. The reason that this proxy was selected is due to the characteristic of the studied area, where the main mean of transportation of the majority of the population is cars (United States Census Bureau, 2000). Also, to analyse this proxy, there was a need to select an infrastructure. For this research, the infrastructure selected was acute care hospitals, for their importance during the response phase and as they do not present a seasonality characteristic.

To analyse the connection between the level of disruption in the accessibility and the functional damage to the acute care hospitals, not only the presence of water was considered, but also and depth and duration of the flood. These three elements of the flooding were important as they could indicate the level of disruption. For example, if there is presence of water, however the water is shallow enabling transitting through, the effect on the facility may be less pronounced than if the water were deep. Analyzing the relation between these three components and the infrastructures' post-disaster functional characteristics, the following question was addressed: what is the relation between the functional damage and the hazards' characteristics?

Also to be considered is that every area is different regarding its functional characteristics and consequently show different promising proxies to observe functional damage. Therefore, in order to assess the damage to certain functions in an area, it is necessary to characterize how the same function was before the disaster, i.e. during 'peacetime'. For this reason, all the analysis during this study were done based on how the elements were presented before the event.

4.2. Road network: indicator of accessibility

The methodology to analyse the accessibility was primarily based on the number of connecting nodes in each polder before and after the disaster. The data utilized to assess the selected remote sensing proxies is also described below.

4.2.1. Data source and pre-processing

The road network data was obtained from the United States Census Bureau's TIGER (Topologically Integrated Geographic Encoding and Referencing) line files. These lines files were created from TIGER's geographic and cartographic databases (United States Census Bureau, 2006). For this study, the road network from 2006 was used. Prior to 2006, the only road network data available had been compiled in 2000. The files used belonged to 2006 second edition, which included files for all U.S. counties, in effect as of 1st of January 2006.

The road network obtained from TIGER files included different feature classes, such as roads, landmarks, physical and non-visible features (legislative boundaries) and pre-processing was needed. As the features were characterized by different Census Feature Class Codes (CFCC), the relevant CFCCs were selected using ArcGIS, as shown in detail in annex 1. Essentially, only features that were related to the road network were considered.

In order to identify if clusters of cars seen in the image could be used as a proxy to indicate loss of efficiency in the road, the flood depth that could cause obstruction and disruption were also considered. Examples of

a cluster of cars and possible obstruction by water on the highway is seen in Figure 9. The height of the highways in the main access points was also analysed in combination, as some of the main highways in Orleans are stacked in height, i.e. above the ground. The flood depth, extent and temporal characteristics were obtained from the study developed by Smith and Rowland (2005). The flood maps are shown in Annex 2. In summary, the authors used satellite imagery and an elevation model to estimate the extent and volume of the flood in New Orleans triggered by Katrina. The study derived the flood extent from Landsat 5, Landsat 7 and SPOT (Satellite pour l'Observation de la Terre) images. These images were obtained in four different dates in 2005: 30th August (Landsat 7), 2nd September (SPOT), 7th September (Landsat 5) and 15th September (Landsat 7). For the purpose of this research, the flood maps (Smith & Rowland, 2005) were georeferenced in order to extract the changes in flood extent and depth for these fours days.



Figure 9. Left image, an examples of the proxy of cluster of cars and to the right, an example of highway possibly obstructed by water.

To evaluate the cluster of cars as a proxy, it was also necessary to analyze the water depth that could potentially be blocking the road access. To estimate the water depth in the highways that are used for the main access to the city and used to analysed the cluster of cars as a proxy, the flood extent was combinated with a Digital Surface Model (DSM) of 30 to 60 cm vertical resolution obtained during the Louisiana StateWide LIDAR Project, funded by FEMA (Cunningham, Gisclair, & Craig, 2002). The project began in 2000 and covered Orleans Parish in 2002. The vertical and horizontal datum used was NAVD88 and NAD 83, UTM zone 15N, respectively. This research also used the Digital Terrain Model (DTM), obtained through the same source.

Differentiating between a post-disaster road blockage and partial disruption can be challenging when flooding is considered, as the presence of water does not solely indicate that the road is blocked. The flood depth is therefore included in the characterization of the level of accessibility in the city. Although road accessibility to vehicles depends also on flood velocity and vehicle's height (e.g. Teo, Xia, Falconer, and Lin, 2012), due to data constraints, only depth is considered.

Defining at which depth the road network transitions from partially disturbed, i.e. still accessible to vehicles, to completely blocked, can be subjective. Although the experimental study of Teo et al. (2012) has considered different flood variables to assess vehicles' accessibility in a flood scenario, it did not indicate at what depth it is still considered safe for a vehicle solely considering the depth. Therefore, the presence of water is considered functional damage to the road network, as water at any level could potentially affect the transportation efficiency.

4.2.2. Connecting nodes

The number of connecting links in roads and highways was used to demonstrate a loss in accessibility after an earthquake (Bono & Gutierrez, 2011) and the robustness of the road system after flooding (Kermanshah & Derrible, 2016). The method proposed by Bono and Gutierrez (2011) used Open Street Map (OSM) data to identify the disruptions in the city's accessibility, making it suitable to be partially applied during this research.

New Orleans' road network system is characterized by different classes of roads and highways running through the same path but stacked in height, i.e. grade-separated highways, exemplified on the left of Figure 10. Considering this, the roads were separated by class to analyse the connecting links and also to decrease the potential of overestimating the number of nodes. An example of the road classes is shown in Figure 10, on the right. After, the road network that was composed of short segments was unsplit, i.e. the short segments that had coincident end points were merged to form a continuous segment. The network dataset was then created with the shapefile containing the number of junctions for each road class (Annex 1) was obtained and aggregated.

The nodes were then analysed against each flood scenario to consider the number of nodes that would possibly contribute to a loss of efficiency in the road network system, i.e. functional damage. This analysis can potentially demonstrate the effect that the flooding had on the accessibility of the city.



Figure 10. The left image illustrates the system of stacked roads. On the right, it is illustrating the different road classes present in the same area.

4.3. Characterizing functional damage of acute care hospitals

In order to assess functional damage the facilities selected were acute care hospitals. For this, the number of nodes within the flood extent and the flood depth were considered. To analyse the presence/absence of vehicles detected through remote sensing one facility in particular was selected, the Tulane Hospital. The methodology utilized throughout this section is described below.

4.3.1. Acute care hospitals

Acute care hospitals³ were selected for analysis as they should be permanently in operation, i.e. open all day and night and during holidays for example. They were also chosen due to the important role they represent during the emergency phase.

Although some of the acute care hospitals in the study area were not affected directly by the floodwater, they also decided to evacuate due to lack of accessibility, electricity, and fuel for their generators. The evacuation was finished on the 2nd of September, leaving the whole city without a properly-equipped acute care hospital. As a backup plan, patients started receiving treatment at Louis Armstrong International Airport, also called the New Orleans Airport (U.S. House of Representatives, 2006).

³ Acute care hospitals are defined as facilities "to treat sudden, often unexpected, urgent or emergent episodes of injury and illness that can lead to death or disability without rapid intervention" (Hirshon et al., 2013).

The location of the hospitals that were considered during this study are shown in Figure 11. The list of acute care hospitals was derived from the report generated from a ground survey performed after the event by the Multidisciplinary Center for Earthquake Engineering Research (MCEER), funded by the National Science Foundation (Arendt & Hess, 2006). The list of the correspondent hospitals, including their names and characteristics is presented in Table 5 in accordance to the numbering in Figure 11.



Figure 11. The location of the acute care hospitals is shown. The numbering corresponds to Table 5. List of hospitals and relevant characteristics as of December 2016.

Table 5 also presents the ownership type of each location, which are represented by investor-owned, notfor-profit and public. The first category corresponds to commercial hospitals that could be owned by private investors. The not-for-profit hospitals have their profit reinvested into the hospital, while the public ones are owned and funded by the government. The status shown corresponds to the hospital's availability after being evacuated, i.e. if they remained closed or reopened, for example. Changes in name and location that happened after Katrina are also shown in Table 5. The information presented was primarily obtained from Arendt & Hess (2006). Some of the up-to-date information on the status and changes was obtained from the hospital's website or from the local news website, The Times Picayune (www.nola.com). The last update on Table 5 was completed in December 2016.

Polder	#	Name	Ownership	Status	Changes
	1	Mercy Hospital (Lindy Boggs Medical Center)	Investor-owned	Permanently closed	NA
Central	2	University Hospital	Public	Closed until relocated in 2016	Moved from public to not-for-profit. It is now Interim LSU Hospital.
	3	Tulane University Hospital	Investor-owned	Reopened 14 Feb 2006	NA

Table 5. List of hospitals and relevant characteristics as of December 2016. Adapted from Arendt and Hess (2006).

	4	Charity Hospital	Public	Closed until relocated in 2015	Relocated and changed name to University Medical Center New Orleans (2015)	
	5	Veterans Administration Hospital	Public	Permanently closed	NA	
	6	Memorial Medical Center (Baptist)	Investor-owned	Reopened late Jan 2009	Ochsner Health System	
	7	Children's Hospital	Not-for-profit	Reopened 10 Oct 2005	NA	
	8	Touro Infirmary	Not-for-profit	Reopened 29 Sept 2005	NA	
East Orleans	9	Methodist Hospital	Investor-owned	Reopened Aug 2014	New Orleans East Hospital	
St. Bernard	10	Chalmette Medical Center	Investor-owned	Permanently closed	NA	

The hospitals that show a 'permanently closed' status had not reopened as of December 2016. The status of the hospitals that were closed until reopened are set as 'reopened' followed by the date of reopening. However, some of the hospitals also relocated, abandoning their previous building. The status of these facilities are as 'closed until' followed by the date of relocating to another building in Table 5. This is the case for the Charity Hospital, for example, that has relocated but left the hospital's previous building unoccupied and unmaintained. The University Hospital has also relocated to another venue. This Hospital has also moved from public to not-for-profit. Characteristic that among the studied hospitals, it was only seen in the University Hospital.

4.3.2. Hazard characteristics and hospital's functional damage

This section aims to develop a methodology to analyse if the hazard's characteristics could influence the functional damage to acute care hospitals in Orleans Parish. As the aftermath considered in this research is mainly caused by the subsequent flood after Katrina, the main characteristics considered are the flood duration, extent and depth. The aim of this analysis is to understand the influence that these could have had on the hospital's functional damage. In other words, this sections addresses the questions that were raised throughout this research, such as: to what extent do the hazard's characteristics play a role in functional damage? Are flood duration and depth related to the duration of hospitals' functional damage?

Regarding the flood characteristics, the hospitals' locations were analysed against the flood temporal maps in four different dates (Smith & Rowland, 2005); the same maps and dates that were also utilized to analyse the road network. To determine the presence or absence of water in the immediate surroundings of the hospitals, a buffer of 300 m was created. The value of 300 m was chosen for the indication if the hospital was still flooded and if the surrounding area was also flooded and if so, how deep. In areas that, inside the buffer, there was more than one class of depth value showing, the lowest and highest value of depth were selected.

4.3.3. Presence/absence of cars

In order to analyse the functional damage to the hospitals, the observable proxy that was selected was the presence/absence of cars in the vicinities' open-air parking lots and adjacent streets. As the main mean of transportation in Orleans is private cars, the logic behind choosing this proxy is that the absence of cars could indicate that the facility's function is damaged (i.e. possibly indicating a loss of efficiency through an

abnormal change in the presence/absence of cars). In this research, it is assumed that an abnormal change in the proxy's characteristics could indicate disruption or loss in efficiency, i.e. functional damage.

The areas of the parking lot immediately next to or surrounding the studied hospitals were considered. The surrounding streets were also considered, as they could serve as a benchmark; i.e. if the surrounding streets present a 'normal' presence of cars and the considered parking lot does not, it could indicate functional damage. The area considered surrounding the hospitals, both for the parking lot and adjacent streets are shown in Figure 12.



Figure 12. Location of parking lots considered for the analysis of presence/absence of cars in Tulane's parking lot and adjacent streets.

In order to characterize the parking lot during normal (or peacetime) circumstances, the same area was analysed before and after the event. The hospital analysed in detailed, Tulane Hospital, had a private parking lot. However, this parking lot was covered and also presented more than one floor, which imposed a barrier to observe vehicles through remote sensing. In order to partially overcome this, the payed, open-air public parking lot that was also located in front of the hospital was considered during the analysis.

Automated method

For the cars to be detected in the image, the method applied during this research was previously developed by Ghaffarian and Gökasar (2016). The method was chosen as it also considers shadows and the results showed that the method is able to overcome the problem of detecting vehicles that are "hidden" by shadows. Also, this method utilises high resolution images, from which the road images are selected. Then, with the use of MATLAB, the code was run using a fuzzy clustering algorithm based on the images' histogram (Automatic histogram-based Fuzzy C-means (AHFCM) described in Ghaffarian and Ghaffarian, (2014)), the Canny edge detector and perceptual grouping to identify the presence of cars. The code is described in detail in Ghaffarian & Gökasar (2016). As per the author's request, the codes are to remain confidential but the basic procedure is briefly explained below.

In short, the first step of the code aims to detect the center of clustered pixels in the image. The code utilized the Fuzzy c-means (FCM) algorithm. This algorithm randomly prepares the centre of each cluster, which serves as the basis to calculate the distance matrix (Zhang & Kirby, 2000). One of the main highlights of AHFCM is that it finds the number of clusters based on the image's histogram, i.e. the number and centre of clusters are based on the histogram of each band (Ghaffarian & Ghaffarian, 2014).

The following step detects the edges in the image, which are the boundaries that separate one object from another based on discontinuities. The edge detector that the code uses is based on the Canny edge detector.

This detector is commonly used in computer vision, and it is less likely to be affected by noise, as it uses two thresholds (Maini & Aggarwal, 2009). In addition, the Canny edge detector focuses on three main criteria to select an edge, good detection with a low error rate, location of the edge and a single response to each edge (Maini & Aggarwal, 2009).

There is also a set of thresholds that need to be tuned for the code to be used in different images, and the edge detection threshold was also one of them. The code also selects the potential cars based on a number of pixels that could form a vehicle in the image, i.e. it is dependent on the resolution. To tune this threshold, the smallest and biggest vehicle was measured on the image so the code could search for groups of pixels within a range in combination with the other thresholds. This is done during the perceptual grouping process, that is run on the outputs from the clustering algorithm and the Canny edge detector (Ghaffarian & Gökasar, 2016). During the perceptual grouping, the clusters that might not correspond to a vehicle (according to the pre-determined number of pixels) are removed. Finally, the trees that were present in the images were removed in order to decrease the possibility of a false-positive detection

5. ANALYSIS OF RESULTS

The purpose of this chapter is to demonstrate and analyse the results found during this research. The first section represents the findings for the accessibility analysis. The following section illustrates the results for the selected observable proxies using RS.

5.1. Functional Damage to Accessibility

The accessibility was analysed in relation to the road network's nodes. The nodes were analysed considering not only all the polders but also the surroundings of the studied hospitals, where the water level was also examined. The results are separated into sections, as it follows.

5.1.1. Nodes

As any loss of efficiency to an element in the system is considered as functional damage, the connecting nodes were used as a proxy for accessibility in two most important aspects. The first aspect is the overall disruption to the roads functionality of providing access to the city. The second one is the functional damage to roads in relation to the accessibility to acute care hospitals. The assumption behind assessing nodes is that the less available nodes, i.e. not within the flood extent, the less efficient the road network would be and could, therefore, provide less access to the city and to the acute care hospitals.

Central Polder

The central polder was the area presenting the highest number of nodes under normal circumstances, i.e. before the event, as shown in Table 6. This area also contained most of the acute care hospitals studied. On the 30th of August, one day after the event, approximately 58% of the nodes were within the flood extent (6224 nodes). This polder showed the highest amount of affected nodes when compared to the other polders during the 30th of August.

		After the disaster					
Polders	Normal	30 Aug 2005	02 Sep 2005	07 Sep 2005	15 Sep 2005		
	conditions	+1 day	+4 days	+9 days	+17 days		
Central	10736	6224	7931	7239	2162		
East Orleans	4087	2072	3463	2985	606		
St. Bernard	3345	1723	2806	1982	1064		

Table 6. Number of connected nodes per polder under normal circumstances and affected nodes after the disaster.

On the 2nd of September was when the Central polder had the largest number of nodes within the flood extent when comparing to the other polders and other dates. The maps developed for the connecting nodes for the Central polder analysis are shown in Figure 13. This polder presented 7931 nodes within the flood extent, representing approximately 74% of the total number of nodes. At this point, nearly 26% of the nodes were outside the flood area, which might have affected the accessibility considerably to different places within this polder. The analysis showed that on the 2nd of September the flood extended reaching the only officially assigned shelter, the Superdome. The number of affected nodes grew in all the polders from the 30th of August to the 02nd of September, one day and four days after the event respectively. This increased number could be attributed to the continuous flow of water coming in through the breaches that had not been interrupted yet. From the 02nd to the 07th of September, the flood extent retreated, uncovering only 7% more of the nodes, i.e. it changed from 7931 covered nodes to 7239.



Figure 13. Maps illustrating the flood extent during the four days of analysis and the affected nodes in Central polder.

Seventeen days after the event, there were approximately 2162 nodes within the flood extent, showing the highest number of nodes still within the extension of the flood when comparing to the other polders. It was also seen that on this last day of analysis, the flood water was still present in some areas in the form of patches. The remaining presence of water could be attributed to the elevation differences within the polder (elevation map of the area can be seen in Annex 3) and to the water pumping. The pumping stations are also shown in Annex 3.

East Orleans Polder

In accordance with the Central polder, the East Orleans polder flood extent increased from the 30th August to the 02nd of September. Also possibly attributed to the inflow of water through the breaches. The East Orleans polder was the polder where most of the nodes were affected on the 2nd of September. This polder went from 51% of the nodes within the flood extent on the 30th of August, to approximately 85% (3463 nodes within the flood extent) on the 02nd of September. This percentage of nodes within the flood area was the highest seen between polder and between all days of analysis. The maps developed for the connecting nodes in the East Orleans polder are shown in Figure 14.



Figure 14. Maps illustrating the flood extent during the four days of analysis and the affected nodes in East Orleans polder.

On the 07th of September the flood extent and the number of possible affected nodes had decreased, reaching the lowest quantity of nodes within the flood area (606 nodes, as shown in Table 6). The flood in this polder extended up to the limit delineated by the floodwalls to the east of the polder. The majority of the flood extension was also seen to the east of this polder on the last day of the temporal analysis, the 15th September. The concentration of flood water in that area could be attributed to the marshes in this location and the presence of only one pump station.

St. Bernard Polder

Although St. Bernard polder showed the lowest total number of nodes before the disaster, under normal circumstances, the flood extent covered approximately 52% of the total on the 30th of August. On the 2nd of September, the percentage of nodes within the flood extent presented the second highest between all polders, approximately 84% (2806 out of 3345 nodes, as seen in Table 6). The maps developed for the connecting nodes in the St. Bernard polder are shown in Figure 15.



Figure 15. Maps illustrating the flood extent during the four days of analysis and the affected nodes in St. Bernard polder.

From the 2nd to the 7th of September, St. Bernard was the polder that showed the highest decrease in the number of nodes in the extent of the flood, decreasing from 2806 to 1982 nodes within the flood extent (nearly 24% reduction). However, on the last day of analysis, 15th of September, this polder still showed the highest percentage of nodes within the flood extent, when compared to the other polders.

5.1.2. Flood depth and nodes around the acute care hospitals

Three elements that could have affected the acute care hospitals were: the flood temporal component (how long the facility was within the flood extension), depth of the surrounding water, and the number of nodes that were within the flood extension in the hospitals' surrounding area. These elements will be further discussed, relating them to functional damage.

For the flooding duration, 300 m area around each acute care hospital was analysed. The results regarding the neighboring nodes within the flood extent and flood depth are shown in Table 7 and Table 8, respectively.

Table 7. Number of connecting nodes that were within the flood extent. The area considered was the surroundings of the hospitals (300 m) after the event and under normal circumstances. The numbers on the table corresponds to the numbering in Figure 9.

		Name	NI a mus al	After the disaster					
Polder	#		Normal	30 Aug 05	02 Sep 05	07 Sep 05	15 Sep 05		
			condition	+1 day	+4 days	+9 days	+17 days		
	1	Mercy Hospital	38	38	38	38	17		
	2	University Hospital	65	65	65	65	0		
Central	3	Tulane University Hospital	36	12	33	26	0		
	4	Charity Hospital	27	22	22	15	0		
	5	Veterans Hospital	33	29	20	17	0		
	6	Memorial Medical Center	27	23	27	27	0		
	7	Children's Hospital	12	0	0	0	0		
	8	Touro Infirmary	34	0	0	0	0		
East	0	Mathediat Hearital	25	25	25	25	0		
Orleans	9	Methodist Hospital	25	25	25	25	0		
St.	10	Chalmatta Madigal Contan	8	8	8	0	0		
Bernard	10	Chaimette Medical Center				ð	0		

The central polder was the area with the highest number of acute care hospitals, and it was also the area where two of the hospitals remained directly unaffected by the flood water. The Children's Hospital and Touro Infirmary remained unreached by the flood extent throughout the days of analysis. With the lowest flood depths in the surrounding area, Tulane and Veterans Hospital presented a maximum of 2.0 m (Table 8).

The Methodist Hospital, located in the East Orleans polder, showed a maximum of 4.5 m during the first day and also four days after the event. This depth represents the highest between all facilities during these two days of analysis. The nodes around the Methodist, University and Mercy Hospital were all within the flood extent on the 30th of August, 02nd and 07th of September.

			Flood depth after the disaster (m)							
Polder	ш	Name	30 Aug 05		02 Sep 05		07 Sep 05		15 Sep 05	
	#		+1 day		+4 days		+9 days		+17 days	
			min	max	min	max	min	max	min	max
	1	Mercy Hospital	3.0	4.0	3.0	4.0	2.0	3.0	0.0	2.0
Central	2	University Hospital	3.0	3.5	3.0	3.5	2.0	3.0	0.0	0.0
	3	Tulane University Hospital	0.0	2.0	1.5	2.0	0.5	1.5	0.0	0.0
	4	Charity Hospital	1.5	2.0	1.5	2.0	0.0	1.5	0.0	0.0
	5	Veterans Hospital	1.5	2.0	0.0	2.0	0.0	1.0	0.0	0.0
	6	Memorial Medical Center	3.0	3.5	3.0	4.0	1.5	2.5	0.0	0.0
	7	Children's Hospital	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	Touro Infirmary	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East	0	Matha diat II. anital	2 5	4 5	2 5	4 5	2.0	4.0	0.0	0.0
Orleans	9	9 Methodist Hospital		4.5	3.5	4.5	3.0	4.0	0.0	0.0
St.	10	Chalmatta Madiaal Cart		4.0	3.0	4.0	2.5	3 5	0.0	0.0
Bernard	10 Chaimette Medical Center		5.0	4.0	5.0	4.0	2.3	5.5	0.0	0.0

Table 8. Flood depth in the surrounding area of the hospitals.

On the 02nd of September, Mercy Hospital, Memorial and Chalmette Medical Center demonstrated the second highest flood depth, 4.0 m. On this day, most of the hospitals that were reached by the flood presented all the surrounding nodes within the flood extent, with exception to Tulane, Charity and Veterans hospitals. Although the University Hospital had the highest number of connecting nodes (65) surrounding the area, they were all within the flood extent, affecting the accessibility, until nine days after the event (7th September).

On the last day of analysis, the 15th September, all but the Mercy Hospital (Lindy Boggs) were outside the flood extent area. Mercy still presented a partial area within the 300 m that included the flood extent, covering 17 of its 38 nodes (44%) and a maximum depth of 2 m.

Summary

The connecting nodes analysis demonstrated that the accessibility within all polders declined due to the flooding, which decreased the connectivity of the road network. The day that presented the highest number of nodes within the flooded area was on the 2nd of September. The same day that some of the remaining hospitals in the studied polders reported evacuation (Arendt & Hess, 2006). The evacuation of the hospitals depended on the situation that each hospital reported, i.e. some hospitals already had an evacuation contract signed with helicopter and ambulance companies (Arendt & Hess, 2006). However, due to the flooding conditions, only helicopters and flood-resistant vehicles could access some of the hospitals. For example, Tulane Hospital had their evacuation for five consecutive days using helicopters (Gray & Hebert, 2007).

5.2. Remote sensing proxies

This section illustrates two of the proxies that were tested in the studied area. The cluster of cars in the road that could be an indication of loss of efficiency in the road network and also the presence/absence of cars in the Tulane's Hospital parking lot before and after the disaster.

5.2.1. Road blockage with remote sensing proxies

This section shows examples using remote sensing of potential proxies that could be further explored in future research. Figure 16 illustrates the location of each section assessed. The number of the section corresponds to the number placed on the top left corner of Figure 17 to Figure 19. These areas were selected as they are part of the Interstate highway I-10, which is one of the main accesses in the city.



Figure 16. Map illustrating the location of the highway sections assessed in the study area.

The cluster of cars was analyzed in one example seen in Pontchartrain Expressway. Figure 17. illustrates the corresponding section 1, which location in the polder is shown in Figure 16. This proxy could be used to determine if a road could be potentially blocked or obstructed, as an indication that cars could not be able to pass, decreasing the efficiency of the road network and possibly indicating functional damage. In the example illustrated in this research, there is a cluster of cars (shown on the top right corner of the image in Figure 17) possibly indicating that the path was blocked or partially blocked. The analyzed section of the highway, shown as a dotted red line, showed that the water level could have been deep for regular vehicles to pass through (around 2 m, as shown on the graph in Figure 17).



Figure 17. First section analyzed of I-10. The red dotted line indicates the section where the cluster of cars was analyzed. The cluster of cars is shown in the right upper corner of the image and the graph represents the elevation of the road, terrain and water level.

As the area of the case study was severely affected by flooding, another relevant consideration was that roads that looked wet might not have been deeply flooded. Therefore, vehicles could still potentially transit through. For this example, a section of I-10, which is one of the main arteries of the city was analyzed (Figure 18). This section showed a flood depth around 1 m, decreasing to less than 1 m toward point B. as seen on the graph in Figure 18.



Figure 18. Section 2 of I-10. The red line indicates the section analyzed. The wet area in the section is shown in the right upper corner of the image and the graph represents the elevation of the road, terrain and water level.

It was also considered that New Orleans was characterized by a stacked roads layout, i.e. roads overpassing each other. This way, it was also important to understand the height above the water that I-10 was. As shown in Figure 19, this section of I-10 was close to two of the studied hospitals, Tulane and Charity, and the Superdome shelter.



Figure 19. Section 3 of I-10. The red line indicates the analyzed section close to the Superdome shelter and two of the studied hospitals. The graph represents the elevation of the road, terrain and water level.

The graph in Figure 19 illustrates the highway, terrain and water level in the section indicated in red on the image on the left side. Analyzing this section of I-10, it can be seen that this portion of the interstate was considerably above the flood water, approximately 5 to 6 m throughout the section.

5.2.2. Presence/absence of cars in the parking lot

This section shows the results obtained and analyzed for the proxy of presence and absence of cars. The results for the Tulane's hospital parking lot and adjacent streets, used as an example, are shown for the automated and visual interpretation methods.

Automated method

The automated method that was tested could potentially be more efficient to detect and count the cars in the analyzed images. The parameters were adjusted and the code was run in a trial-and-error basis on 18th of April 2005 image. The image of the area is illustrated on the left side of Figure 20, while on the right, the image shows the cars detected.

The vehicle detection obtained with the automated method resulted in a number of false-positives. In the indicated image on the right side of Figure 20, there were 7 vehicles recognized as a true-positive, 2 false-negatives and the approximately 40 points remaining were false-positives. This amount of false-positives could be attributed to the resolution of the image that was obtained through Google Earth Pro as the methodology applied required a very high resolution image (Ghaffarian & Gökasar, 2016).



Figure 20. Image on the right: assessed area surrounding Tulane Hospital. On the left, the detected vehicles through the automated method, emphasizing the false-positives in red.

As the main goal of applying this methodology was to know the number of vehicles as accurately as possible, this technique was judged to be unsuitable for the purpose, in light of the images available. Consequently, the method that was applied and considered acceptable was through visual interpretation of the images.

Visual interpretation

Visual interpretation to detect vehicles was performed on eight images of different dates, but in the same location, in Tulane Hospital's premises. The vehicles that were considered were the ones present in the parking lots and also in the adjacent streets. Vehicles that seemed to be in movement and parked were both considered for the analysis. Also, when vehicles were in the shadow but could still be identified, as illustrated in Figure 21, they were counted.



Figure 21. Example of vehicles that were in the shade but could be identified as such due to their bright color.

The results obtained with visual interpretation are shown in Figure 22. The date of each image is shown on the top right corner of each image. The images indicate, throughout the time, how many vehicles were in the surroundings of Tulane hospital and also in the front parking lot. The private hospital Tulane provides an indoor multi-story car park, while the front open-air parking is public. This parking lot was also considered due to the proximity to the hospital, i.e. it was assumed that people going to the hospital and also the staff could be using that parking space as well.



Figure 22. Cars detected using visual interpretation on analyzed images.

The first image obtained, on the 07th of February (Friday), showed 88 vehicles in the parking lot, while there were 209 in the adjacent streets. These were not the highest numbers, as they occurred on the following available image, on the 09th of April of 2004 (Friday). This image represented the highest number of vehicles that could be identified both in the parking lot and streets, 111 and 356 identifiable vehicles, respectively.

The 18th of April 2005 (Monday) image showed the second highest number of recognisable vehicles in the streets, 340. At the same time, the image represented the lowest amount of cars in the parking lot, 27 vehicles, before the disaster occurred on the 29th of August of 2005. Between the 2005 April image and the disaster event, no images were available.

After the disaster, a decline in the number of cars was observed. More predominantly seen in the adjacent streets, as represented in Figure 23. From the last day before the Katrina, the number of cars in the roads has dropped from 340 to 70. Amount which has remained approximately the same until the 02nd of November of 2005 (Wednesday). On this day, there were not identifiable vehicles in the front parking lot. The next available image was only found on the 26th June 2006.



Figure 23. Graph representing the number of vehicles in the adjacent streets and parking lot in each day analyzed.

On the last two images, the 26th June 2006 (Monday) and 03rd November 2006 (Friday), there was an increase of vehicles, especially seen in the adjacent streets. A similar increase was not seen in the correspondent amount of cars in the parking lot, although the number increased.

As a general trend in the vehicles in the street, it is seen in Figure 23 that the amount of cars changed abruptly when comparing the numbers from before and right after the event. It is also seen a trend increasing the number of vehicles in the streets after the event. However, the trend at the same scale was not perceived in the vehicles located in the front parking lot.

6. DISCUSSION

This chapter discusses the main findings of this research, considering and also reflecting upon the limitations of the methods applied. The primary objective of this study was to understand and conceptualize post-disaster functional damage, also identifying observable proxies using mainly remote sensing data.

Functions in the urban settings are very complex, involving numerous links, interconnecting parts of the system that would otherwise not be able to function properly. The classification of land use according to the economic function, suggested by Guttenberg (1959), was one of the first published definitions of functions found during this research. More recently, functionality was defined relating the land use to the goods and services that were provided by them (Verburg et al., 2009; Willemen et al., 2008). Also found was the functions defined as the land use type, e.g. as residential and commercial (Aubrecht et al., 2009; Li et al., 2016). Interconnecting the system through a more comprehensive point of view, Goddard (1970) and Manley (2014) considered the connections in the urban system, while analyzing the traffic flow among the sectors. The definitions found for urban functions varied considerably according to each purpose of the study. Although there were many definitions found for urban functions, not many were found for functional damage.

Surprisingly, the definition for functional damage proposed by Galderisi and Ceudech (2013) did not seem to be derived from the definitions found for urban functions. Broadly, Galderisi and Ceudech (2013) defined functional damage relating it to the loss of functioning or efficiency to any of the elements that are within the boundaries of study. This definition could then be applied either to the interconnections of the system, e.g. in Manley (2014) or perhaps to the land use type (e.g. Aubrecht et al., 2009). Meaning that the definition suggested for functional damage could potentially be applied to the studies of urban functions, even using the diverse definitions found in the literature.

Functional damage was also defined as to be a consequence of physical damage (Galderisi & Ceudech, 2013). Therefore, through the beginning of this study, the functional damage was described as the same as Galderisi and Ceudech (2013). However, after reflecting upon the results of this research, it is suggested that functional damage might not always be only the result of physical damage. The damage to any element of a system, either by losing efficiency or functionality, may also be the result of, for example, lack of staff, or people in general. It could also be due to the lack of funding from the government, preventing an establishment to reopen. This was, for example, seen among the analyzed hospitals. The investor-owned Tulane University Hospital was able to come back within six months after Katrina. As a matter of fact, most of the investor-owned hospitals were able to reopen soon after the disaster, whereas most of the public facilities reopened only recently and were even relocated. The building of the Charity Hospital, which was located in front of the Tulane Hospital, became non-operational after Katrina (Arendt & Hess, 2006). The flood depth analysis and nodes around the facilities indicated that the Charity Hospital had the flood water at a slightly deeper level and a higher relative number of the connecting nodes within the flood extent when compared against the Tulane Hospital. Also to be considered is that perhaps the hospital could already in the process of shutting down, although no evidence of such was found in literature.

The main hazard considered during this research was flooding, and functional damage was analyzed based on the damage caused by it. Although there were reports indicating that the damage caused by the hurricane passage was extensive in hospitals, as these two events were interconnected, it was difficult to separate them. Also, as reports were indicating that some hospitals kept operating to some extent even after the hurricane passage (Arendt & Hess, 2006), the reasons for their loss of functionality could perhaps be attributed to other factors that could also be flood related. That this analysis is solely based on the flood, could have negatively influenced the results, i.e. analyzing the scenario without being able to fully understand and separate all the elements (e.g. wind, flood, and loss of power), which could have affected the functional damage analysis.

Also to be considered is the type of damage. Galderisi and Ceudech (2010) assessed functional damage in a different disaster scenario, an earthquake. The nature of disaster and the type of corresponding damage that it can cause should also be considered. This research raised the question that perhaps different categories of disaster could also cause different types of functional damage, and also potentially distinct ways of assessing them. This research analyzed functional damage considered to be caused primarily by flooding. This kind of disaster can affect structures in the long term, causing humidity on the walls, molding the interior (Green, Bates, & Smyth, 2007).

As the conceptual framework shown in Chapter 2 was developed based on the literature, and not in this research findings, it is suggested that the framework for functional damage is revised in future studies, also to incorporate functional damages that are not only a result of physical damage. In addition, the framework used resulted to be slightly too static for such a dynamic issue. The urban functional links do not seem to be connected unidirectional, but yet, the links seem to be bidirectional, as indicated by this research. In addition, the links could potentially not only be presented in a one-to-one relationship, but also a one-to-many or even many-to-many. This means that the elements considered should not be analyzed separately from the other interconnected elements, which is also applied for the functional damage analysis. Indeed, the links and their relationship can become even more evident when one element is disrupted, also demonstrating the type of relationship.

Even though the analysis was based on images of four days of the flood, the last day of analysis (15th of September 2005) was not the actual last day of flooding. This could also have influenced the analysis. Although most of the studied hospitals were outside the flooded area, it would have been beneficial analyzing the connecting nodes with the full temporal extent of the flood. This, combined with more frequent data would enable a more detailed approach on the analysis regarding the hospitals functional damage and accessibility.

The research from which the flood extent was obtained was a study performed using Landsat images (Smith & Rowland, 2005). These mid-resolution images could have caused a misconception on the flood extent, which could have been propagated to this research. Also, there were patches of flood water toward the edge of the central polder on the flood analyzed on the 30th of August of 2005, where there were no indications of being caused by breaches alone. In order to find a correspondence for those patches, the area was also compared against the high water report from FEMA that also described the cause of flooding (Federal Emergency Management Agency, 2006). No correlation was found between the patches of water and another source other than breaches.

The hospital analyzed for the cluster of cars was located in an area known to have a high transit of vehicles (close to the Superdome). In addition, the area also presented other businesses and medical centers in the surroundings. Consequently, the number of vehicles in the studied parking lot might not have been linked to Tulane Hospital and could be linked to people in other facilities. As the hospital's private parking lot had several floors, the vehicles inside could not be detected by remote sensing, which could have had an influence on the results. Although the presence/absence of vehicles used as a proxy may be promising, it appears that in order to clearly assess functional damage more data is needed beyond the RS data. Information about the surrounding business and their operational status would benefit the analysis.

The automated method utilized to detect vehicles presented some limitations. The code needs to be tuned for each image, as the images also presented different resolution. The low and high values for the Canny edge detector thresholds were selected based on trial-and-error. Another limitation was that the method detected, for example, trees and the roads' crosswalk as vehicles (false-positives).

6.1. Critical analysis of the flood depth surrounding the facilities

There were a few facilities that showed an increase in the minimum level of the flood without an increase in the maximum value of the surrounding flood depth. This could be attributed to the remote sensing images that capture a certain moment in time. The cases that showed an increase were related to the 30th August 2005 and the 2nd of September 2005, when reports indicated that water was still flowing in (Freudenburg et al., 2012). As New Orleans area is a "bowl", there is a possibility that when the image was taken, the bowl was still filling up with water. Therefore, the surrounding depth increased, as the flood extended, but the depth at a particular terrain depression may not have, i.e. due to the terrain elevation changes. Perhaps if the images presented a higher spectral and temporal resolution, part of this issue could have been addressed. Although for analyzing many processes, including for slow onset, the flood temporal analysis as the one used in this research could be useful. For the New Orleans case, the water was flowing in relatively rapidly, as the study area is below Lake Pontchartrain and the Mississippi River levels.

6.2. Accessibility

Analyzing the accessibility based on the flood extent and number of connecting nodes can be inaccurate, as not all roads and nodes that were within the flood extent were not accessible. However, regarding functional damage, the nodes and roads within the flooded area could be used as indicators of loss of efficiency in the road network. Analyzing the three sections of the I-10, close to the Superdome, Tulane and Charity hospitals, it is seen that even though the interstate was within the flood extent, it was actually not covered by water. This meant that due to New Orleans road network layout (grade-separated highways), possibly not all nodes that were within the flood extent were blocked.

This way, another assumption for the accessibility during this research was that if the number of connecting nodes was lower, the relevant facility or area could be then less accessible. This is not always the case and studies regarding accessibility analysis can consider different aspects of the accessibility, which also shows that the closest point could not be the most accessible (Dou & Zhan, 2011).

6.2.1. Network analysis

Network analysis can be used to assess accessibility. When flood water is taken into consideration as a barrier or disruption in the road network, the analysis becomes more complex. The vast area that a flood usually occupies, making detours on the network analysis more complicated. Detours might even not be possible in a flood scenario, considering the availability of the road network in the surroundings. In order to analyze comprehensively the effect that the flood has in the road network, a few considerations should be taken into account.

Firstly, the complexity of the road network should be considered. As the example in this research, New Orleans presented a complex road network, with grade-separated highways. The results found in this research showed that this network layout could enabled that some roads, even though within the flooded area, were not deeply flooded and potentially trafficable using regular vehicles. However, to determine if the road allows access can be subjective and certain studies have already addressed the issue (Mioc & Liang, 2008; Teo et al., 2012).

To evaluate if the road network could be trafficable, detailed flood depth data is needed. During this research, the depth classes used varied every half meter, which for a comprehensive network analysis might be a high interval, and a more detailed flood depth would then be needed (Mioc & Liang, 2008). The authors separated the accessibility for each flood class, e.g. 0 to 0.2 m would be for an 'all-terrain vehicles' type, to perform a comprehensive network analysis, the food categories should be separated into the same categories of the vehicles accessibility. However, accessibility relating to flood depth is not so straightforward, as seen in the study from Teo et al. (2012). The authors studied the safety of driving a car through a flooded area regarding not only the depth of the flood but also the size of the car and velocity. This way, different

scenarios for network analysis could be implemented and evaluated. In the case of New Orleans, as the flood depth intervals are 0.5 m, only two types of the vehicle would be able to pass through the flooded area, fire trucks (up to 0.5 m) and boats (above 0.5) (Teo et al., 2012). In the case of boats, the road network could be used as if they were waterways, without a real rule for the traffic, possibly having bridges and buildings as obstacles.

With a case showing stacked roads layout, as presented in New Orleans study case, it would also be possible to evaluate the roads that were within the flood extent but not actually flooded. Data availability would be the only constraint, as a DTM, DSM and a detailed flood depth are needed. Evaluating these roads combining with the network analysis would give a more realistic view over the analysis. In addition, knowing the drainage rate of the flood water would also enable the analysis of the network 'emerging' as the water level decreased.

Origin and destination also need to be determine for the network analysis. The New Orleans case would impose some difficulties as the entire area was evacuated and assumption would need to be made regarding the people. There could be three potential scenarios to evaluate using the network analysis tool. Considering the network access from people to hospitals, one of the analysis could originate in the Superdome shelter, which was also surrounded by water, having as destination the closest accessible hospital. Another relevant scenario would be having as origin the Superdome and the hospitals, and as a destination, a highway access that would lead to an unflooded area, as an option for evacuation route. The last scenario would be to address the accessibility from the main roads that give access to each polder, i.e. the ones highly used by vehicles, the traffic 'bottlenecks,' to the hospitals and shelter. Each scenario would be assessed based on the characteristics that it was presented before the event and compared with the analysis performed after the disaster.

6.3. The link between vulnerability, functional damage, and recovery

Several of the proxies for post-disaster functional damage described in this research were derived from the recovery and vulnerability studies. This section briefly describes the links between these three types of analysis, illustrating how these three could influence and benefit each other.

The vulnerability can be composed of studies carried out before the disaster, which can involve the assessment of different scenarios. Recovery studies, on the other hand, can be executed after a period from the event, which can be as a plan for recovery or, for example, a measurement to what extent the area has recovered after the disaster. Timewise, functional damage can be placed in between the vulnerability and the recovery analysis, as it occurs a short time after the event. Vulnerability studies can indicate the possible functional disruption in in the interconnected links after a disaster. It has been seen that the higher the number of interconnecting links, the higher is the vulnerability of certain elements (Pescaroli & Alexander, 2016; Vespignani, 2010).

Although the recovery phase takes place after the response, functional damage assessment could possibly contribute to the recovery process. The contribution could be toward assessing functional damage in order to prioritize which of the elements is more essential, perhaps ranking them by their interconnected links. This way, once the damage to the functions is identified and characterized, the recovery could take place at a faster pace.

6.4. Research limitations

The flood extent was obtained through a previous study developed in the area, i.e. it was not the shapefile or the raw data. Numerous contact attempts to obtain the data from the authors and their sources were unsuccessful. The data was then obtained after georeferencing the maps published in Smith and Rowland (2005), which could have had an effect in this research analysis. The flood extent could not be easily

identified and delineated. Also, the analysis carried out for the flood depth could have also been subjective, as different colors and intensities had to be visually correlated to the flood depth.

The images for the cluster of cars analysis were obtained from Google Earth Pro, as it was not found another source with free images and suitable resolution for the analyzed dates. This could have compromised the analysis looking at specific days. As an example, there is the image from the 18th of April 2005. Although the date of the image obtained in Google Earth Pro refers to a Monday, looking at the volume of cars in the streets, it did not appear to be so. As doubts were raised regarding the date of the image, the image source was checked. Although the image could not be downloaded for the resemblance to be fully verified, the only image found around the 18th of April 2005 was actually on the 17th of April 2005, a Sunday. This represented a significant limitation, as the traffic on Sundays can differ considerably from the traffic during the week. Therefore, the confidence level regarding the image dates was low.

Using cars for the analysis can be significantly dependent on resolution, as to detect a car, a high-resolution image is needed. The resolution was different between images, which could have influenced the number of cars detected and therefore, influenced the results. Another limitation was that there were some areas covered by shadows where not many vehicles could be detected (only white colored vehicles could sometimes be seen in the shade).

7. CONCLUSION

This research presented another step toward a path to improve the understanding of post-disaster functional damage. To assess functional damage, the use of observable proxies through remote sensing has demonstrated to be challenging. This thesis established four objectives: 1) to identify and characterize different types of damage that can occur; 2) to develop a comprehensive conceptual framework of functional damage; 3) to also develop a list of potential proxies that can identify and characterize functional damage using remote sensing; and 4) to evaluate if selected potential proxies can be used to identify and characterize post-disaster functional damage through remote sensing.

The conceptual framework developed for this research, presented in section 2.5 contributes as a comprehensive analysis of the connections that functional damage presented in literature. Mainly, what was found in published research regarding functional damage was directly linked to physical (structural) damage, which during this research, it has been shown that this might not always a direct connection. Functional damage could also be caused by elements beyond the observable physical damage, such as political issues or lack of staff for the workforce.

This thesis used the flooding disaster that followed the hurricane Katrina in the Greater New Orleans as a study case. The area separated into three polders was used to analyse the accessibility within each polder. Also, ten acute care hospitals were selected as the facilities to be used to further investigate functional damage. The area and the selected facilities were considered to be suitable for this research as there were several studies addressing the disaster and its impact in different sectors.

The results found using proxies through remote sensing are promising. However, it is recommended that the proxies are used as a support in combination with other relevant data. To investigate the flood water level for accessibility, it is recommended that other data sources are considered, such as DSM and DTM. The proxies should be further explored also analyzing the applicability in different study areas and disaster types.

7.1. Recommendations for future work

Regarding the study case, the primary mean of transportation in New Orleans is private cars. However, analyzing the data from other means of transportation, such as public busses, could have contributed to a more comprehensive analysis of functional damage using means of transportation. This is therefore, recommended for future research to be developed toward this field.

To assess the cars as a proxy showed limitations specially when considering the multi-story parking lot of Tulane's hospital. Although the vehicles used as a proxy may be promising, it is advisable that a fully open area is selected, where most vehicles can be observed and considered. If not available, this proxy could be supported with information obtained on the ground.

It is recommended for future work that more studies focusing on proxies related to functional damage are further developed. Using and combining different sources of data is recommended for post-disaster functional damage. For example, geo-data from mobile phones could be utilized to analyse the functional damage to different sectors within a city. The changes in traffic reported by users through phone applications, such as Waze, also presents a potential to assess functional damage and the level of disruption.

There are indications that functional damage may vary according to the nature of the disaster. It is suggested that this path is investigated in future researches, assessing what the relation between the functional damage and the disaster type is. Also, assessing to what extent could the list of proxies developed be used in other scenarios and study case is advisable.

Additionally, it is suggested that the conceptual framework for post-disaster functional damage is revised. It is seen that a conceptual framework illustrating more dynamic connections may be more appropriate to depict the links between elements. Also to be addressed is the relationship between the links. It was seen that an element could present more the one single unidirectional connection in the system.

While reflecting upon this research, some questions were raised and they are recommended to be addressed in future research. For example: having the full temporal extent of the flood would have made it possible to link it to some sectors of the city: perhaps the areas that were affected for the longest were also the ones that business and residents did not return, and if there is a connections, would a priority order have made a difference on functional damage?

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ANNEX

Group	CFCC	Description
Primary Highway With	A15	Primary road with limited access or interstate highway, separated.
Limited Access (A1)	A19	Primary road with limited access or interstate highway, bridge.
Primary Road Without	A21	Primary road without limited access, US highways, unseparated.
Limited Access (A2)	A25	Primary road without limited access, US highways, separated.
	A29	Primary road without limited access, US highways, bridge.
Secondary and Connecting Road (A3)	A31	Secondary and connecting road, state and county highways, unseparated.
	A35	Secondary and connecting road, state and county highways, separated.
	A39	Secondary and connecting road, state and county highways, bridge.
Local, Neighborhood,	A41	Local, neighborhood, and rural road, city street, unseparated.
and Rural Road (A4)	A43	Local, neighborhood, and rural road, city street, unseparated, underpassing.
	A45	Local, neighborhood, and rural road, city street, separated
	A47	Local, neighborhood, and rural road, city street, separated, underpassing.
	A49	Local, neighborhood, and rural road, city street, bridge.
Road with Special Characteristics (A6)	A63	Access ramp, the portion of a road that forms a cloverleaf or limited access interchange.
	A64	Service drive, the road or portion of a road that provides access to businesses, facilities, and rest areas along a limited-access highway; this frontage road may intersect other roads and be named.
Road as Other Thoroughfare (A7)	A74	Private road or drive for service vehicles, usually privately owned and unnamed. Primary type of use is for access to oil rigs, farms, or ranches.
Provisional Features	P15	Primary road with limited access or interstate highway, separated
(P) *	P19	Primary road with limited access or interstate highway, bridge
	P21	Primary road without limited access, US highways, unseparated.
	P25	Primary road without limited access, US highways, separated.
	P29	Primary road without limited access, US highways, bridge.
	P35	Secondary and connecting road, state and county highways, separated.
	P41	Local, neighborhood, and rural road, city street, unseparated.
	P43	Local, neighborhood, and rural road, city street, unseparated, underpassing.
	P45	Local, neighborhood, and rural road, city street, separated
	P63	Access ramp, the portion of a road that forms a cloverleaf or limited access interchange.

Annex 1. List of the selected attributes (CFCCs) to analyse the road network from the 2006 TIGER files.

* Provisional features may appear on street features only. They indicates that the feature has not been verified during field operations or imagery.



Annex 2. Flood maps of the research area (Smith & Rowland, 2005).

Legend

Depth in feet	
0 to 1.6	9.8 to 11.5
1.6 to 3.3	📃 11.5 to 13.1
3.3 to 4.9	13.1 to 14.8
4.9 to 6.6	14.8 to 16.4
6.6 to 8.2	>16.4
8.2 to 9.8	

Annex 3. Above: elevation of great New Orleans area. Map was obtained from the Southeast Louisiana Data Center (2005). Below: location of pump stations. Obtained from Kent (2005).

