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Vulnerability Assessment of Climate Change Impact on Critical Oil/Gas Infrastructure: A Decision-Maker's Perception in the Niger Delta

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Abstract: The impacts of climate change arising from flooding, the intrusion of high saline tidewater, rising temperature, wind storms, and rising Atlantic level are exacerbating significant threats to oil and gas critical installations in the Niger Delta. Understanding the hierarchies of vulnerable critical infrastructure could help assets managers in the industry to adopt sustainable adaptation measures against the looming impacts of climate change–induced stress on systems. In this article, the analytic hierarchy process (AHP) is implemented in prioritising vulnerable critical oil and gas infrastructure in the Niger Delta for effective and sustainable adaptation planning and response. A mix of an exploratory investigation involving interdisciplinary participants' engagement in focus groups were conducted in four multinational oil companies in the Niger Delta to elicit data for analysis. Participants in the study compared seven selected critical installations using an AHP questionnaire. A Mi-AHP spreadsheet analysis of stakeholders' perceptions revealed infrastructure vulnerability in hierarchical form: pipelines, terminals, roads/bridges, flow stations, loading bays, transformers/high voltage cables, and wellheads. The study shows that the vulnerability in the region is influenced by exposure, the presence of climate burdens, and proximity to inundated coastal areas below 4.5 meters above sea level. It also shows that critical systems are vulnerable due to interdependence and level of linkages that exist between directly vulnerable and non-directly vulnerable assets. Results also show that vulnerability in the region is due to critical perception, age and obsolescence, and weak adaptive capacity. This study furnished decision-makers in the oil and gas sector with information on which infrastructure is to be protected in terms of adaptation planning, investment, and implementation with particular attention on climate change.

Keywords: Vulnerability Assessment, Climate Change, AHP, Infrastructure, Niger Delta

Introduction

The consequences of climate change impacts are severely affecting built systems in the Niger Delta coast. The coastal land is being submerged by rising sea level and Atlantic tides at an unprecedented rate, faster than scientific predictions (Udie, Bhattacharyya, and Ozawa-Meida 2018a, 11). The geographical location and deltaic nature of the region are attributed for intensifying climate stressors and further impacts on communities and inherent oil and gas infrastructure (Taft and Haken 2015). The Niger Delta is a sensitive region in Nigeria and West Africa due to the intensive activities of fossil energy exploration, production, transportation, and processing. Oil and gas profits constitute about 83 percent of governments' revenue, 90 percent of export trade, and about 40 percent of gross domestic product for the Nigerian Economy (Uwubanmwen and Omorokunwa 2015). According to the OPEC (2016) report, there are 37,062 million barrels of proven crude oil reserve in the Niger Delta (Figure 1) with critical economic infrastructure that is vulnerable to climate change impact.

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Figure 1: Map showing the Niger Delta where vulnerable critical infrastructures are located in Nigeria.
Source: Badaru et al. (2014, 90–99)

Factors associated with emerging vulnerability include exposure to extreme climatic events due to geographical location, sensitivity, interdependency, obsolescence, weak adaptive capacity, prevailing climate burdens and proximity (Straub 2008; Smit and Wandel 2006; Moteff and Parfomak 2004). Increased frequency of extreme events augmented by these factors has triggered the attention of stakeholders (government agencies, oil/gas multinationals, assets managers, experts, and academics) in recent times, calling for adaptation planning. The result is the urgent need for vulnerability assessment by prioritising critical assets for effective adaptation planning and investment.

More so, the rise in global temperature can cause a corresponding rise in local temperature within the operational environment of some critical assets such as flow stations, compressors, and storage tanks (Udie, Bhattacharyya, and Ozawa-Meida 2018b). High ambient temperature can trigger the malfunctioning of these systems and reduce crude oil output, cause infrastructure damage, and reduce efficiency (Tingley and Huybers 2013). Increased temperature and salinity of ocean water from tidal intrusion can result in corrosion of crucial cathodic and carbon steel systems which can rupture prematurely due to wear and tear (Zhang and Zhuang 2003). Heavy rainfall, on the other hand, is causing flooding in nearly all onshore platforms, infesting residential sites and local communities with wild reptiles and the spread of diseases. The exploratory investigation of this study indicated that personnel on board (POB) of oil/gas platforms in the Niger Delta are frequently reduced due to flood and the above-mentioned direct and indirect impacts on the systems (Ologunorisa 2004). These secondary impacts make the entire environment, including marginal platforms and access to offshore, dangerous to operate. A scoping investigation of the research area showed that tropical storms, lightning, and thunderstorms are also on the increase in the region, widening the index of vulnerability (Rowan et al. 2013). The investigation revealed that the impact of thunderstorms and regular lightening charges on metallic systems have been reported as a potential for fire ignition and combustion and, hence, constitutes a very high risk for oil/gas field installations. However, recent research into renewable hydrogen energy options has argued that critical renewable infrastructure could also be vulnerable to thunderstorms induced by torrential rainfall (Rahil and Gammon 2017). The unpopularity of renewable options in the Niger Delta context is failing to provide a realistic alternative to fossil energy, hence the need for protection of oil/gas systems from climate change–induced destruction. Vulnerability assessment of critical oil/gas infrastructure by prioritising existing and planned systems is a crucial approach to adaptation planning (Rutherford, Hills, and Tissier 2016). As a result of effective and sustainable adaptation planning, investment in critical assets protection could be incentivised.

Weak adaptive capacity poses a serious risk not only to critical infrastructure but also to the social, economic, and environmental well-being of the host communities and the entire country. Therefore, a pragmatic approach to vulnerability assessment with the view to profiling systems in order of susceptibility could assist with the focus of attention toward sustainable adaptation alternatives (Kates, Travis, and Wilbanks 2012).

The main question, therefore, is how are critical oil/gas infrastructures exposed to climate change burdens in the Niger Delta? The purpose of this article is to present the systematic application of analytic hierarchy process (AHP) in evaluating the vulnerability of critical infrastructure to extreme climate events in the Niger Delta oil/gas industry.

Vulnerability and Criticality of Infrastructure

The phenomenon of vulnerability has been explored from different subject backgrounds with various contextual definitions. Vulnerability is usually associated with weaknesses, predisposition, deficiencies, and absence of adaptive capabilities, which permit the impacts of adverse events. In the context of the Niger Delta, it is the lack of resilience and resistance of exposed infrastructures, such as flow stations, pipelines, roads, bridges, and terminals, to extreme climatic events (Birkmann et al. 2013; Smith et al. 2009; Bizikova et al. 2009). Criticality of an asset, on the other hand, is the evaluation of an infrastructures' disruption and its cascading negative effects on the economy, environment, and social systems (Alcaraz and Zeadally 2015). These views on vulnerability and criticality define the present situation of oil/gas assets in the Niger Delta. Hence, this article identified and prioritised vulnerable critical infrastructure to climate change impacts. This is necessary for urgent sustainable adaptation planning and investment for susceptibility installations in the industry.

Severity of Climate Impacts in the Niger Delta

The severity of climate change impacts on critical infrastructure in different regions has been investigated using various scientific approaches and stochastic models (Yuen, Jovicich, and Preston 2013; Islam and Malak 2013). The severity of climate change impact on oil/gas infrastructure in the Niger Delta could be attributed to lack of investigations that focus on ranking the most exposed systems. Hence, adaptation planning for vulnerable critical systems has remained a challenge for stakeholders in the industry, leading to various degrees of exposure and impact from flood, wind, temperature, and tidal intrusion. Adelekan (2011) conducted research on the vulnerability of urban areas in South Western Nigeria to flooding through opinion sampling of urban dwellers. Though this was in a quasi-region to the Niger Delta, he argued that 50 percent of respondents agreed that they were experiencing severe flooding impact on social housing and critical infrastructures such as electrical installations, telecommunication systems, roads, and bridges. Roads and bridges are the most relevant transportation infrastructure in the Niger Delta—connecting cities and allowing easy movement of goods and services to and from onshore platforms (IPIECA 2013). Impact of flooding on roads and bridges could disrupt supply chain operations, alter communication, and cause an emergency shutdown of operational sites.

In the UK, Denner et al. (2015) conducted a vulnerability assessment of the coastal Loughor Estuary in Wales using the coastal vulnerability index, which examines physical parameters. The investigation revealed that shorelines were vulnerable due to the coastal slope and beach width and highlights that a significant percentage of critical infrastructures such as housing, energy, and transport assets located on the shoreline are vulnerable. These findings are indications that coastal infrastructure such as the oil/gas systems in the Niger Delta coast could be severely exposed and vulnerable to prevailing climate threats.

Research Methodology

This study was an empirical investigation that combined intensive fieldwork with desk reviews for critical analysis. Traditionally, decision-makers in the Niger Delta oil/gas industry depend on benchmarking approaches of other organisations to determine when infrastructure requires upgrades, reinforcement, or routine maintenance (Hassan and Kouhy 2013); organisations engage in management and board meetings to brainstorm possible emergency response strategies mainly for oil spills and pollution. The conventional approach could be irregular as the frequency of assessment is often sporadic.

This article presents an alternative approach through a multi-stakeholder engagement and an intensive exploration of relevant literature on climate change vulnerability, adaptation, and sustainability in the study area. From the review, seven criteria (indicators) were developed for evaluating the vulnerability of critical assets in the context of the Niger Delta. Further analysis in the exploratory stage identified seven alternative critical infrastructures for vulnerability assessment (see Table 1). Vulnerability criteria were used to prioritise selected critical infrastructure through a systematic pairwise comparison in an AHP matrix approach used in previous research conducted in other applications (Vaidya and Kumar 2006; Liaghat et al. 2013; Siraj, Mikhailov, and Keane 2015).

Table 1: Identified Criteria and Critical Infrastructure

S/N	Climate-based Criteria	Infrastructure
1	Exposure	Terminals
2	Adaptive capacity	Flow stations
3	Proximity	Roads and bridges
4	Presence of climate burdens or risks	Transformers and high voltage cables
5	Criticality	Pipelines
6	Age of infrastructure	Loading Bays
7	Interdependence	Wellheads

Source: Udie, Bhattacharyya, and Ozawa-Meida

In Table 1, exposure is defined as the level of susceptibility and/or the likelihood of being impacted by climate risks. For example, the extent to which systems built in inundated areas, located in coastal regions, or under the direct impact of temperature, flood effects, or storms, could be exposed (Hinkel 2011). Adaptive capacity is the ability of a built system to withstand or adjust to climate-induced impacts. Infrastructure with weak or no adaptive capacity could be judged as vulnerable to climate change impacts (Smit and Wandel 2006). Proximity is a physical parameter used to evaluate the distance between the location of a critical infrastructure and possible vulnerable locations. The closer a system is to environmental burden(s), the more likely it could be impacted (November 2004). Assessment based on “presence of climate burdens” as a criterion suggests that vulnerability is only a concern in scenarios of abundant impacts of climate change and where there is a high potential for impacts. Criticality, as used in this context, is the extent to which assets that are crucial to an economy, organisation, or agency could be disrupted and their cascading impacts on the economy, environment, and the society. “Age of infrastructure" directly relates to asset's obsolescence and the older an infrastructure, the weaker and more vulnerable it could respond to adjustments in climate burdens. Finally, "interdependence" refers to the inter-relatedness associated with critical systems across the oil and gas value chain such that impact on one end could cascade through the entire chain with serious effects (Chappin and van der Lei 2014; Kröger 2008). These criteria have been used by several researchers (Rezaei-Moghaddam and Karami 2008; Fekete 2011; Lai, Wong, and Cheung 2002; Kassab, Hegazy, and Hipel 2007) in assessing the vulnerability of different critical infrastructure in multiple industries at the global level.

Procedure for Selecting Decision-Makers

Nineteen participants (decision-makers) with a minimum of ten years' experience in the Niger Delta oil/gas industry were selected through stratification strategy in four international oil companies (IOCs). The sampling strategy used in this study consisted of a systematic approach adapted to scope data from participants mainly based on trust and confidentiality in restricted and high ethical organisations (Atkinson and Flint 2001). They include assets managers, environmental officers, and servicing contractors with the required experience in their respective area. Participants were randomly placed into four independent focus groups and familiarised with the assessment process. AHP questionnaires were administered accordingly for data collection. Data from the groups were merged and independently incorporated into the Goepel (2013) multiple inputs (Mi-AHP) excel spreadsheets for quantization.

Application of AHP in Prioritising Vulnerable Critical Infrastructure

The first step in the application of AHP in prioritising vulnerable infrastructure for climate adaptation planning involves a systematic matrix of pairwise comparison process based on stakeholder perceptions (Vaidya and Kumar 2006). Identified criteria and infrastructures are compared in a 7 X 7 matrix illustrated in equation one to determine individual criteria weights:

$$\mathbf{A} = \begin{vmatrix} a_{11} & a_{12} & a_{13}\ldots a17 \\ a_{21} & a_{22} & a_{23}\ldots a27 \\ a_{71} & a_{72} & a_{73}\ldots a77 \end{vmatrix} == equation\ 1$$

Where if $a_{ij} = 1$, $a_{ji} = 1/a_{ij}$ (example; if $a_{13} = 5$, $a_{31} = 1/5$);
If $a_{ii} = 1$; i and j are equally important, and if $a_{ij} = a_{ji} = 1$
aij is used to determine their relative importance of *i* with respect *j*.

The second step of pairwise comparison focused on brainstorming and prioritisation of infrastructure for vulnerability. The completion process followed a criterion-by-criterion pairwise comparison process to underpin the vulnerability of each infrastructure to each climate indicator above. Computation of responses was independently conducted and consolidated using the Mi-AHP spreadsheets.

An AHP-structured questionnaire was designed to suit Saaty's (2003) numerical scale (see Table 2) and used to compare alternatives (sample questionnaire is attached as an appendix). The pairwise process involves comparison of any two infrastructures based on a given criterion by assigning a weight (1–9) specified by the participants.

Table 2: Saaty AHP Numerical Scale

Numerical Scale	**Verbal Scale (interpretation)**
1	Equal important ($i = j$)
3	Moderate important (i is lightly important than j)
5	Strong important (i is strongly important than j)
7	Very strong importance (i is very strongly important than j)
9	Extreme importance (i is extremely important than j)
2, 4, 6, 8	Intermediate values

Source: Saaty (2008, 83–98)

Calculation of Principal Eigenvector

Seven separate Mi-AHP spreadsheets were created to evaluate the vulnerability of critical infrastructures based on each criterion. Results from each criterion are summarised by adding vulnerability scores for each criterion (see the blue column in Table 3). Consolidated scores for each infrastructure are calculated and normalised as principal eigenvectors (EV) and final vulnerability weights for the seven critical infrastructures. EV literally translates the participant's perceptions into the levels of susceptibility, exposure, and vulnerability of critical infrastructure under consideration. Vulnerability hierarchies are calculated by adding the row scores for each criterion vulnerability score.

However, for each criterion, 100 points are allocated to seven alternatives (infrastructures) in matrix columns based on vulnerability perception of participants. The Row Geometric Means (RGM) or EV are calculated for each infrastructure by the sum of each row by the application of the formula below:

$$\frac{RGM}{EV} = \frac{\sum score}{700}\ x\ 100 == \ equation\ 2$$

The AHP principle states that sum of RGM/EV must be equal to one, as in equation three.

$$RGM = \sum\ ((\sum score)/700\ \ x\ 100) = 1 == \text{Equation 3}$$

Normalised principal eigenvectors (EV) represent the vulnerability outcomes for each infrastructure. The sum of principal EV arising from the pairwise comparison and their normalisation provides accuracy and transparency (Goepel 2013; Dong et al. 2010; Saaty 2001) as well as validity of the assessment outcome. This procedure is in accordance with existing AHP applications conducted by Al-Harbi (2001), Jagtap and Bewoor (2017), Xu (2000), and Zimmerman (2004).

Results and Discussion

Participants pairwise compared the criteria to determine their individual weights. The weight of a criterion has a significant impact on the outcome of the vulnerability of alternatives (infrastructure) in the overall priority. The outcome of the criteria weighting is indicated in the AHP matrix (based on equation one) and is illustrated in Figure 2 below. The white section indicates average participants' numerical scale inputs while the grey section shows the reciprocals of entries. Normalised principal eigenvectors (EV) were calculated automatically from horizontal aggregates of mean values and represents the global weights of each criterion.

Matrix		Exposure 1	Presence of Burdens 2	Criticality 3	Proximity 4	Adaptive Capacity 5	Age of Infrastructure 6	Interdependence 7	Normalised principal Eigenvector
Exposure	1	1	3	5	1	5	3	1	27.47%
Presence of Burdens	2	1/3	1	1	1	3	3	3	17.09%
Criticality	3	1/5	1	1	1	3	3	1	12.61%
Proximity	4	1	1	1	1	5	5	1	17.92%
Adaptive Capacity	5	1/5	1/3	1/3	1/5	1	1/3	1/3	3.88%
Age of Infrastructur	6	1/3	1/3	1/3	1/5	3	1	1/5	5.59%
Interdependence	7	1	1/3	1	1	3	5	1	15.43%

Figure 2: Comparison matrix and normalised Eigenvectors for criteria

Source: Udie, Bhattacharyya, and Ozawa-Meida

The results indicated that exposure (27%), proximity (17.9%), and presence of burdens (17.1%) ranked first, second, and third, respectively. Interdependence (15.4%), criticality (12.6%), and age of assets (5.6%) were ranked fourth, fifth, and sixth, respectively, while adaptive capacity ranked least (3.9%). The implication is that the magnitude of the vulnerability of selected infrastructure depends on the weight of each criterion.

Table 3: Consolidated Result Computed from AHP Excel Spreadsheet on the Vulnerability of Critical Infrastructure

	Results from AHP Ranking of Most Vulnerable Critical Infrastructure								
Criteria Alternatives (infrastructure)	**Adaptive Capacity**	**Age of Infrastructure**	**Interdependence**	**Presence of Burdens**	**Exposure**	**Criticality**	**Proximity**	**Sum of Score**	**Normalised Principal (Ev) Values**
Terminal	6.1	11.4	34	18.3	17.3	19.4	12.4	**118.9**	**0.17**
Flow Station	6.1	13.4	10.5	11.2	6.8	28.8	10	**86.8**	**0.12**
Pipelines	23.2	27	16.9	36	25.3	19.2	25.1	**172.7**	**0.25**
Loading Bays	23.4	5.8	4.4	4.4	20.3	3.8	20	**82.1**	**0.12**
Roads/Bridges	12.1	17.5	17.3	15.6	12	11.1	13.4	**99**	**0.14**
Transformers/HVC	9.5	10.9	11.6	9.7	12.1	10.5	11.8	**76.1**	**0.11**
Oil Wellheads	19.6	14	5.3	4.8	6.2	7.2	7.3	**64.4**	**0.09**
Aggregate Score	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**700**	**1**
Consistency Ratio	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**9.1**	**0.09**
Consensus Level	**71**	**71.7**	**78.5**	**73.3**	**66.9**	**77.6**	**62.4**	**501.4**	**71.6**

Source: Udie, Bhattacharyya, and Ozawa-Meida

Analysis of Consistency Ratio (CR)

Table 3 shows calculated consistency ratios (CR) and prioritisation consensus arising from consolidated participant's comparison process in line with the AHP terms as calculated from Goepel (2015). A consistency ration of 0.09 is recorded, which implies that perception judgements of the participants were more accurate than recommended the 10 percent (0.1) and, hence, does not require revision (Saaty 2003; Xu 2000; e Costa, Bana, and Vansnick 2008). Hence, 9 percent CR is an indication of a near-perfect consistency in the participant's decision-making process and portrays the validity of the results, suitability of stratified participants, and effectiveness in the application of AHP. The CR outcome further justifies the effectiveness of applying AHP in collecting and converting qualitative data in quantitative forms in empirical studies. More details on how to apply and calculate CR in multi-criteria investigations are found in the works of Xu (2000), Al-Harbi (2001), Saaty (2001), Al-Harbi (2001), Saaty (2001), and e Costa, Bana, and Vansnick (2008).

Consensus Analysis

The accuracy of the consensus level in Table 3 is an indication of a corresponding positive participants' consensus in the overall vulnerability assessment outcome. The study produced 71.6 percent consensus, indicating that there was about a 72 percent level of agreement between participants prioritising critical infrastructure in terms of vulnerability. It further shows how the application of AHP could reduce bias in critical stakeholder judgement and organisational decision-making process. It agrees with the position of Dong et al. (2010) and Vaidya and Kumar (2006), who argued that though an absolute agreement is not expected from the application of AHP in interdisciplinary multi-criteria decision-making processes, a 60 percent consensus is acceptable with a high CR. It is being contended that if the consensus level is below 50 percent, alternative assessment models (geometric means, individual voting) could be used for further evaluation (Lai, Wong, and Cheung 2002). The consensus and consistency ratio outcome of this study meets all AHP application principles and negates plans of alternative approaches.

Discussion of Consolidate Results and Analysis

The normalised principal EV values aggregated in Table 3 were used to compute the principal priority ranking of critical infrastructure vulnerability to climate change impact in the Niger Delta context. It presents the results of the entire study in the order of most to least vulnerable among the selected systems, shown in Figure 4.

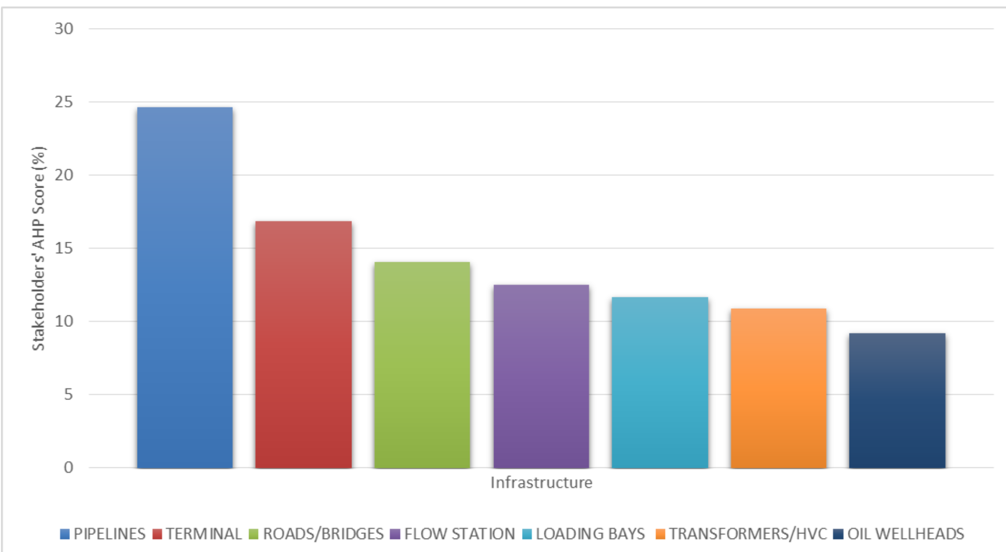

Figure 4: Consolidated result showing the level of vulnerability of critical infrastructure to climate change impact
Source: Udie, Bhattacharyya, and Ozawa-Meida

Vulnerability outcome is based on climate-based indicators such as exposure, adaptive capacity, the age of systems, proximity to risk factors, criticality and sensitivity, interdependence, and presence of climate burdens. The results indicated that the vulnerability of critical infrastructure is linked with the presence of climate burdens, assets obsolescence, and interlinkages of assets in the oil/gas value chain.

The results further indicated that pipelines are the most vulnerable critical assets to climate change in the Niger Delta with a vulnerability score of 25 percent. This result confirms that pipelines in the Niger Delta are both vulnerable to climate change impacts and social risks because they are often prematurely replaced due to vandalism (Obi 2014; Anifowose et al. 2012;

Ikelegbe 2005). Anifowose et al. (2012) further agreed with the reality of pipeline destruction, stressing that Nigeria has suffered its share of vandalism and substantial incidence of attacks and interdictions on oil and gas pipelines. This contends to have caused regular premature replacements and rehabilitation of pipelines, which are expected to reduce their vulnerability to climate risks in terms of obsolescence. Research participants further verified the constant replacement of pipelines, arguing that "our pipelines are not vulnerable to climate change because they are frequently being replaced." On the contrary, field personnel (engineer asset inspectors and environmental managers) argued unanimously that most pipelines (especially the carbon steel trunk lines) have been in place for more than five decades without being attacked. This implies that the constant replacement of critical pipelines may only reduce vulnerability due to age and obsolescence. More so, vandalised pipelines are often negligibly exposed flow lines compared with trunk lines, which remain vulnerable in-situ due to climate-induced impacts.

The above contradiction is likened to the opinion of Karapetrou, Fotopoulou, and Pitilakis (2017), who argued that "age" as a single attribute could be used in assessing vulnerability. Judging vulnerability based on age could skew adaptation planning in a complex and uncertain climate change scenario. This study proves that continual replacement of pipelines could only address the challenge of vulnerability due to age and obsolescence because the vulnerability of pipelines and other critical assets depends more on the other factors described in Figure 2. This study further proves that in the Niger Delta, "age of infrastructure" contributes second to the least weight (Figure 2) in prioritising vulnerable infrastructure. This implies that the effect of age is less significant in vulnerability assessment in the Niger Delta context.

Nevertheless, the study shows terminals (17%) and roads/bridges (14%) as the second and third most vulnerable infrastructure in the region. This is probably because most oil/gas terminals in the Niger Delta are located on the inundated coast of the Atlantic with projected loading bays into the ocean bight for badging and bunkering. The elevation of these terminals (between 0 and 5.4 m above sea level) signifies a high vulnerability due to proximity, criticality, exposure, and location. It described the threats and impacts of rising sea levels and Atlantic tides which regularly flood critical assets across the region (Tami and Moses 2015).

Roads and bridges are considered by some researchers as pedestal infrastructure in the region but the acceptability and ranking of roads and bridges as the third most vulnerable oil/gas infrastructure confirmed the criticality of road infrastructure in the Niger Delta scenario. An exploratory survey outcome on the criticality of roads in the region agrees with Moteff and Parfomak (2004) and Moteff, Copeland, and Fischer (2003), who classified road transport systems as national assets of priority and which could be vulnerable to environmental threats. Findings further align with Schweikert et al. (2014) who advocated for a robust system of maintenance for vulnerable road infrastructure. More so, the Niger Delta geographical area is characterised by several "bird foot" deltas and estuaries that require bridges and access roads between onshore operational platforms for easy freight and movement of people. The vulnerability of roads and bridges poses a serious challenge to daily movement and has the tendency of bridging supply chains.

In the case of flow stations (12.5%) and loading bays (11.7%), the study indicates an almost equal vulnerability, ranking fourth and fifth, respectively. The vulnerability of flow stations' might have emerged due to age, proximity, and sensitivity of the systems in the asset value chain. Loading bays, on the other hand, have weak adaptive capacities, suffers exposure, and share borders directly with Atlantic shore. Assets close to the sea shore are likely to be impacted by flooding, tidal waves, and inundation stress. Unlike the flow station, the loading bay is interim transport infrastructure between the terminal and the loading vessels and crude-carrying badges. It is exposed to flooding, sea level rise, high tides, and storms but relatively resistant to coastal adverse impact. It is often not sensitive as the *flow station* because its destruction may obstruct loading and unloading of crude materials but may not have a significant impact on the environment and human health and safety in terms of an oil spill. The vulnerability outcome and resilience of loading bays agree with Cabral et al. (2017) and Cardona et al. (2012), who argued that location or proximity could not be used to ascertain vulnerability of coastal systems if the system in place has high resilience and resistance to prevailing climate burdens.

From among the selected systems for this study, the least vulnerable are transformers and high voltage cables (HCV) with 11 percent and oil wellheads scoring 9 percent, ranking sixth and seventh in the prioritisation scale (see Figure 3). Transformers/HCV convey electricity from the grid across hundreds of miles to various platforms and facilities (Hall and Foxon 2014). The interconnectivity and linkages with other infrastructure could trigger the vulnerability of high voltage cables. Interdependence in this study has 15.4 percent weight in measuring vulnerability (see Figure 2). Wellheads priority outcome is probably due to their less complexity but very delicate assets in the first stratum of the upstream oil/gas infrastructure. Wellheads are cased and designed to function in isolation. Their low ranking is an indication of high adaptive capacity, minimal interdependence, and age as their life depends on the commercial viability of the well.

Conclusion and Recommendation

Since the 2012 flood disaster in the Niger Delta, multinational companies and government agencies have realised that critical infrastructures are vulnerable to climate change. This is because the severe impact of the 2012 flood overwhelmed available adaptive capacities of critical infrastructure and reactive emergency response systems. Oil revenue plummeted and devastated communities and several onshore oil/gas platforms. Most importantly, emergency responders were unable to release a response strategy according to the vulnerable systems; hence, about 500,000 barrels of crude oil were lost due to spill. These impacts motivated this study with the focus on ranking vulnerable critical infrastructure that could aid prioritisation, effective, and efficient adaptation planning in the regional industry. This study presents the first effective use of the analytical hierarchy process (AHP) approach in ranking critical oil/gas infrastructure through stakeholder participation in focus groups and intensive exploratory survey in the Niger Delta. Climate-based criteria developed for this study (exposure, age, criticality, interdependence, proximity, adaptive capacity, and presence of burdens) have been found suitable for evaluating climate change impacts and prioritisation of vulnerable critical assets. These could be adopted for evaluation of the vulnerability of similar or allied infrastructure in different sectors where climate burdens are felt. The results of this study present a sophisticated hands-on tool for decision-makers such as asset managers, field engineers, and consultants in the industry in deciding suitable adaptation and possible mitigation measures against climate change impact.

However, this study falls short in terms of suggesting possible adaptation strategies and their application processes for the industry. Further investigation is required to unveil suitable adaptation options such as substitution of carbon steel pipes with glass reinforcement epoxy (GRE) systems, infrastructure upgrade, timely decommissioning, and emergency evacuation planning systems. Future researchers could also consider the combination of AHP with other multi-criteria decision-making analysis (MCDA) tools such as analytic network process (ANP) and/or fuzzy AHP methods in assessing systems across the industry in different geographical locations with the aim of aiding hierarchical adaptation planning.

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