The 10th International Conference on Climate Change, Impacts and Responses;
University of California, Berkeley, 2018

Evaluation of Oil/Gas Infrastructure Exposure to Climate Change Burdens in the Niger Delta

Justin Udie[1], Subhes Bhattacharyya[2], and Leticia Ozawa-Meida[3]

Institute of Energy and Sustainable Development,
School of Engineering and Sustainable Development, Faculty of Technology
De Montfort University, The Gateway, Leicester, LE1 9BH, UK

Abstract

Climate change extreme weather events such as flood, rising temperature and windstorms pose significant threats to oil and gas infrastructure in the Niger. Due to a gap in evaluation of assets exposure in the region, little is known about their level of exposure hierarchies. In this paper, analytic hierarchy process (AHP) is used to evaluate the exposure of selected oil and gas infrastructure to prevailing climate burdens for sustainable adaptation planning. A combination of observational and interdisciplinary stakeholder decision-making process in four (4) multinational oil companies was used to elicit data through focus group and face-to-face interviews. Participants pairwise compared selected infrastructure using AHP questionnaire for pairwise comparison of infrastructure in a matrix system. Multiple-input (Mi-AHP) analysis revealed assets exposure to climate burdens in the following order; pipelines, terminals, roads/bridges, flow stations, loading bay, transformers/HVC and oil well-heads. Exposure is forces vulnerability of infrastructure to flood and direct heatwaves while the presence of climate burdens and proximity to areas below 4.5 m above sea level further exacerbate exposure. The research also found that interdependence, criticality, obsolescence, and adaptive capacity are other factors responsible for exposure and vulnerability of infrastructure in the Niger Delta. The result further revealed that infrastructure with weak adaptive capacities and significant obsolescence are more vulnerable if exposed to severe climate burdens. The outcome of this investigation provide hands-on data for responsible stakeholders and policymakers in the oil and gas industry for effective and sustainable planning and prioritisation of adaptation investment strategies.

Keywords: vulnerability assessment, climate change, AHP, infrastructure, Niger Delta

1. Introduction

The changing extreme weather situation due to climate change is constantly ravaging the inundated locations of Niger Delta coast at different levels. Coastal land is being submerged by rising sea level and Atlantic tides at an unprecedented rate; faster than scientific predictions. The geographical location and deltaic nature of the region are blamed for aiding climate stressors in exacerbating more impact on communities and inherent oil/gas infrastructure. 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 proceeds constitute about 83% of governments' revenue, 95% of export trade and about 40% of gross domestic products. According to (OPEC, 2016), there are 37,062 million barrels of proven crude oil reserve in the Niger Delta with crucial economic infrastructure which are at risk of climate change impact. Factors associated with emerging vulnerability include exposure to extreme weather events due to geographical sensitivity, exposure, interdependency, age and obsolescence, weak adaptive capacity, prevailing climate burdens and proximity. Rapid impact of climate change forced by these factors has triggered the attention of stakeholders (government agencies, oil/gas multinationals, assets managers, experts, and academics). The result is the urgent need for vulnerability assessment to aid industrial adaptation planning, investment, and subsequent mainstreaming of findings into the core assets management code of the energy industry.

More so, the rise in global temperature has the capacity to cascade a corresponding rise in temperature within the operational ambient of flow stations compressors. The high temperature could cause malfunctioning effects capable of reducing oil output, infrastructure damage and reduction in efficiency. Increase in temperature and the high salinity of ocean water from tidal intrusion could result in corrosion of crucial cathodic systems which could rupture prematurely due to wear and tear (Zhang and Zhuang, 2003). A heavy downpour, on the other hand, has flooded industrial areas with an infestation of residential and onshore platforms with wild reptiles rendering personnel on board (POB) to secondary vulnerabilities. These secondary impacts make marginal platforms unsafe for operations. Tropical storms, lightning and thunderstorms are also on the increase in the region. The impact of thunder blasts and regular lightening charges on cathodic metallic systems have the potential for combustion, hence, constitutes a very high risk for oil/gas field operations. In recent times, research into renewable energy options (Rahil, Gammon and Brown, 2017) is contended to have been influenced by climate change impact on fossil systems. The unpopularity of renewable options is failing to provide a realistic alternative to fossil energy, hence the need for vulnerability assessment of critical oil/gas infrastructure. In addition, vulnerability assessment pave way for effective and sustainable adaptation planning and investment for assets protection.

The impacts of extreme weather events have uncovered adaptive weaknesses associated with the infrastructure, to prevailing environmental stressors such as flood, rising tides, thunderstorms, and temperature in the Niger Delta (Udie, Bhattacharyya and Ozawa-Meida, 2018). Adaptive capacity weaknesses posse a negative effect on the social, economic, and environmental well-being of the entire country. Therefore, a pragmatic approach to vulnerability assessment with the view to profiling possible sustainable adaptation alternatives could salvage the porosity and exposure of the assets.

The main questions therefore are; how are critical oil/gas infrastructure vulnerable to climate change stressors and what are the vulnerability hierarchies of critical infrastructure in the Niger Delta? The purpose of this paper is to present the systematic use of analytic hierarchy process (AHP) in evaluating the vulnerability (hierarchies) of critical infrastructure to extreme climate events. In this paper, section 2 deals with the review of relevant literature on climate vulnerability from an academic perspective is carried out to underpin the gaps and indicators used in this assessment. The research methodology presents selected infrastructure and attributes used in the assessment and describes the procedural AHP pathways for data collection and synthesis in section 3. Section 4 focus on the critical analysis of result by presenting a systematically consolidated outcome of overall AHP normalised eigenvalues, consistency ratios and consensus levels while conclusion and recommendations are prominent in section 5.

2. Literature Review

Researchers have carried out vulnerability investigation of critical infrastructure in different regions using various scientific approaches and stochastic models (Yuen, Jovicich and Preston, 2013; Islam, Malak and Islam, 2013). The severity of climate change impact in the Niger Delta is associated with the lack of such investigations that focus on the vulnerability of different systems in the Niger Delta context. Dealing with environmental vulnerability has remained a challenge for stakeholders in the oil/gas industry, leading to various degrees of exposure of critical infrastructure to extreme weather events. (Adelekan, 2011) carried out an investigation on the vulnerability of urban areas in South Western Nigeria to flood through opinion sampling of urban dwellers. Though this was in a quasi-region, it was discovered that 50% of respondents agreed that they were experiencing severe flood impact on social housing and critical infrastructures such as electrical installations, GSM mast, roads, and bridges. Roads and bridges in the Niger Delta are crucial inter-connecting infrastructure that allows for easy movement of goods and services to and from onshore platforms. Impact of the flood on roads and bridges could halt activities such as supply chain and operations. Furthermore, (Denner et al., 2015) conducted a vulnerability assessment of coastal Loughor Estuary in Wales using coastal vulnerability index which dwells on physical parameters for analysis of the result. The investigation revealed that shorelines were vulnerable due to the coastal slope, beach width and highlights that "significant percentage" of critical infrastructures such as housing, energy, and transport assets located on the shoreline are vulnerable. This is an indication that coastal infrastructure such as the oil/gas systems in the Niger Delta coast could be exposed and vulnerable to severe weather threats.

The concept of vulnerability has been explored from different subject backgrounds with contextual definitions. In the context of oil/gas infrastructure, it the lack of resilience, exposure and susceptibility of sensitive or critical systems such as flow stations, terminals, etc. to adverse effects of extreme weather events - flooding, wind storms, heavy downpours etc (Birkmann et al., 2013; Füssel, 2007; Livia Bizikova et al., 2009). Vulnerability is akin to weaknesses, predisposition, deficiencies, and absence of adaptive capabilities that permit the impact of adverse events. A critical asset, on the other hand, is an infrastructure which disruption could have significant negative effects on the economy, environment, and social systems. These views of vulnerability and criticality define the context of oil/gas assets in the Niger Delta, hence this investigation. Identification and prioritisation of vulnerable critical oil/gas infrastructure is necessary for a complete understanding of susceptibility of the entire industry to climate change.

It could provide additional data for the understanding of social well-being of coastal communities and requires institutional investment in plausible adaptation mechanisms both in policy formulation, economic management, and physical system building (Yuen, Jovicich and Preston, 2013). However, effective adaptation planning demands an efficient approach to identifying the hierarchies of infrastructure vulnerability and suggestion of technical approaches through an interdisciplinary decision-making process. (Yuen, Jovicich and Preston, 2013) have used a qualitative approach to conduct vulnerability assessment with the aim of inciting social learning and adaptation in South-eastern Australia. Reliance on pure qualitative vulnerability assessment could lack the effectiveness in providing tangible output for adaptation planning. It is argued that a mixed method technical mechanism for quantitative and qualitative evaluation could lead to more dependable and tangible output for stakeholder's implementation (Havko, Titko and Kováčová, 2017). This implies that a combination of quantitative AHP and observational approaches for assessing critical infrastructure vulnerability in the Niger Delta could produce acceptable and tangible output.

Observational investigation has been extensively combined with quantitative methodologies in investigating infrastructure vulnerability (Taylor, 2008; Curry and Moore, 2003; Svendsen and Wolthusen, 2007; Marko and Weil, 2010). This implies that a mix methodological approach could be suitable for vulnerability assessment involving stakeholder decision-making approach. The AHP is a multi-stakeholder decision-making tool for prioritising alternatives using multi-criteria approach for reaching objective consensus and consistency evaluation. This paper presents an effective application of AHP in assessing and ranking vulnerable infrastructure and corroborates the findings of (Al-Harbi, 2001; Lai, Wong and Cheung, 2002) who engaged AHP in multi-stakeholder group decision-making projects.

3. Research Methodology

This is research is an empirical investigation that combines both field data collection and intensive desk reviews. In the past, decision-makers in the Niger Delta industry depend on benchmark approaches and methodologies to determine infrastructure that requires an upgrade, reinforcement, and routine maintenance. The norm is that decision-makers with the responsibilities of managing infrastructure rely on individual or group inputs for evaluations of emerging concerns. In this study, exploration, and intensive desk review of relevant literature on sustainability indicators and oil/gas assets in the study area revealed seven criteria and critical infrastructure respectively (see Table 1). Decision makers pairwise compared these infrastructures using the criteria in an AHP structured questionnaire.

Table 1; Identified criteria and critical infrastructure

S/N	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

3.1. Procedure for selecting decision-makers

Nineteen (19) decision-makers with a minimum of ten (10) years' experience in the Niger Delta oil/gas industry were selected through informal and formal stratification strategies from four multinational companies in the study area. An informal strategy is a systematic approach used in scoping data from appropriate participants based on trust and confidentiality in restricted and volatile regions. The decision makers completed and signed consent forms upon formal notification and approval from respective organisations' management to participate in the study. Decision makers were categorised into four (4) mix independent focus groups of 5:5:5:4. Prior to the assessment process, decision makers received thorough familiarisation tutorial on the procedures of pairwise comparison and completion of the AHP questionnaire.

3.2 Procedure of assessment using AHP questionnaire

AHP structured questionnaire was designed in a 21x11 columns (for infrastructure) and rows (for (Saaty, 2003a) numerical scale); see Table 2. The pairwise process involved the comparison of any two infrastructures based on a given criterion by assigning a weight (1 – 9). Following AHP principle, the goal of assessment and further decomposition of criteria into sub-criteria was independently synthesised from desk reviews.

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

3.3 Steps of AHP assessment

Ranking of vulnerable infrastructure for vulnerability involves a systematic matrix pairwise comparison process based on decision makers' judgement. The seven criteria and infrastructure are compared in a 7x7 matrix. The equation below illustrates the determining factor for estimating the involvement of 7x7 criteria and alternatives pairwise comparisons outcome.

$$\text{The equation} \quad \frac{n(n-1)}{2}$$

where n = number of items (7) to be pairwise compared. In this study, 21 matrices of pairwise comparisons by each decision maker was independently established by completing the provided questionnaire.

Illustration of a typical AHP matrix is shown below as an indication of the model.

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

Where if $a_{ij} = 1$, $a_{ji} = 1/a_{ij}$ (example; if $a_{13} = 5$, $a_{31} = 1/5$);

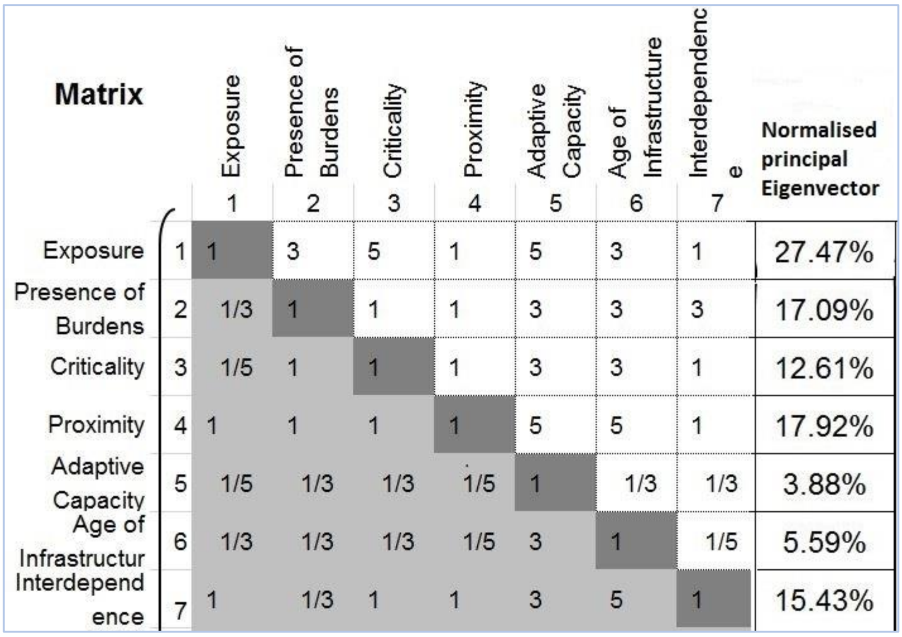
$a_{ii} = 1$; i and j are equally important, $a_{ij} = a_{ji} = 1$

aij is used to determine their relative importance of *i* with respect *j*.

4. Results

4.1 Determination of criteria weight

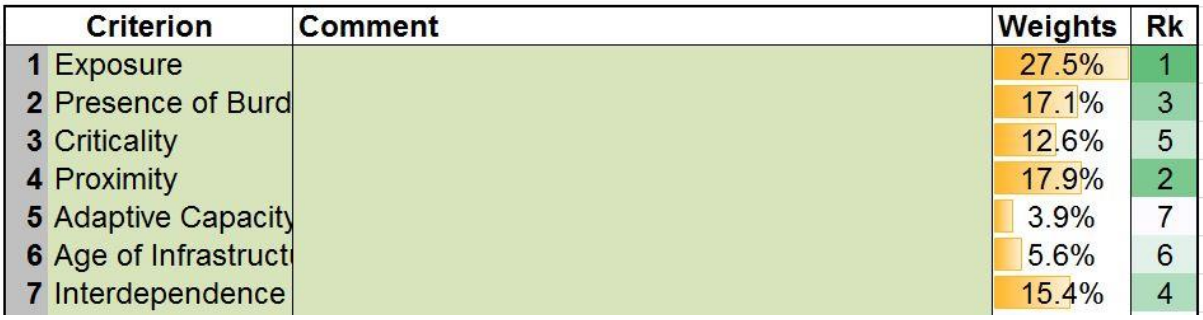
The seven (7) attributes were pairwise compared by decision-makers to determine their individual weights. The weight of a criterion has a significant impact on the outcome of the vulnerability of alternatives (infrastructure) in the overall ranking. Responses from the groups were merged but independently fed into the (Goepel, 2013) multiple inputs (Mi-AHP) excel spreadsheets. The outcome of criteria weighting is indicated in the matrix in Figure 1 below. The white section indicates averages of decision-makers' numerical scale (Table 2) while the grey section shows the reciprocals of entries. Normalised principal eigenvectors (EV) was calculated from horizontal aggregates of mean values and represents the 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 1 showing the comparison matrix and normalised principal Eigenvectors

The result indicates that exposure (27%), proximity (17.92%), and presence of burdens (17.09%) ranked 1st, 2nd and 3rd respectively. Interdependence (15.43%), criticality (12.61%), and age (obsolescence of assets) (5.59%) were ranked 4th, 5th and 6th respectively while adaptive capacity ranked least with 3.88%. This result implies that the vulnerability of infrastructure in the future analysis would be mostly influenced by these criteria in order of their ranking. See Figure 2 for a modelled summary of ranking outcome.



	Criterion	Comment	Weights	Rk
1	Exposure		27.5%	1
2	Presence of Burd		17.1%	3
3	Criticality		12.6%	5
4	Proximity		17.9%	2
5	Adaptive Capacity		3.9%	7
6	Age of Infrastruct		5.6%	6
7	Interdependence		15.4%	4

Figure 2 summary of attributes ranking from Mi-AHP

4.2 Determination of infrastructure vulnerability

Decision-makers in the four focus groups brainstormed and systematically completed vulnerability assessment questionnaire. The completion process followed a criterion-by-criterion pairwise comparison to underpin the vulnerability index of each infrastructure. Responses were independently computed and consolidated using the Mi-AHP spreadsheets. Details of the criteria-by-criteria computation, result, and analysis are discussed in the next sections.

4.2.1 Computation approach

Seven (7) separate Mi-AHP spreadsheets were created for each criterion assessment. The result was consolidated by calculating the aggregate means for each criterion from the Mi-spreadsheets (see Table 3). The table shows a consolidated score for each infrastructure in column 2 and normalised principal eigenvectors (EV%) on column 3. For each criterion, the matrix distributed 100% scores amongst the seven infrastructures based on vulnerability perception

	Infrastructure (alternatives)	**consolidated score**	**Normalise Eigenvector (%)**
1	Terminal	118.9	16.9
2	Flow station	86.8	12.5
3	Pipelines	172.7	24.7
4	Loading Bays	82.1	11.7
5	Roads/bridges	99	14.1
6	Transformers/HVC	76.1	10.9
7	Oil wellheads	64.4	9.2
	Aggregate score	**700**	**100**
	Consistency ratio (CR)	9.1%	0.09
	Consensus level	501.4	71.6

by decision-makers. Each ‘cell’ in column 2 of Table 3 is a consolidated score of nineteen (19) different score. Each ‘*consolidated score’* is divided by 100 to obtain the eigenvector (EV) values and sum up to 100. AHP principle insists that the sum of means (EV) of pairwise comparison must normalise to ‘1’, using row geometric means method (RGMM) (Goepel, 2013; Dong et al., 2010; Saaty, 2003b). Normalising to ‘1’ from ‘100’ EV in this study depicts accuracy, transparency and validity of assessment outcome and agrees with existing AHP applications by (Al-Harbi, 2001; Jagtap and Bewoor, 2017; Xu, 2000; Saaty, 2001; Zimmerman, 2004).

Table 3 Consolidated result computed from AHP Excel spreadsheet on the vulnerability of critical infrastructure

	Infrastructure (alternatives)	**consolidated score**	**Normalise Eigenvector (%)**
1	Terminal	118.9	16.9
2	Flow station	86.8	12.5
3	Pipelines	172.7	24.7
4	Loading Bays	82.1	11.7
5	Roads/bridges	99	14.1
6	Transformers/HVC	76.1	10.9
7	Oil wellheads	64.4	9.2
	Aggregate score	**700**	**100**
	Consistency ratio (CR)	9.1%	0.09
	Consensus level	501.4	71.6

4.2.2 Analysis of consistency ratio (CR)

Orange columns in Table 3 shows calculated consistency ratios (CR), and consensus outcome for the ranking by consolidated participant’s row geometric mean method (RGMM) as used by (Xu, 2000). In this study, CR = *0.09 and* conforms with the opinion of (Saaty, 2003a; Xu, 2000) that 10% CR for AHP investigation is acceptable. This implies that there was a near-perfect consistency in the participant's decision-making process and portrays the validity of result, suitability of participants and effectiveness of application process. The CR outcome further justifies the efficiency of combining AHP with the designed conceptual study framework. Consistency outcome further agrees with the research opinions of (Al-Harbi, 2001; Xu, 2000; Saaty, 2001) who categorise assets and social parameters using the analytic hierarchy process.

4.2.3 Consensus analysis

The accuracy of CR above is an indication of a corresponding positive participants' consensus in the overall vulnerability assessment outcome. The study produced 71.6% consensus. It implies that there was about 72% unanimous agreement between participants decision-making in the pairwise comparison process. It agrees with the position of (Dong et al., 2010). He posits that absolute agreement is not expected for empirical application of AHP in interdisciplinary multi-criteria decision-making process, an acceptable CR is a pointer to an acceptable consensus. Literature suggests that if consensus level is not high, alternative models such as geometric means, individual voting, compromise and or separate models could be used for further evaluation (Lai, Wong and Cheung, 2002). But this study outcome negates the need for the use of alternative approaches though Mi-AHP spreadsheets synthesise and present the geometric means (normalised EV).

4.3 Consolidate analysis and discussion

The normalised principal eigenvector values aggregated in **Table 3** are used to compute the ranking of infrastructure to demonstrate a clearer order of vulnerability. It presents the result of the entire study in the order of most to the least vulnerable. Infrastructures with the highest percentage are the most vulnerable as shown in **Figure 3**.

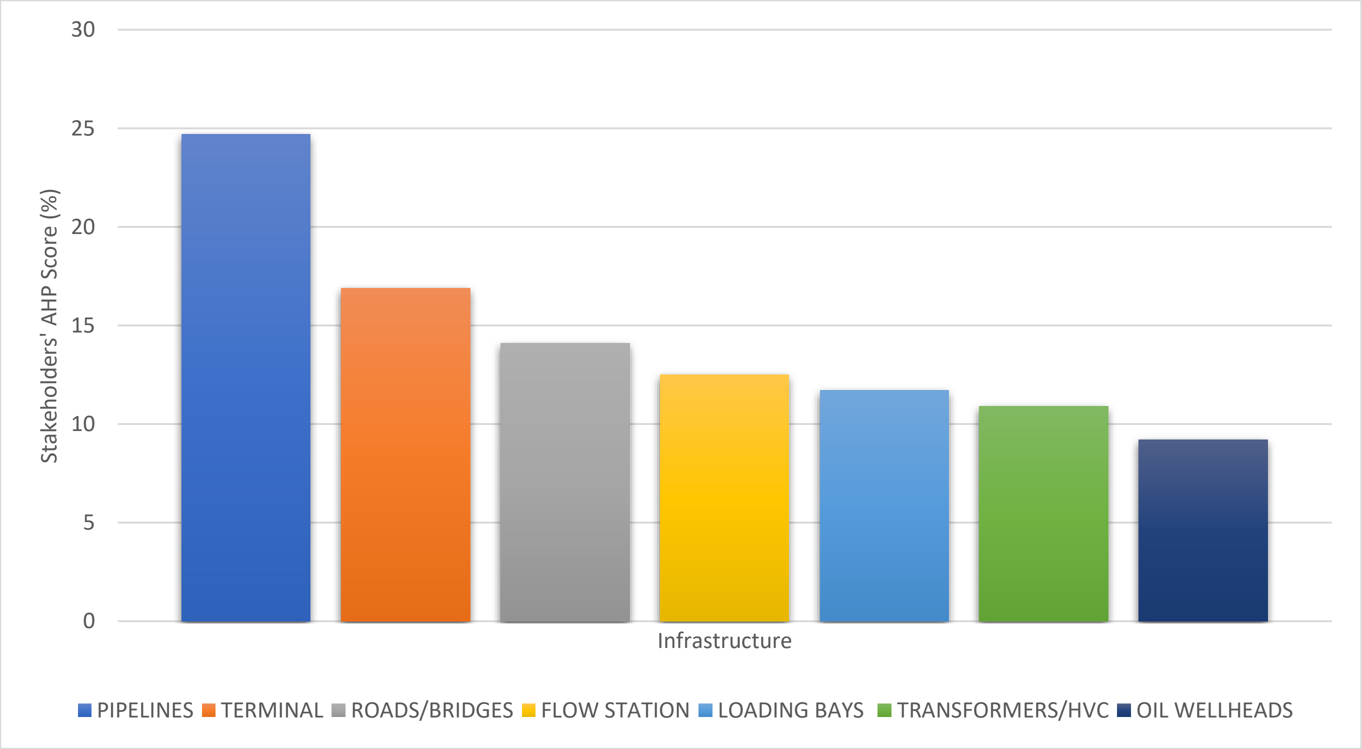


Figure 3 Consolidated result showing the percentage of the vulnerability of selected infrastructure to climate change impact

The ranking is based on exposure of these assets to climate stressors, the ability of assets to withstand stressors (adaptive capacity), proximity to risk factors, criticality and sensitivity of selected infrastructure. The result indicates that vulnerability or infrastructure is linked with the presence of climate burdens, assets age (obsolescence) and interdependency of assets value chain.

However, the consolidated vulnerability outcome indicates that *pipelines* are the most vulnerable assets to climate change risks in the Niger Delta with a vulnerability score of 25%. This is contrary to the expected result because filed exploration revealed that pipelines in the Niger Delta are prematurely replaced due to social risk factors of vandalism (Obi, 2014; Ikelegbe, 2005; Anifowose et al., 2012). (Anifowose et al., 2012) further argued in support of the reality of vandalism stressing that Nigeria has suffered her share of vandalism and substantial incidence of attacks and interdictions on oil and gas pipelines. This is contended to has caused regular premature replacements and rehabilitation of pipelines. Decision-makers who participated in the research 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 cathodic trunk lines) have been in place for more than five decades without being attacked. This implies that vulnerable pipelines to social attacks could be reachable by minor pipes while generally, most of the systems remain vulnerable in their installed states.

The contradiction arising from this research 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 when other factors evolve. This study proves that continual replacement of pipelines could only address the challenge of vulnerability due to a single factor (age). This is because the vulnerability of pipelines and other assets depends more on other factors described in Figure 1. This study proves that in the Niger Delta context, "Age of infrastructure" contributes second to the least weight (Figure 2) in ranking vulnerability. This implies that the effect of age is less significant.

Nevertheless, the study reveals *terminals* (17%) and *roads/bridges* (14%) as second and third most vulnerable oil/gas 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/Bridges are considered by some researchers as pedestal infrastructure in the region but the acceptability and ranking of *roads and bridges* as 3rd most vulnerable oil/gas infrastructure confirmed the criticality. Exploratory survey concurs with (Moteff and Parfomak, 2004; Moteff and Parfomak, 2004; Moteff, Copeland and Fischer, 2003) who classified transport systems as national assets of priority which could be vulnerable to environmental and social threats. It further aligns with (Schweikert et al., 2014) who advocate for a robust system maintenance for vulnerable road infrastructure. More so, the Niger Delta geographical area is characterised by several '*bird foot'* deltas that require bridges and access roads between onshore operational islands for free movement of people, general goods, and service. The vulnerability of roads/bridges pose a serious challenge to daily movement and affects the supply chain in the industry.

In the case of *flow stations* (12.5%) and *loading bays (*11.7%) study indicates an almost equally vulnerability having ranked 4th and 5th respectively. The significance of *flow stations'* vulnerability outcome might have relied on their age, proximity, and sensitivity in the infrastructure value chain. The *loading bays* have weak adaptive capacities, exposed, and are located at short distances to the shore. Unlike the *flow station, loading bay* is interim transport infrastructure between the terminal and the transport ship. It is exposed to flood, sea level rise and storms but often not sensitive as the *flow station* but always resistant to coastal environmental impacts. The vulnerable location and resilience of loading bays agree with (Cabral et al., 2017; Cardona et al., 2012) who argued that location or proximity could not be used to ascertain vulnerability of coastal systems.

From among the selected systems for this study, the least vulnerable are *transformers/HVC* (11%) and *oil wellheads* (9%) which ranked 6th and 7th in the prioritisation scale. Transformers/HVC convey electricity from the grid across hundreds of miles to various platforms and facilities. Hence, could be vulnerable due to interdependence which has about 15% weight in this study. Wellheads are less complicated but delicate assets that occupy the first stratum of crude oil production process. They are cased and designed to function in isolation. Their low ranking is an indication of high adaptive capacity, minimal interdependence, and exposure.

5. Conclusion and recommendations

Since the 2012 flood disaster in the Niger Delta, multinationals companies and government agencies have realised that critical infrastructures are vulnerable to climate change. This is because the severe aftermath of 2012 on national planning and revenue was overwhelming. This is motivated by a vulnerability study of selected assets to aid prioritisation of adaptation planning. This study presents the first effective use of analytical hierarchy process (AHP) approach in ranking critical oil/gas infrastructure through stakeholder participation in focus groups and intensive field exploration in the Niger Delta. The sustainability 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 on critical assets. These could be adopted for evaluation of similar infrastructure in a different sector with similar environmental characteristics. The result of this study is a sophisticated hands-on tool for decision makers such as asset manager, field engineers and consultants in the industry for deciding suitable adaptation measures.

However, this study did not capture details adaptation strategies and their possible application processes. Further research is required on the discovery of suitable options such as substitution of cathodic pipelines with glass reinforcement epoxy (GRE) systems, infrastructure upgrade, timely decommissioning, and emergency evacuation planning. Future researchers could consider the combination of AHP with analytic network process (ANP) and or fuzzy AHP methods in assessing similar systems in same or different geographical locations with the aim of aiding hierarchical adaptation planning.

Acknowledgement

The first author is gratefully acknowledging the financial support of Petroleum Technology Development Fund (PTDF), Nigeria; for his doctoral study at De Montfort University, Leicester; for participating in the conference.

References

ADELEKAN, I.O. (2011) Vulnerability assessment of an urban flood in Nigeria: Abeokuta flood 2007. *Natural Hazards*, 56 (1), pp. 215-231.

AL-HARBI, K.M.A. (2001) Application of the AHP in project management. *International Journal of Project Management*, 19 (1), pp. 19-27.

ANIFOWOSE, B. et al. (2012) Attacks on oil transport pipelines in Nigeria: A quantitative exploration and possible explanation of observed patterns. *Applied Geography*, 32 (2), pp. 636-651.

BIRKMANN, J. et al. (2013) Framing vulnerability, risk and societal responses: the MOVE framework. *Natural Hazards*, 67 (2), pp. 193-211.

CABRAL, P. et al. (2017) Assessing Mozambique's exposure to coastal climate hazards and erosion. *International Journal of Disaster Risk Reduction*, 23, pp. 45-52.

CARDONA, O. et al. (2012) Determinants of risk: exposure and vulnerability.

CURRY, A. and MOORE, C. (2003) Assessing information culture—an exploratory model. *International Journal of Information Management*, 23 (2), pp. 91-110.

DENNER, K. et al. (2015) A coastal vulnerability and environmental risk assessment of Loughor Estuary, South Wales. *Ocean & Coastal Management*, 116, pp. 478-490.

DONG, Y.et al. (2010) *Consensus models for AHP group decision making under row geometric mean prioritization method* Available from http://www.sciencedirect.com/science/article/pii/S0167923610000643.

FÜSSEL, H. (2007) Vulnerability: a generally applicable conceptual framework for climate change research. *Global Environmental Change*, 17 (2), pp. 155-167.

GOEPEL, K.D. (2013) Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises–a new AHP excel template with multiple inputs. In: *Proceedings of the international symposium on the analytic hierarchy process*, pp. 1-10.

HAVKO, J., TITKO, M. and KOVÁČOVÁ, J. (2017) *Vulnerability of the City Infrastructure as a Part of the Resilient City Concept* Available from http://www.sciencedirect.com/science/article/pii/S1877705817325997.

IKELEGBE, A. (2005) The economy of conflict in the oil-rich Niger Delta region of Nigeria. *Nordic Journal of African Studies*, 14 (2), pp. 208-234.

ISLAM, M.N., MALAK, M.A. and ISLAM, M.N. (2013) Community-based disaster risk and vulnerability models of a coastal municipality in Bangladesh. *Natural Hazards*, 69 (3), pp. 2083-2103.

JAGTAP, H.P. and BEWOOR, A.K. (2017) *Use of Analytic Hierarchy Process Methodology for Criticality Analysis of Thermal Power Plant Equipments* Available from http://www.sciencedirect.com/science/article/pii/S2214785317302341.

KARAPETROU, S.T., FOTOPOULOU, S.D. and PITILAKIS, K.D. (2017) *Seismic Vulnerability of RC Buildings under the Effect of Aging* Available from http://www.sciencedirect.com/science/article/pii/S187802961730141X.

LAI, V.S., WONG, B.K. and CHEUNG, W. (2002) Group decision making in a multiple criteria environment: A case using the AHP in software selection. *European Journal of Operational Research*, 137 (1), pp. 134-144.

LIVIA BIZIKOVAet al. (2009) *Vulnerability and Climate Change Impact Assessment for Adaptation*. An integrated Environmental Assessment and Reporting Training Manual ed. Online: United Nation Environmental Programme (UNEP). Available from: http://www.unep.org/ieacp/files/pdf/ClimateChange_Manual_Final.pdf [Accessed October 2015].

MARKO, N.F. and WEIL, R.J. (2010) The role of observational investigations in comparative effectiveness research. *The value in Health*, 13 (8), pp. 989-997.

MOTEFF, J., COPELAND, C. and FISCHER, J. (2003) Critical infrastructures: What makes an infrastructure critical?. In:: Library of Congress Washington DC Congressional Research Service.

MOTEFF, J. and PARFOMAK, P. (2004) Critical infrastructure and key assets: definition and identification. In: : LIBRARY OF CONGRESS WASHINGTON DC CONGRESSIONAL RESEARCH SERVICE.

OBI, C. (2014) Oil and conflict in Nigeria's Niger Delta region: Between the barrel and the trigger. *The Extractive Industries and Society*, 1 (2), pp. 147-153.

OPEC (2016) *The OPEC Annual Statistical Bulletin*. [Online] Organisation of the Petroleum Exporting Countries. https://www.opec.org/opec_web/static_files_project/media/downloads/publications/ASB2016.pdf [Accessed 15/12/2017].

RAHIL, A., GAMMON, R. and BROWN, N. (2017) Dispatchable hydrogen production at the forecourt for electricity grid balancing. In: *AIP Conference Proceedings*: AIP Publishing, pp. 020011.

SAATY, T.L. (2003a) Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research*, 145 (1), pp. 85-91.

SAATY, T.L. (2003b) Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research*, 145 (1), pp. 85-91.

SAATY, T.L. (2001) The seven pillars of the analytic hierarchy process. In: *Multiple Criteria Decision Making in the New Millennium*: Springer, pp. 15-37.

SCHWEIKERT, A.et al. (2014) *The infrastructure planning support system: Analyzing the impact of climate change on road infrastructure and development* Available from http://www.sciencedirect.com/science/article/pii/S0967070X14001188.

SVENDSEN, N.K. and WOLTHUSEN, S.D. (2007) Connectivity models of interdependency in mixed-type critical infrastructure networks. *Information Security Technical Report*, 12 (1), pp. 44-55.

TAMI, A.G. and MOSES, O. (2015) Flood vulnerability assessment of Niger Delta states relative to 2012 flood disaster in Nigeria. *Vol*, 3, pp. 76-83.

TAYLOR, M.A. (2008) Critical Transport Infrastructure in Urban Areas: Impacts of Traffic Incidents Assessed Using Accessibility-Based Network Vulnerability Analysis. *Growth and Change*, 39 (4), pp. 593-616.

UDIE, J., BHATTACHARYYA, S. and OZAWA-MEIDA, L. (2018) A Conceptual Framework for Vulnerability Assessment of Climate Change Impact on Critical Oil and Gas Infrastructure in the Niger Delta. *Climate*, 6 (1), pp. 11.

XU, Z. (2000) On consistency of the weighted geometric mean complex judgement matrix in AHP. *European Journal of Operational Research*, 126 (3), pp. 683-687.

YUEN, E., JOVICICH, S.S. and PRESTON, B.L. (2013) Climate change vulnerability assessments as catalysts for social learning: four case studies in south-eastern Australia. *Mitigation and Adaptation Strategies for Global Change*, 18 (5), pp. 567-590.

ZHANG, H. and ZHUANG, J. (2003) Research, development and industrial application of heat pipe technology in China. *Applied Thermal Engineering*, 23 (9), pp. 1067-1083.

ZIMMERMAN, R. (2004) Decision-making and the vulnerability of interdependent critical infrastructure. In: *Systems, Man and Cybernetics, 2004 IEEE International Conference on* IEEE, pp. 4059-4063.