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Urban critical infrastructure interdependencies in emergency management

Findings from Abeokuta, Nigeria

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Abstract

Purpose – The purpose of this paper is to map the cascade effects of emergencies on critical infrastructure in a fast-growing city of a developing country. The paper specifically seeks to refocus the attention of decision makers and emergency managers towards a more effective way of reducing risk and costs associated with contingencies.
Design/methodology/approach – The study was based on a 2D representation of the three initiating events of fire, flood and automobile crashes. Detailed analysis was undertaken of the effects on the critical infrastructure, based on the probability of occurrence, frequency, spatial extent and degree of damage for the emergencies studied. Subsequently, a cascade matrix was generated to analyse the level of interaction or interdependencies between the participating critical infrastructures in the study area. A model of the cascade effects under a typical emergency was also generated using a software model of network trace functions.
Findings – The results show that while different levels of probability of occurrence, frequency and extent of damage was observed on the evaluated critical infrastructure under different emergency events, damage to the electricity distribution components of the critical infrastructure recorded the highest cascade effect for all emergency events.
Originality/value – This paper underlines the need to pay greater attention to providing protection to critical infrastructure in the rapidly growing cities, especially in developing countries. Findings from this study in Abeokuta, Nigeria, underscore the needs to expand the prevailing critical infrastructure protection beyond the current power and oil sectors in the national development plan. They also highlight the urgency for greater research attention to critical infrastructure inventories. More importantly, the results stress the need for concerted efforts towards proactive emergency management procedures, rather than maintaining the established "fire brigade, window dressing" approach to emergency management, at all levels of administration.

Keywords Nigeria, Disaster risk reduction, Critical infrastructure, Cascade effect, Interdependencies, Urban settlements

Paper type Research paper

1. Introduction

One of the fundamental challenges of modern human settlements is urbanization. The ever-increasing concentration of people and activities, in many of the world's spatially confined urban settlements, particularly in the last three decades, has transformed these highly dynamic human settlements into contexts characterized by complex risks. These events, varying in initiation, propagation, magnitude, effect or impact, have had marked influence on the development, function and structure of contemporary urban settlements (Kandel, 1992; Pantelic *et al.*, 2005; Patel and Burke, 2009; Ali *et al.*, 2015).

The growing recognition of the importance of managing urban risk has stimulated interest in issues of resilience, especially as these apply to cities in developing countries.

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The concept of resilient urban environment is based on the premise of the ability to absorb shocks while maintaining function (Godschalk, 2003; Chang *et al.*, 2014; Comes and Van de Walle, 2014; Brassett and Vaughan-Williams, 2015). As pointed out by Chang *et al.* (2014), the ability of cities to be resilient or resistant, as used by Geis, is significantly underpinned by the level and state of their critical infrastructure. This underlines the need for robust critical infrastructure that can accommodate an emergency situation, including appropriate shield mechanisms against latent and existing disaster and the capacity for prompt recovery in the event of a disaster.

While attention has been massively geared towards making cities resilient and resistant to large-scale emergency events, the occurrence of minor emergency events (also known as contingencies) is increasing particularly in developing countries. The occurrences of all forms of urban contingencies such as road accident (Worley, 2015; Esmael *et al.*, 2013; Jacobs and Sayer, 1984), flooding (Du *et al.*, 2015; Güneralp *et al.*, 2015; Lee and Mohamad, 2014; Jha *et al.*, 2012), building collapse (Bendito and Gutiérrez, 2015; Kamau *et al.*, 2014; Mkula, 2014; Patralekha, 2014; Windapo, and Rotimi, 2012, fire outbreak (Navitas, 2014; Forkuo and Quaye-Ballard, 2013; PreventionWeb, 2011; Ansari, 1992) and civil unrest (Ghimire *et al.*, 2015; Hendrix and Haggard, 2015; Hiatt and Sine, 2014), among others, have significantly increased in many urban centres across the globe (Lambert, 2015; Mitchell *et al.*, 2015; Liu *et al.*, 2014; Bull-Kamanga *et al.*, 2003). Because these classes of urban events are not perceived to generate severe impacts compared to other environmental threats, the level of preparedness for them is often low, especially in developing countries, where they are seen as necessary components of urbanization.

2. Critical infrastructure interdependencies and urban settlement resilience

Generally, infrastructure is built to provide a foundation for socio-economic well-being, as well as enhance and progress human condition in the built environment (Pagano and Perry, 2008). In other words, infrastructure influences vertical and horizontal growth of settlements by determining the distribution of people and the location of other sectors of settlements (Tibaijuka, 2009). The classes of urban infrastructure whose absence or limited functioning or performance have far-reaching consequences on urban system performance are classified as core or critical infrastructure (Gordon and Dion, 2008) or lifeline system (O'Rourke, 2007). Moteff and Parfomak (2004) defined critical infrastructure as facilities so vital that they underpin a nation's defence, strong economy as well as the general health and safety of her citizens.

Critical infrastructure exists as a complex system whose operation and functioning are intertwined at both local and higher levels; be it through direct connectivity, policies and procedures, or geospatial proximity, most critical infrastructure systems interact. These interactions often create complex relationships, dependencies and interdependencies across infrastructure boundaries. Basically, there are two types of relationships existing between critical infrastructures, namely, dependencies and interdependencies. While the dependency refers to the easy to identify and analyse, direct, unconditional relationship existing among a class of critical infrastructure (Setola *et al.*, 2009), the interdependencies relate to the directional and mutual relationships or dependencies usually among different classes or groups of critical infrastructure and which, in most cases, cause a reverberation or breakdown in one class to affect the performance in other classes (Setola *et al.*, 2009). Stapelberg (2008) called these disturbances flow-on consequences.

The relationship between critical infrastructures can further be broken down into direct and indirect. According to Johansson and Jonsson (2009), direct dependency, also called first order or linear dependency, exists when the behaviour of an infrastructure "*x*" directly influences another infrastructure "*y*". On the other hand, however, an indirect or second-order relationship exists among two or more infrastructures, when the behaviour or reaction of infrastructure "*x*" does not directly influence the behaviour or reaction of infrastructure *y*, but there is an intervening infrastructure "*z*" which directly affects infrastructure "*y*" and whose reaction is also subject to the behaviour of infrastructure "*x*". This type of interdependencies was referred to by Svendson as cyclic interdependencies because it often leads to a feedback effect. Critical infrastructure interdependencies can, therefore, refer to relationships or influences that an element in one infrastructure imparts upon another infrastructure or its elements (Pederson *et al.*, 2006). It is this interwoven relationship that makes the critical infrastructure vulnerable to the impact of contingencies, thereby affecting the efficiency and effectiveness of the whole emergency management process (Rosenthal *et al.*, 2001).

Failure to understand the dynamics and interplay between critical infrastructure and urban emergency events and disaster has been associated with ineffective response and poor coordination between decision makers and agencies responsible for rescue, recovery and restoration (Pederson *et al.*, 2006). This implies that critical infrastructure plays a strong role in ensuring urban settlement resilience and resistance. In this context, this study sought to specifically identify, describe, formalize and mimic the interdependencies (Trucco *et al.*, 2012) between critical infrastructure elements in emergency situations in one fast-growing urban centre of Nigeria.

3. Urbanization and critical infrastructure scenarios in Nigeria

An analysis of the growth rate and pattern of development of Nigeria shows that the country is highly urbanized. With an urban population of about 84 million (47 per cent of the total population) in 2014 and an average annual rate urban change of 1.9 per cent; Nigeria is expected to reach a staggering urban population of ~144 million (67 per cent of the total population) by 2050 (United Nations, 2014). In addition to this remarkable expansion, the associated urban growths has been extremely haphazard (Isma'il *et al.*, 2015; Abila, 2014; Adelekan *et al.*, 2014; Anestina *et al.*, 2014).

The implication is that such growth does not take proper account of the need to protect the people and their livelihoods from contingencies. Apart from the few cities that have inculcated and strictly enforced sustainable urban practices, many Nigerian cities are characterized with crises, most of which are immediate signs and consequences of the state of decline of Nigerian urban centres. Challenging conditions, including illegal urban structures, poor road networks, increasing rate of development of shanty towns and slums, inaccessibility to basic socio-economic facilities, poor sanitary condition, development of illegal dumpsites, skewed distribution of facilities and institutions among many others, have become daily issues that contemporary Nigerian cities face (Uwadiegwu, 2015; Adefolaju, 2014; Oluwaseyi *et al.*, 2014; Okorie *et al.*, 2014).

Although many other developing countries also face similar challenges, the Nigerian scenario is quite unique. This is because the country's rapid population growth and unplanned urbanization, as well as sociopolitical issues, compounded by ethnic plurality, have resulted in increased competition for scarce resources, thus leading to deteriorating livelihoods, social marginalization, crime and general insecurity, especially in the last three decades. With this trend, emergency situations such as fire outbreak, oil spills, flooding, building collapse, erosion, riots, terrorism as well as industrial and technological hazards, among others, have become regular occurrences, particularly in the urban centres (Asuelime and David, 2015; Nkwunonwo *et al.*, 2015; Adams and Ogbonnaya, 2014; Mohammed and Kawu, 2014; Vincent and Kenneth, 2014).

Compounding this situation is the dismal state of the country's critical infrastructure (Ariyomo and Abiodun, 2014; Adebayo and Iweka, 2014; Emmanuel *et al.*, 2014; Oyedepo *et al.*, 2014; Olotuah and Taiwo, 2013; Daramola and Ibem, 2010; Alabi and Ocholi, 2010) and failure to understand the complex relationship between it and the management of the various forms and dimensions of contingencies. While developed countries have long acknowledged the role of critical infrastructure for general urban functioning and emergency management (Hsieh *et al.*, 2014; Boin and McConnell, 2007; Schmitt *et al.*, 2007; Ouyang, 2014; Rinaldi, 2004; Lindell and Prater, 2003; Wallace and De Balogh, 1985), this has yet to be adequately addressed in developing countries, including Nigeria.

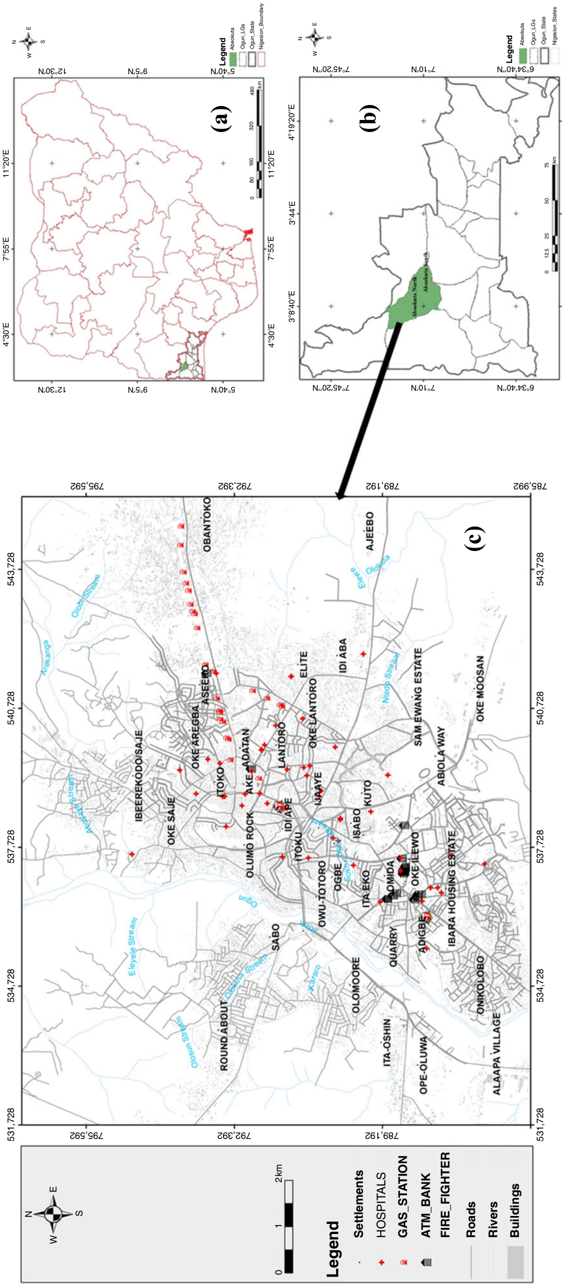
Two typical examples highlighted below reflect the limited understanding of the strategic role of critical infrastructure in emergency management in Nigeria. First is the dearth of academic research in respect of critical infrastructure and emergency management. A survey of the literature in respect of emergency management in the country shows that this area of research is almost nonexistent. Second, unlike the developed countries, where infrastructure may be clearly defined and enjoys uncompromised attention and protection, in Nigeria, the concept of critical infrastructures is restricted to oil, gas, and the power sectors. This is overly reflected in many developmental policy and programmes of the government, as indicated by the huge sum of money voted in respect of the power as well as oil and gas sectors of the country (*The Sun*, 2015).

The result of this disconnect between urban critical infrastructure and emergency management is expressed daily in the form of the late arrival of emergency and rescue personnel to the scene of emergency events, outrageously poor coordination between emergency management agencies and decision makers, and prolonged suffering of victims of human-induced contingencies. This further aggravates the exposure of the already vulnerable urban settlements. Hence, there is the need to understand the link between critical infrastructure interdependencies and emergency management, especially in developing countries such as Nigeria. In addition, the country will be better poised to reduce risks and impacts associated with emergency events, thereby going a long way in achieving the purpose of the Hyogo Framework for Action for emergency reduction and management.

4. Study area description

The study was undertaken in Abeokuta, a rapidly growing urban centre of Ogun State in southwestern Nigeria. Comprising two local government areas, Abeokuta North and Abeokuta South, the study area, as shown in Figure 1, covers an approximate area of 781.16 km^2. Abeokuta lies between longitudes 3°E and 3°25′E and latitudes 7°3′, 11.375″N, and 7°25′, 6.294″N. It is bounded in the west by Yewa North local government, in the south by Ewekoro and Obafemi-Owode local governments, in the east by Odeda local government, while in the north it is bounded by parts of Imeko-Afon and Odeda local governments as well as the southern part of Oyo State. Administratively, Abeokuta has a total of 31 political wards and a projected population of 602,022, estimated by applying an annual state growth rate of 3.3 per cent to the 2006 National Population Commission (NPC) figure of 449,088.

Abeokuta, like many indigenous cities of Nigeria which emerged as administrative centres, has witnessed massive haphazard development. Its proximity to Lagos, the former federal capital and industrial base of the nation, has contributed significantly to the sporadic growth of the city, especially in the last two decades. However, until recently, the city of Abeokuta has not experienced any marked difference in its spatial extent. This is shown by the thick concentration of buildings and structures at the core of the indigenous areas of the city, which also doubles as the commercial nodes of the city. The effects of the unplanned development of Abeokuta are particularly noticeable in narrow roads, especially in the congested city centre and adjacent developing sprawls. These, in many cases, affect vehicular traffic and results in bottlenecks, a situation not favourable for emergencies, as there are no dedicated routes for vehicles on emergency services. Another challenge that may limit effective emergency management in the city is the location of the two fire stations



Notes: (a) Nigeria; (b) Ogun State; (c) Urban Abeokuta

Figure 1.
Map

(FRFT) in the city. Apart from being outside the United States Insurance Services standard of 1.5 miles and 2.5 miles service area for fire service stations with engine and trucked ladder respectively, Abeokuta is serviced by only ten linearly arranged fire hydrants (FH) (Baloye and Palamuleni, 2016). The unplanned development in the city, characterized with skewed distribution of infrastructure and continuously declining meagre resources, its increasing population and its rapidly increasing risk profile underline the need to examine the robustness of the city's critical infrastructure as a prototype for cities of developing countries.

5. Materials and method

Primary and secondary data were used for this study. Primary data included coordinates of some of the infrastructure used in the study, acquired with handheld GPS receivers. Secondary data were acquired from the archive of some of the agencies in charge of the infrastructure, particularly the Power Holding Company of Nigeria (PHCN), the country's electricity company. Seven sectors of urban infrastructure were used and in each sector, essential elements of interest were considered (Table I).

The study was based on a 2D representation decomposed into points, lines, and polygons. The entity-relationship (E-R) diagram shown in Figure 2 shows the concise description of the spatial relationships and constraints existing among the various elements of interest in the study. In other words, the, E-R diagram describes the objects of interest, otherwise called entities, together with the relationships among them; where entities are instances of entity types and relationships are instances of relationship types. It also includes the cardinality ratio which shows the minimum-maximum participation in the relationship existing between entities. Figure 3, on the other hand, shows the geometric composition of the elements.

Analysing the interdependencies existing among critical infrastructure usually involves two stages. First is the detailed analysis of the initiating event or sometimes referred to as the causative agent responsible for the emergency. At this stage, a detailed understanding of the behaviour of the agent is required. This involves describing the nature of the emergency agent, the spatial behaviour of the event, and other environments in which event

Urban sector	Critical infrastructure elements	Aliases
Transport	All classes of roads including highways	ROADS
	Bridges	BRDG
Water supply	Water pipelines	WP
	Water fittings	WF
	Fire hydrants	FH
Public health services	Hospitals of all levels and types	HSPT
Emergency services	Police station	PLST
	Fire fighter station	FRFT
	Road safety corps	FRSC
Power (electricity distribution)	Substation transformer	PSST
	Injection_substation	PHIS
	High_tension_line	PPHTL
	High_tension_poles	HTP
	Low_tension_poles	PLTP
	Low_tension_service_line	PLTL
	PHCN_Customer_line	PCSL
	PHCN_Feeders	PHFD
	PHCN_upriser	PHUP
Oil and gas	Gas stations	GAST
Banking and finance	Banks/ATM	ATMB

Table I.
Classes of urban critical infrastructures used for the study

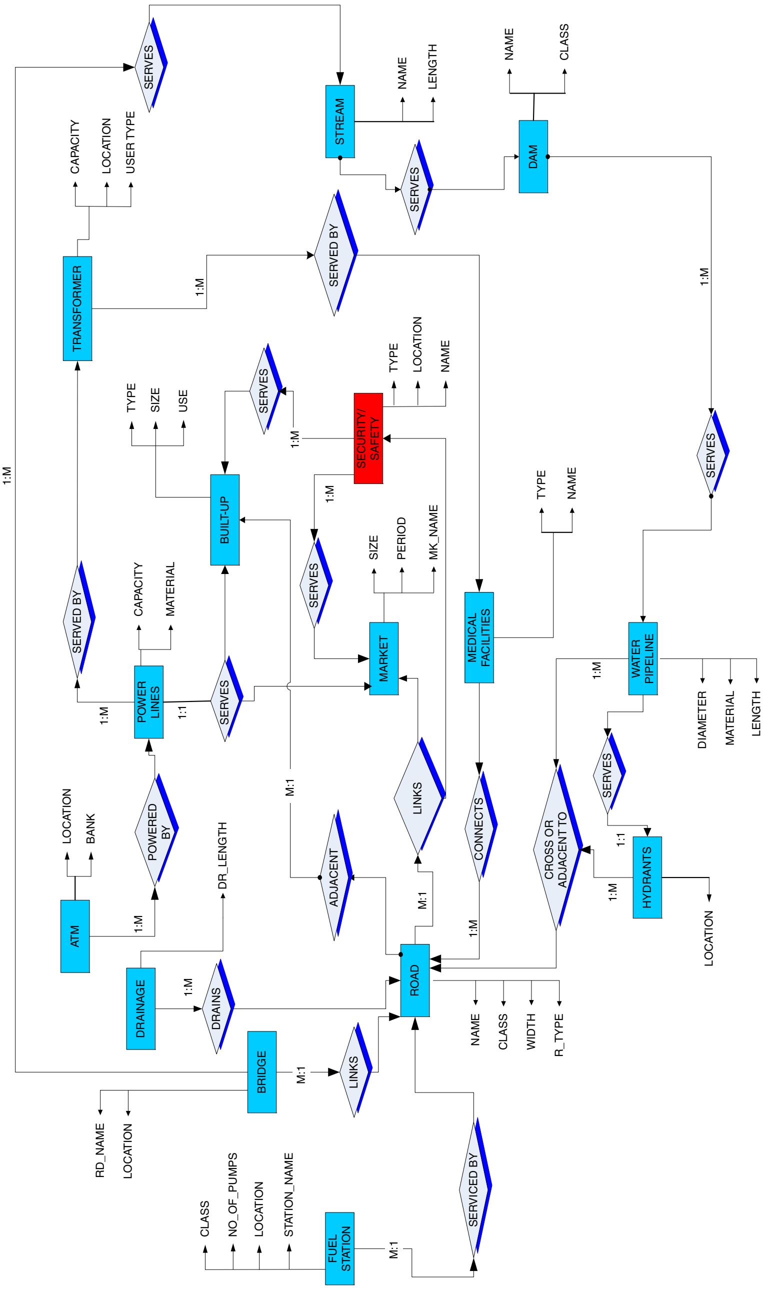


Figure 2.
Entity-relationship diagram of critical infrastructures in Abeokuta

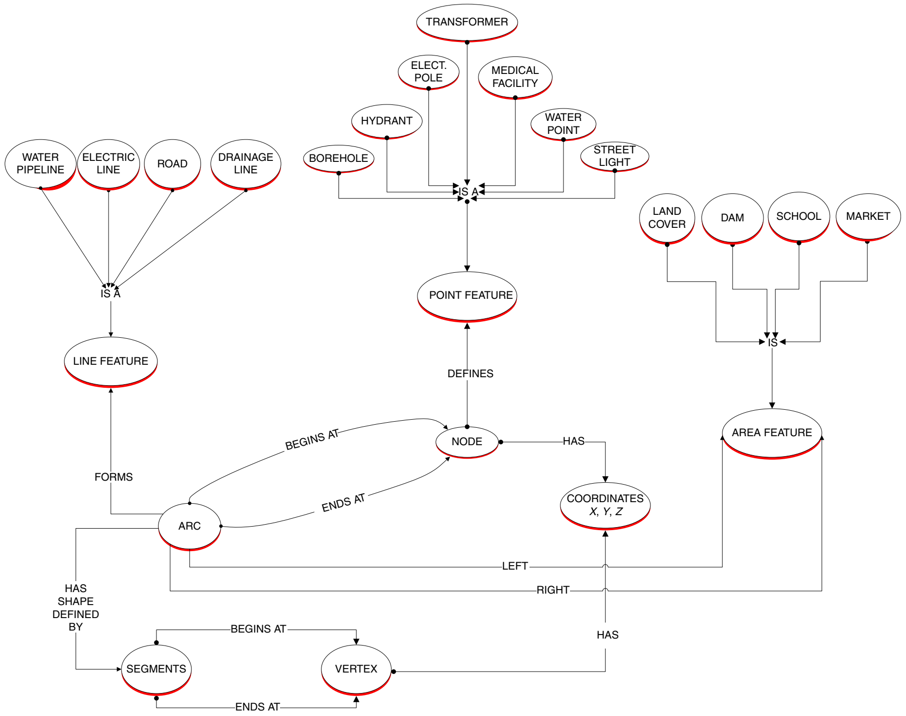


Figure 3.
Geometric composition of urban critical infrastructures in Abeokuta

types take place. Second are the qualitative and quantitative analyses of identified existing critical infrastructure.

For this study, three initiating events of fire, flood and automobile crashes were used. In each of these events, detailed analysis of the likely effects of the initiating event or contingencies was evaluated by analysing the effect of the event on all participating critical infrastructure and their subcomponents or elements. This was done on the basis of the probability of occurrence of the contingences, the frequency of occurrence of the event, the spatial extent of the impact of the contingencies, and the extent of damage in terms of the impact. For the probability and frequency of occurrence as well as the extent of damage, four classes were created namely: low, medium, high and very high.

Using the spatial extent of the event, three classes were identified namely, no coverage, implying that no area occupied by the critical infrastructure is affected; total coverage, signifying that the event, say flood, can affect the total area occupied by the critical infrastructure, for instance, the spatial relationship between flood and bridges; and partial coverage, which signifies that the event can occupy some part of the geographical area covered by the critical infrastructure. Using the tables of probabilities and occurrences, a cascade matrix was generated to analyse the level of interaction or interdependencies between the participating critical infrastructures in the study area. Further, a model of cascade effects using a typical emergency was generated using a software model of network trace functions.

6. Results

The probability that an emergency event will affect critical infrastructure varies among the infrastructure and their components (Table II). Two factors were considered in this

Table II.
The probable level of occurrences and effects of flood on critical infrastructure

Infrastructure	Probability of Occurrence	Frequency of Occurrence	Coverage	Extent of Damage
ATMB	Low	Low	Partial coverage	Low
BRDG	High	High	Total coverage	High
BULD	Medium	Medium	Partial coverage	High
PLST	Low	Low	Partial coverage	Low
FRFT	Low	Low	Partial coverage	Low
FRSC	Low	Low	Partial coverage	Low
GAST	Low	Low	Partial coverage	Low
HSPT	Low	Low	Partial coverage	High
PPHTL	Low	Low	No coverage	Low
HTP	Medium	Medium	Partial coverage	Medium
PLTP	Medium	Medium	Partial coverage	Medium
PLTL	High	High	No coverage	High
PCSL	High	High	No coverage	High
PHFD	Low	Low	Partial coverage	Medium
PHIS	Low	Low	Partial coverage	Medium
PHUP	Low	Low	Partial coverage	Medium
PSST	Medium	Medium	Partial coverage Total coverage	Medium
ROAD	High	High	Total coverage	High
WF	Low	Low	Total coverage	Low
WP	Low	Low	Total coverage	Low
FH	Low	Low	Total coverage	Low

respect: the topography of the immediate location of the infrastructure and the closeness of the infrastructure to the event.

With respect to probability of flood affecting critical infrastructure, those that return high, for instance, bridge, low-tension_service_lines, PHCN_customer_lines and roads, are either in close proximity to the flood channel or that the floodwater can cause a displacement in the location of the infrastructure. The frequency of occurrence, which was based on experience of previous interactions between flood and critical infrastructure in the study area, shows that only bridge, roads, electricity service poles and lines have been affected by flood in the past, while others have recorded low or medium occurrences. On the extent of coverage, only bridge, roads and water distribution pipelines and fittings usually experience total coverage during flood, while in some cases, partial coverage or no coverage has been recorded by other infrastructures. The extent of damage of critical infrastructure by flood shows that bridges, buildings and roads can be severely damaged during severe floods.

Table III shows the probable occurrence of fire and its extent of damage on critical infrastructure. The distribution shows that the probability and occurrences of fire on subsurface and supersurface critical infrastructure elements, such as water fittings and high-tension wire, respectively, is low. Also rescue and emergency facilities such as police stations (PLST) and FRFT have low chances of being affected by fire. However, facilities such as gas stations (GAST), some components of electricity distribution such as injection substation, feeder pillars, uprisers, substation transformers as well as buildings in the study area have high probability of being damaged by fire. Depending on the spatial proximity to the initiating point of fire, the coverage may vary from partial to total coverage.

On the probability and occurrence of automobile crashes on critical infrastructure, Table IV shows that roads and facilities in close proximity to them, like low-tension service poles, lines and PHCN customer lines are usually the most affected. Facilities such as buildings, high-tension poles (HTP) and lines have medium impact from automobile crashes,

Infrastructure	Probability of occurrence	Frequency of occurrence	Extent/coverage	Extent of damage
ATMB	High	High	Total coverage	High
BRDG	Low	Low	Partial coverage	Low
BULD	High	High	Total coverage Partial coverage	High
PLST	Low	Low	Total coverage Partial coverage	Medium
FRFT	Low	Low	Total coverage Partial coverage	Medium
RFSC	Low	Low	Total coverage Partial coverage	Medium
GAST	High	High	Total coverage	High
HSPT	Medium	Low	Total coverage Partial coverage	Medium
PPHTL	Low	Low	No coverage	Low
HTP	Low	Low	No coverage	Low
PLTP	Medium	Medium	Partial coverage	High
PLTL	Medium	Medium	Partial coverage	High
PCSL	Medium	Medium	Partial coverage	High
PHFD	High	High	Partial coverage Total coverage	High
PHIS	High	High	Partial coverage Total coverage	High
PHUP	High	High	Partial coverage Total coverage	High
PSST	High	High	Partial coverage Total coverage	High
ROAD	Low	Low	Partial coverage	Low
WF	Low	Low	No coverage	Low
WP	Low	Low	No coverage	Low
FH	Low	Low	No coverage	Low

Table III.
The probable level of occurrence and effect of fire on critical infrastructure

depending on the speed and size of the automobiles involved. On the other hand, other facilities have low probability of occurrence, coverage and extent of damage from automobile crashes, except where there are cascade effects.

Moreover, the interdependencies existing between selected critical infrastructures, under various emergency events, were generated using a weighted cascading effect matrix that compares the likelihood of cascading effects among critical infrastructure. As shown in Table V, every participating element of critical infrastructure in the study was evaluated against one another. The matrix has three probability dimensions of no, low and high probability in the weight order of 0, 1 and 2. The weighted score reflects the possibilities of having a direct or indirect dependency among the elements of the critical infrastructure. Thus, the cascading effect matrix describes the probability of the effect of any possible emergency event on a critical infrastructure or its component influencing other critical infrastructure or their elements.

As could be seen on the matrix, the summed weighted value of between zero and 9, classified as low cascade effects, is found among elements of the critical infrastructure that other critical infrastructure or their elements have low influence on. For instance, ATMs/banks (ATMB), PLST and FRFT may be minimally affected by other elements. Their inclusion in the matrix shows that they have some level of influence on other components in the matrix. While there may not be absolute direct relationships between these classes of critical infrastructure, services provided by them could determine the speed with which the impact or effect of contingencies may be propagated or curtailed.

Infrastructure	Probability	Frequency of occurrence	Extent/coverage	Extent of damage
ATMB	Low	Low	Total coverage	Low
BRDG	Medium	Medium	Partial coverage	Low
BULD	Medium	Medium	Partial coverage	High
PLST	Low	Low	Partial coverage	Low
FRFT	Low	Low	Partial coverage	Low
RFSC	Low	Low	Partial coverage	Low
GAST	Medium	Medium	Partial coverage	Low
HSPT	Low	Low	Partial coverage	Medium
PPHTL	Medium	Medium	No coverage	Low
HTP	Low	Low	No coverage	Low
PLTP	High	High	Partial coverage Total coverage	High
PLTL	High	High	Partial coverage Total coverage	High
PCSL	High	High	Partial coverage Total coverage	High
PHFD	Low	Low	No coverage	Low
PHIS	Low	Low	No coverage	Low
PHUP	Low	Low	No coverage	Low
PSST	Medium	Medium	Partial coverage Total coverage	Medium
ROAD	High	High	Total coverage	High
WF	Low	Low	Total coverage	Low
WP	Low	Low	Total coverage	Low
FH	Low	Low	Total coverage	Low

Table IV.
The probability of critical infrastructure being affected by automobile crash effect

CI	ATMB	BRDG	BULD	PLST	FRFT	FRSC	GAST	HSPT	PPHTL	HTP	PLTP	PLTL	PCSL	PHFD	PHIS	PHUP	PSST	R	RD	WF	WP	FH	WCV	CE
ATMB		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Low
BRDG	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	3	Low
BULD	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	3	Low
PLST	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Low
FRFT	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Low
RFSC	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Low
GAST	0	0	2	1	1	1		1	0	0	0	0	1	0	1	1	1	0	1	0	0	0	11	Medium
HSPT	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Low
PPHTL	2	0	2	2	2	2	2	2		2	1	2	2	2	2	2	2		0	0	0	0	29	High
HTP	2	0	2	2	2	2	2	2	2		1	2	2	2	2	2	2	0	0	0	0	0	29	High
PLTP	2	0	2	2	2	2	2	2	0	0		2	2	0	0	1	2	0	0	0	0	0	21	High
PLTL	2	0	2	2	2	2	2	2	2	2	1		2	0	0	1	2	0	0	0	0	0	24	High
PCSL	2	0	2	2	2	2	2	2	0	0	0	2		0	0	0	2	0	0	0	0	0	18	Medium
PHFD	2	0	2	2	2	2	2	2	2	1	0	2	2		1	2	2	0	0	0	0	0	26	High
PHIS	2	0	2	2	2	2	2	2	0	0	1	2	2	1		2	2	0	0	0	0	0	24	High
PHUP	2	0	2	2	2	2	2	2	0	0	0	0	2	1	0		2	0	0	0	0	0	19	Medium
PSST	2	0	2	2	2	2	2	2	0	0	0	1	2	1	0	2		0	0	0	0	0	20	High
RIVER	0	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0		2	1	1	1	9	Low
ROAD	0	0	2	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0		1	1	1	15	Medium
WF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2	2	4	Low
WP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2		2	4	Low
FH	2	0	2	2	2	0	2	2	0	0	0	0	0	2	2	2	2	0	0	0	0		20	High

Table V.
Weighted cascade effect matrix

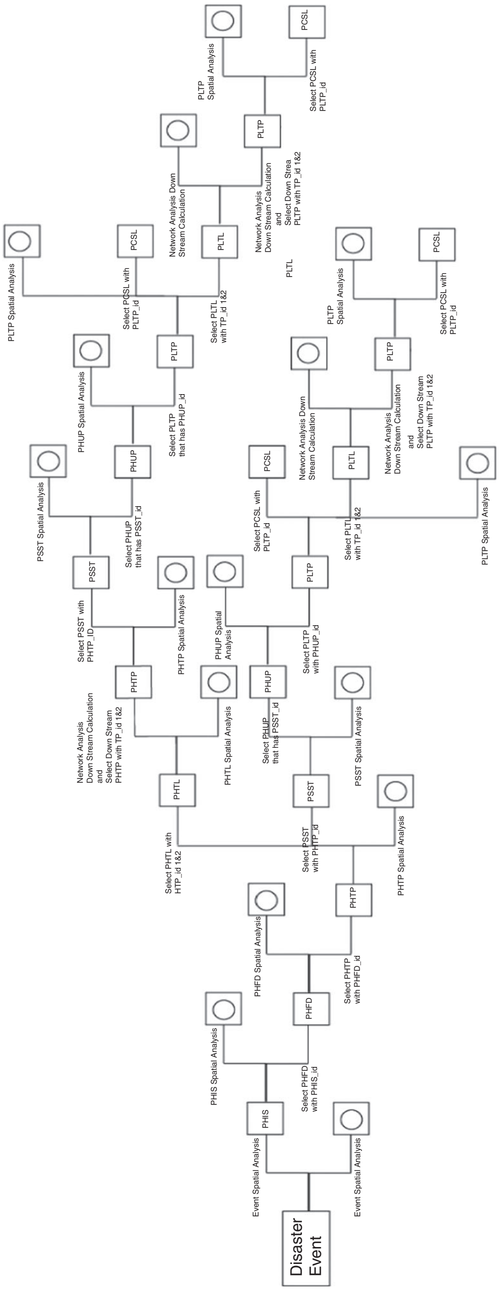
Also, infrastructures such as GAST, customer electricity distribution lines (PCSL), substation transformer uprisers (PHUP) and roads (ROADS) have medium cascade effect values of between 10 and 19, implying that they have moderate level of influence during any type of emergency. As could be noted, the influence exerted by this group of critical infrastructure is mostly on those components of critical infrastructure whose services are required in mitigating or managing contingencies. For instance, gas station, user-end electricity facilities such as customer service lines and roads provide accessibility for locations to and from emergency initiating points. On the other hand, the highest cascade effect is found among HTP and lines (PPHTL), low-tension poles (PLTP), and low-tension service lines (PLTL), electricity feeders (PHFD), substation transformers (PSST) and injection substations (PHIS). FH also fall among the critical infrastructure with a high cascade value.

Owing to its centrality in the independency interactions of critical infrastructure, not only in the general urban system functioning but also in the management of contingencies, the electricity distribution components of critical infrastructure in the study area were further analysed to show the typical cascade nature of critical infrastructure components. As shown in Figure 5, a cascade diagram, based on the network trace spatial analyses could be used to simulate possible reactions of each and every component. The diagram assumed an emergency event, and then traced the effects upstream and downstream of the various components of the electricity distribution system.

From an initiating point, the cascading diagram assesses each succeeding component; if a possible effect is encountered, the diagram traces the network further; otherwise, the trace is terminated. For instance, a trace from the injection substation (PHIS) could be performed and if there is no effect, the trace terminates, but when there is an effect on the PHIS, the effect cascades into the feeders (PHFD). At this stage, the effect is traced further by generating a query which fetches all feeders served by the affected injection substation (PHIS) using their identifier, that is PHFD_id. If the effect terminates, the network trace is also terminated, but if it cascades further, the effect will be on the HTP carrying the high-tension wires. The effect from the feeders can cascade into a nearby or connected local transformer. The affected transformer (PSST) can be traced by searching for the PSST having the identifier of the affected feeder through the high-tension pole (PHTP) carrying it. For a further trace, the effect from PSST cascades into the upriser (PHUP) taking power from the PSPT. At this point, the effect goes into the PLTP carrying the service lines. Affected low tension lines (PLTL) can be identified using an identifier of the poles carrying the lines (TP_id) from this point and a downstream calculation to select all affected customer service lines (PCSL) can be performed. In cases of multiple effects from a single initiating point, a spatial analysis can be performed on the network to trace the effect at the same time from the same point, to different cascaded infrastructures.

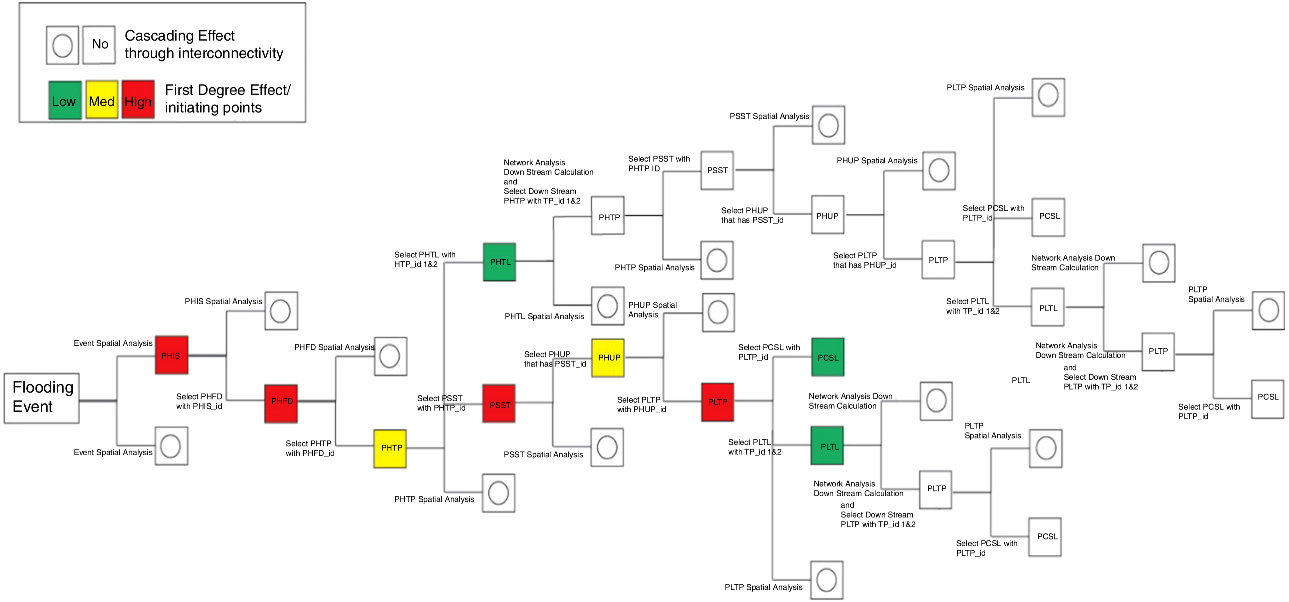
Specific reactions or first-degree effect scenarios of electricity infrastructure components were also simulated for flood emergencies. This was carried out by combining the results obtained in Tables II-V with that of Figure 4, thereby by showing the cascading effects on electricity components explicitly. As shown in Figure 5, high degree effects were recorded at injection substations (PHIS), feeders (PHFD), substation (local) transformers (PSST) and PLTP. This implies that the effect of flood on the highlighted points on the network is great. For instance, under a heavy flood accompanied by continuous rain, the feeders, PLTP, and transformers are more likely to be damaged and other connecting components have equivalent or more aggravated impact. On the other hand, high-tension lines (PPHTL), low-tension lines (PLTL), and customer service lines (PCSL) recorded a low cascading effect. Uprisers (PHUP) and high-tension lines (PHTP) have medium effects.

To further show the interdependencies existing among the critical infrastructure, especially during emergency events, cascading effects from special facilities under flood,



Notes: PHUP: PHCN Upriser; PHFD: PHCN Feeder; PSST: Substation Transformer; PPHTL: High Tension Line; HTP: High Tension Pole; PLTP: Low Tension Pole; PLTL: Low Tension Line; PCSL: PHCN Customer Line; PHIS: PHCN Injection Substation; PDSL: Distribution Substation_Line

Figure 4.
Electricity infrastructure interdependencies



Notes: PHUP: PHCN Upriser; PHFD: PHCN Feeder; PSST: Substation Transformer; PPHTL: High Tension Line; HTP: High Tension Pole; PLTP: Low Tension Pole; PLTL: Low Tension Line; PCSL: PHCN Customer Line; PHIS: PHCN Injection Substation; PDSL: Distribution Substation_Line

Figure 5.
Electricity interdependencies under flooding contingency

fire, and automobile crashes were highlighted. As shown in Figure 6, the special facilities were created based on the spatial proximity of the facility to the initiating point, their criticality functions as well as their capability to initiate, influence or escalate the cascading effects. For instance, under fire outbreak, GAST were identified as special facilities while in flooding cases, bridges, roads and buildings were identified as special facilities, with only road and any other facility close to the initiating points, selected in automobile crashes. The selection of these special facilities were rather based on intuition and assumed values.

7. Discussion and conclusion

The study attempted to create the needed awareness at all levels of decision making for the recognition of the interplay of critical infrastructure in contingencies and their management.

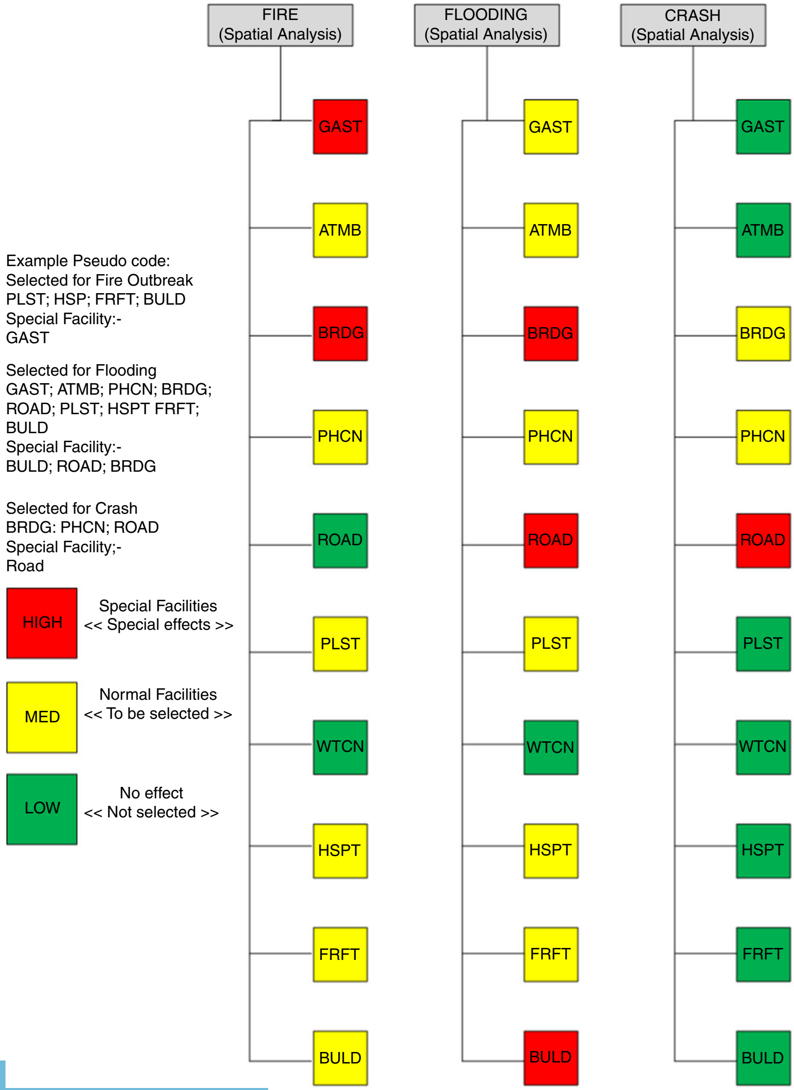


Figure 6.
Software model of first-degree effect from fire outbreak, floodingand automobile crash

By highlighting the dangers associated with the non-inclusion of different components of critical infrastructure in emergency management processes, the study aimed to score a three-fold point of: reducing damages to critical infrastructure and their components as a result of the present limited understanding of the vulnerability of these facilities during emergency events; improving emergency management and coordination, thereby significantly reducing response time and efficiency of the whole management process; and thereby helping to achieve the overall goal of the Sendai framework of substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries.

To achieve this global action locally, the study assessed the coverage and extent of damage from probable and actual occurrences of urban contingencies. As could be seen from the results, flood has the lowest probability of affecting the critical infrastructure in the study area followed by automobile crashes and fire. However, the records indicate that fire outbreaks have the highest occurrence Abeokuta, followed by automobile crashes and flood. In terms of the extent of damage to critical infrastructure, flood shows the least possible damage followed by automobile crash and then fire. Also, the extent of damage on critical infrastructure components suggest that fire outbreaks tend to affect more the critical infrastructure components compared to flood and automobile crash. Furthermore, it can be noted that damage on electricity distribution components is common under the three emergency events analysed.

It is important to note that critical infrastructure types with the highest cascade effects are mostly those associated with electricity distribution, affirming the study by Rinaldi *et al.* The implication is that for effective emergency preparedness, response and mitigation, the electricity distribution subsystem must be properly protected, as it becomes useful in information sharing, especially in emergency reporting, coordination and restoration. Another very vital component that requires attention, by the virtue of its weight in the matrix, is FH infrastructure. As at the time of the study, the city of Abeokuta had ten FH located almost linearly along some major roads. In cases where access to these crucial infrastructure components is broken, the effect may be more than can be tolerated. This underlines the importance of protecting all critical infrastructures with high cascading values before, during and after emergencies.

This paper underlines the need to pay greater attention to protecting critical infrastructures in rapidly growing cities, especially in developing countries. Findings from this study in Abeokuta, Nigeria, underscore the needs to expand the prevailing critical infrastructure protection beyond current power and oil sectors in the national development plan. They also highlight the urgency for greater research attention to critical infrastructure inventories. More importantly, the results stress the need for concerted efforts towards proactive emergency management procedures, rather than maintaining the established “fire brigade, window dressing” approach to emergency management, at all levels of administration.

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