Environmental Risk Analysis and Management Research Paper

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Flood risk assessment – evaluation of study based in the Abidjan District, Côte d’Ivoire

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1. Introduction

Numerous regions worldwide have experienced severe floods that resulted in significant impacts on ecosystems, human life, and socio-economic activities. Flood events have caused considerable economic harm and loss of life on a global scale. Africa suffers this kind of natural phenomenon more than other areas of the world. Its vulnerability to disasters is high due to various factors, such as rapid population growth, high poverty rates, mismanagement of natural resources, and deficiencies in policy and institutional frameworks. In addition, the situation is expected to worsen due to the effects of human-induced climate change (Komi et al., 2016) .

Western Africa has been affected with flood events more and more severely and frequently. The life of their inhabitants and the infrastructures of entire regions have been devastated, especially in the last 30 years. The Emergency Events Database (EM-Dat) has counted almost 250 flooding events for a total amount 3800 deaths and over 25 million people that were affected by them (Wagner et al., 2021).

Moreover, a region's susceptibility to flood hazards is largely determined by its flat topography, geological conditions, urbanization, and inadequate drainage systems.

Flash-flood pose a significant threat to urban areas since their roads and buildings compress the soil and prevent the water to infiltrate the surface. The water accumulates on above the ground causing damages to the infrastructure and putting the population in danger (Engel et al., 2017). Establishing effective measures to manage flood risk is a challenging task due to the issue's complexity and uncertainty. The complexity arises primarily due to the involvement of multiple stakeholders with varying backgrounds and objectives. Additionally, the precise estimation of flood magnitudes and resulting damages is challenging and often remains uncertain (Madruga de Brito & Evers, 2016).

To mitigate the harm caused by the combined impact of climate change and land use alterations, it is crucial to manage flood risk. To manage it, one can either decrease the hazard's probability or magnitude or reduce the exposed population's and infrastructures' vulnerability (Komi et al., 2016).

This paper focuses on flood risk assessment in Abidjan, Côte d´Ivoire a region, which has been impacted by severe flood events in the past. The city borders on the Ebrié lagoon, which is connected to the Atlantic Ocean through the shallow strait known as Canal de Vridi (N'Guessan et al.). Abidjan is considered to be the economic capital of Cote d'Ivoire, the lagoon is vital to the country's economy as it houses the main harbor and numerous tourist attractions (N’Guessan et al.). Additionally it is subject of an exponential demographic growth and coupled with that, consequently phenomena like rapidly increasing urbanization and poor land use management occur (Danumah et al., 2016). The lacking structure of such an expansion enhance critical consequences in case of flood events (N’Guessan et al.).

Abidjan is situated between latitudes of 5° 10′ and 5° 38′ North and longitudes of 3° 4′ and 5° 21′ West, as illustrated in Figure 1.
The district encompasses an area of approximately 2,119 km2 and has a dense population of about 4,739,752 inhabitants in the metropolis and 4,460,355 inhabitants in the main city, according to the 2013 census by the National Institute of Statistics (INS). The population represents 20.3% of the national population as of 2013 (Danumah et al, 2016).

Figure 1: Abidjan Region. N'Guessan et al., 2021

The equatorial climate is characterized by four seasons: A long dry season from December to March, followed by a long rainy season from March to July. From August to September the short dry season takes places, followed by a short rainy season from October to November. According to OCHA, the long rainy season is responsible for two-thirds of the annual rainfall, with an average start date of March 23 and end date of July 31. (Kouassi et al. 2018) Yet, every rainy season brings numerous fatalities and significant destruction. The Office for the Coordination of Humanitarian Affairs (OCHA) reported that Abidjan experienced an average of 13 flood-related deaths per year from 2009 to 2014 (Kablan et al., 2017).

2. Methodology & Relevant Literature

The following paper aims to provide a review of multi-criteria decision-making applications to manage the natural hazard of floods. Geographically, the study area is situated in the city of Abidjan at the Ivory Coast in West Africa, which is considered as heavily exposed to the risk of flooding (Danumah, 2016). Literature research is being conducted to gain an overview regarding the approach of MCDM in the scope of flood risk assessment.
Studies as “multi-criteria decision-making for flood risk management:
a survey of the current state of the art“ by Madruga de Brito and Evers; “A systematic literature review of multicriteria and multi-objective models applied in risk management” by Almeida et. al, “A review on flood risk assessment using multicriteria decision making technique” by Abdulrahman and Bwambale as well as “Analytic Hierarchy Process (AHP) in Spatial Modeling for Floodplain Risk Assessment” by Siddayao et. al promote the foundation of a comprehensive understanding regarding MCDM and AHP in flood risk assessment.
Research papers like the ones written by Kablan et al., 2017 (“Assessment of Social Vulnerability to Flood in Urban Côte d’Ivoire Using the MOVE Framework”) and Attoumane et al.,2022 (“Individual perceptions on rainfall variations versus precipitation trends from satellite data: An interdisciplinary approach in two socio-economically and topographically contrasted districts in Abidjan, Côte d'Ivoire”), helped us take into consideration social inequalities that reflect in the infrastructures of different zones of a region at risk and integrating them in the analysis during and following the AHP analysis.

3. Multi-criteria Decision Making

The use of multi-criteria decision making MCDM as such a decision support tool can be beneficial in flood risk management. MCDM refers to a collection of methods that structure and evaluate alternatives based on multiple criteria and objectives. As such, these methods allow for targeted decisions resulting in a more explicit, rational, and efficient decision-making process. The promoted role of participants enhances the exchange of a wide range of information and knowledge, facilitates compromise and group decisions while providing a platform for stakeholders to achieve long-lasting management programs (Madruga de Brito & Evers, 2016).

The figure 1 depicts different MCDM methods. The following paragraphs provides an introduction into the different types, furthermore, going into depth on the specific method of Analytical Hierarchy Process (AHP).

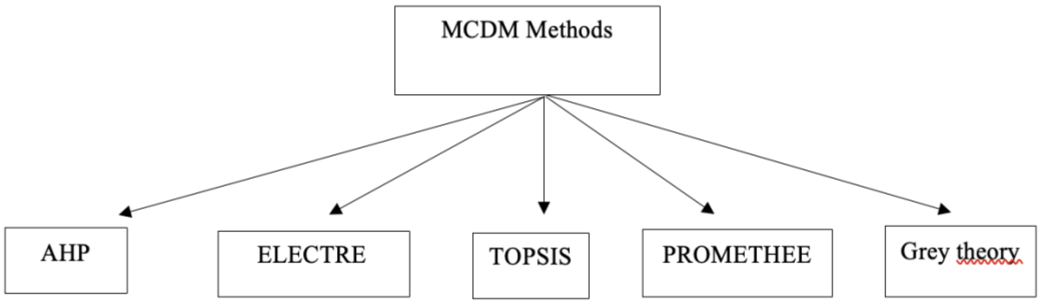

Figure 2: Multi-criteria decision making methods

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method assumes that each criterion exhibits a tendency of monotonically increasing or decreasing utility, which simplifies the identification of the positive and negative ideal solutions. In order to determine the relative closeness of the alternatives to the ideal solution, the Euclidean distance approach is suggested. While comparing the relative distances between the alternatives and the ideal solution, the preference order of the alternatives is being revealed. The chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the greatest distance from the negative ideal solution (NIS). The TOPSIS method is used for ranking purpose and to achieve the best performance in MCDM (Aruldoss, 2013).

ELECTRE (Elimination EtChoix Traduisant la REalité) is an approach which enables decision makers to choose the best option with the highest benefit and minimal conflict among various criteria. The main idea of the concept is to aim an effective utilization of “outranking relations”, which can be achieved by modelling the decision problem with coordination indices. By using concordance and discordance indices the outranking relations among different alternatives can be analyzed and the decision maker can select the best alternative. Various versions of ELECTRE such as ELECTRE I, II, III, IV and TRI have been developed sharing the same fundamental concept, but differing in the type of problem they address. This enables an application of the method on a wider range including selection problems assignment problems and ranking problems (Aruldoss, 2013).

PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) is, due to its particular simplicity, very popular among decision makers. In the scope of the outranking method of PROMETHEE alternative actions are being ranked and selected among criteria, which are often conflicting. PROMETHEE I comprises partial ranking of the alternatives, whereas PROMETHEE II provides a complete ranking of the given alternatives from best to worst. The concept is based on a pairwise comparison of the alternatives along each criterion. Decision-makers have to determine the weights of the criteria and translate the difference between the evaluation obtained by two alternatives into a preference degree ranging from zero to one. After defining a relevant preference function for each criterion, a global preference index is being calculated. Further positive and negative outranking flows for each alternative are calculated and partially ranked. Finally, a net outranking flow for each alternative is being calculated and a complete ranking follows as the last step of the PROMETHEE procedure (Behzadian et al., 2010).

Grey Theory differs from the other MCDM methods fundamentally, as it deals with insufficient data and weak knowledge, systems that are partly known and partly unknown. When the decision-making process is not straightforward, Grey Theory examines the interactive analysis of a vast amount of input data that is often distinct and insufficient (Aruldoss, 2013).

AHP (The Analytical Hierarchy Process) developed by Thomas Saaty in 1980 promotes the decision-making process by breaking down the complexity of a problem into a hierarchical structure. The hierarchy of issues simplifies the problem and provides a comprehensive overview. This is necessary to set relevant criteria and identify priorities for the choice of different alternatives. To clarify the difference between criteria and alternatives, the criteria determine the quality of reaching the objective using any of the alternatives, while the alternatives represent options, choices or alternatives that could be used to achieve the goal. The hierarchical structure of the AHP elements is being illustrated in the following Figure 2

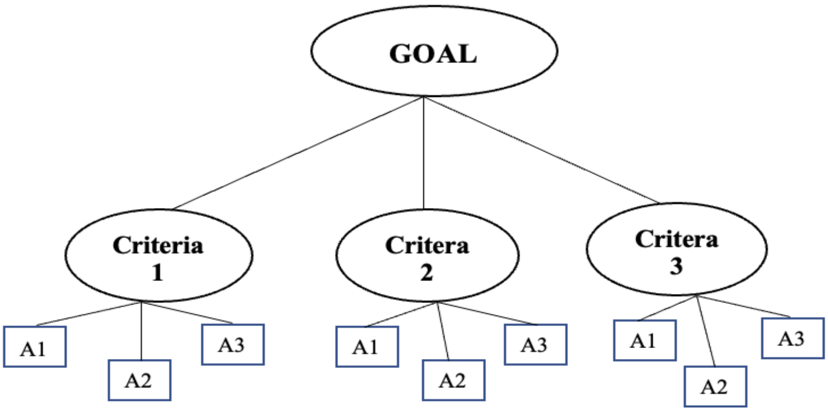

Figure 3: The hierarchical structure of the AHP elements. Saaty, 1980

The defined criteria are then appointed a relative importance by the user of the AHP based on their subjective judgement. This procedure is referred to as the Pairwise Comparison Method and forms the basis for the decision on the final goal. Typically, this is carried out by asking how much more valuable an element is than another one expressed as appointed values between 1 and 9. 1 means that the compared criteria are equally important and 9 means that the judged criteria is absolutely more important than the criteria which it is compared to. The result is Finally, the result is a square matrix with element values ranging from 1/9 to 9. Following the pairwise comparison, values for the weight of the criteria are computed in order to identify the optimal option for achieving the objective.
Before completing the AHP one crucial step needs to be taken. Since the preference systems subjective, the user´s pairwise comparison matrix might be inconsistent. To account for the fuzziness that comes along with this type of decision support method, the Consistency Ratio (C.R.) has to be determined. First the matrix product of the pair-wise comparison matrix and the weight vectors are computed, followed by adding all the elements of the resulting vector. After that the Consistency Index (C.I.9 is calculated, which is further used to calculate the Consistency Ratio following the formula:

$$C.R. = \frac{C.I.}{R.I.}$$

Obtaining a result of C.R < 0.10 indicates a reasonable level of consistency, whereas C.R > 0.10 can be interpreted as inconsistent judgments. (Siddayao et. al, 2014; Saaty, 1980).

Multi-criteria Decision making in flood risk assessment

MCDM is regarded as a useful tool to solve complex problems with multiple variables, a high degree of uncertainty and socioeconomic challenges, particularly when there is a lack of qualitative ground data. The application of MCDM coupled with geographical information system (GIS) enables three dimensions of risk assessment, including hazard, exposure and vulnerability to take the social, economic and environmental aspects into account (Abdulrahman & Bwambale, 2021). Natural hazards can be assessed using different approaches such as heuristic, statistical, and deterministic methods. The most widely and frequently used heuristic method is the Analytical Hierarchy Process (AHP). It´s popularity is due to its accuracy, flexibility and applicability in cases with incomplete data situation. To revise, the AHP approach merges qualitative and quantitative factors. Alternatives are being ranked and evaluated accordingly to their assigned value after a pairwise comparison has been conducted. This chapter discusses the application of MCDM and AHP for flood risk assessment. (Abdulrahman & Bwambale, 2021; Vignesh et al., 2020)
As flood risk composes of the following three components it is a product of hazard, exposure, and vulnerability. Mathematically, flood risk is being expressed as a function of flood hazard and flood vulnerability. The equation comprises as follows:

$$F_{RI} = F_{HI} \times F_{VI},$$

Flood risk is defined as F_{RI}, whereas flood hazard is defined as F_{HI}, and flood vulnerability as F_{VI} is.

Hazard can be defined as the probability of a potentially dangerous event occurring in a given location within a period of time (Youssef & Hegab, 2019). More specific, flood hazard can be described as a physical phenomenon, natural and non-manageable occurrence with an intensity that can cause damage by overflow stream and the extension of the field in the water flood. Hydro climatic phenomena as well as geomorphological characteristics such as slope, drainage density, soil types as essential factors, need to be taken into account to enable a holistic approach to hazard determination. (Danumah et al., 2016). Vulnerability can be regarded as the measure of potential risk coupled with the socio-economic capability to cope with the worst circumstances resulting from the disaster. The term can be extended referring to it as the conditions determined by physical, social, economic, and environmental aspects that amplify susceptibility of a community or system to the impact of hazards (Vignesh et al., 2020; Mavhura et. al, 2017). By mapping potential vulnerable areas, appropriate land planning measures can be set to mitigate negative consequences of flood events and reduce future risks (Vignesh et al., 2020). According to Abdulrahman and Bwambale (2021) flood hazard is given more attention to during the process of flood risk assessment, than to vulnerability. This can be explained by the fact that hazard determination is based on the probability of flood occurrence and its magnitude. Yet Mavhura et al. (2017) suggests putting less emphasis on hazards but more on the surrounding social environments in which vulnerability arises. Factors of the social processes comprises people who are the most at risk, where they live and work, the extent of disaster preparedness, income, access to information and many others. Mavhura et al. states "better quantification of the multifaceted nature of social vulnerability is an important and long overdue addition to the hazard mitigation planning and implementation processes especially in the context of climate change adaptation and disaster risk reduction strategies" (Mavhura et al., 2017, p.1).

Flood risk in Abidjan, Côte d´Ivoire

Although Abidjan is representative for severe floodings in the past, there are very few studies assessing the flood risk in this area. Yet Danumah et al. performed an examination in 2016 using AHP and GIS to identify and map areas of flood risk. As mentioned in the previous chapter the core of the AHP is to develop a hierarchy to simplify the given issue.
The authors set "flood risk map" on level one, defined as the goal, followed by the criteria "flood hazard map" and "flood vulnerability map" on level 1 and their associated elements on level two. The AHP model can be seen as follows:

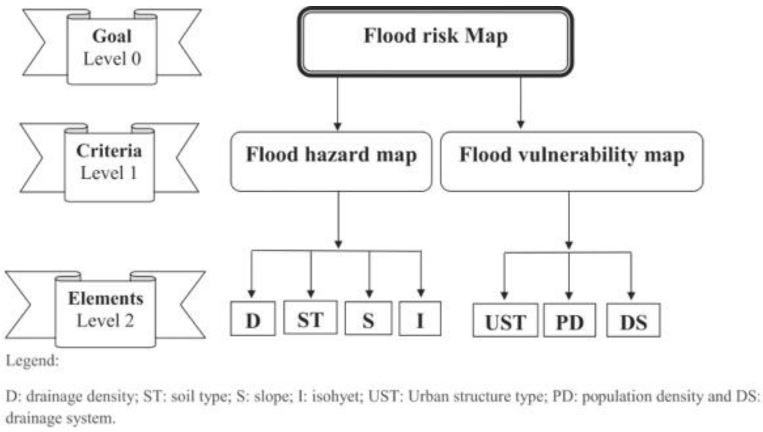

Figure 4: AHP-Hierarchy according to (Danumah et al. 2016)

It is necessary to emphasize that the authors decided to divide the criteria into flood hazard and flood vulnerability. As already explained in the previous chapter, floodings occur not solely due to climatic and geomorphological unfavorable conditions but coupled with anthropogenic factors such as mismanagement of land use or population density. Taking that fact into account, Danumah et al. defined hazard criteria as natural, physical phenomena whereas vulnerability criteria is viewed as the degree of susceptibility due to man-made circumstances (Danumah et al, 2016).

Elements relevant for the assessment of a flood hazard map were considered to be slope, soil type, isohyet and drainage density. Indicators for the vulnerability of the area were chosen to be urban structure types, population density and drainage system.

Following the process of AHP, Danumah et al. ranked Isohyet as the most significant element, followed by the element slope. The indicator type of soil is being viewed as third relevant, whereas drainage density was assigned the least importance. (Danumah et al, 2016).

Regarding the vulnerability of the area of Abidjan, population density is being prioritized followed by land use. The element of drainage system is considered least relevant.

Following the process of AHP, explained in the previous chapter, a hazard matrix and a vulnerability matrix were performed. According to the judgments of ten experts, the pairwise comparison reveals a ranking of the elements. By computing the eigenvector Vp, the prioritization becomes obvious, as one can see in the two tables below (Danumah et al, 2016).

Table 3 Hazard matrix

	D	Ts	S	I	V_P	C_P
D	1	3	1/3	1/5	0.67	0.13
Ts	1/3	1	1/3	1/5	0.38	0.08
S	3	3	1	1/3	1.31	0.26
I	3	5	3	1	2.59	0.52
Sum	7.33	12	4.66	1.73	4.95	1

Figure 6: Hazard Comparison Matrix. Danumah et al., 2016

Table 5 Vulnerability matrix

	LU	PD	DS	V_p	C_P	λ_{max}	CI	CR
LU	1	1/3	3	1	0.26			
PD	3	1	5	2.47	0.64			
DS	1/3	1/5	1	0.4	0.1	**3.03**	**0.02**	**0.03**
Sum	4.33	1.53	9	3.87	1			

Figure 5: Vulnerbility Comparison Matrix. Danumah et al., 2016

The necessity to integrate social vulnerability in the discourse of flood risk is being emphasized by Kablan et al. in a study regarding urban floodings conducted in Cocody. The authors point out that in the developed world urban floods are related to hazards such as climate change, flash floods and heavy precipitations mainly. This does not apply in developing countries, since widespread issues as precariousness of the drainage system, lack of maintenance of the infrastructure and mismanagement of domestic waste are jointly responsible and cannot be excluded from the assessment of risk (Kablan, 2017). The fact that urban inhabitants in Africa are expected to double by 2030, the unplanned urban development of areas comes along with lack of adequate adaptation of the infrastructure resulting in even worse flood events. (Kablan, 2017).

4. Conclusion

The main challenge in assessing flood risk in a given area arises with the complexity of multiple relevant factors and the uncertainty of the magnitude of the flood. Therefore, a multi-criteria decision-making approach might assist decision makers to reduce natural hazards as such to a minimum. One useful method to combine qualitative and quantitative elements is the Analytical Hierarchy Process. By structuring the issue and conducting a pairwise comparison, an obvious ranking of the elements can promote to manage a complex problem rationally and efficiently. It is crucial to take the socio-economic status of the given area into account. Developing countries such as Côte d´Ivoire are shaped by limitations in economy, rising population growth, rapid urbanization, lack in adequate drainage management and disadvantageous land use planning. The impacts of such hazardous events can be significantly reduced by acknowledging that flood occur when physical conditions are coupled with unfavourable anthropogenic factors and appropriate management measures are set. In the purpose of a holistic and realistically transferable risk assessment, the integration of such a vulnerability dimension is indispensable and has to be part of the criteria definition in the application of AHP.

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