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Exploring the Unseen Hazards of Our World

Edited by Mohammad Mokhtari

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Earth Sciences

Volume 3

Aims and Scope of the Series

The world of Earth Sciences, considering the interactions within the geosphere and between the geosphere–biosphere, is a place in which a large number of scientists find and have found over time their own relationship or sector of application precisely because it is absolutely transversal to many disciplines and subdisciplines, which do not necessarily fall within the Geosciences. The objective of this book series is to welcome original scientific contributions both in consolidated contexts and in new frontiers of research, as well as review papers included in the various disciplines of Earth Sciences, but above all, those that show a modern and transversal vision of applications and impacts on the community in a particular historical context, which, following the COVID-19 pandemic, has shifted global attention to sectors that were previously more neglected. In particular, those of mining research and fossil and renewable energy sources, environmental geology and the sustainable use of natural resources and impacts on the built environment, land consumption, geoarchaeology, forensic geology, geotourism/geoheritage, georisks and climate and environmental changes, considered at different scales, up to new applications of geostatistical and geospatial analysis, GIS and artificial intelligence for the definition of forecasting models and scenarios in various sectors of basic and applied research.

Meet the Series Editor

Dr. Maurizio Lazzari has a Ph.D. in Earth Science and is a researcher at the Italian National Research Council, Institute of Cultural Heritage Sciences. Since 2001, Dr. Lazzari has been a Professor of Pedology at the University of Basilicata (Italy) and a geoarchaeologist at the University of Salento (Italy). His research activities are focused on natural and anthropic hazards and risk factors, aimed at safeguarding and conserving settlements and the historical–monumental heritage of the Mediterranean, with particular attention to landslide processes, susceptibility maps, monitoring, and modelling. Since 2004, he has been working as a scientific coordinator for several national research projects studying landslides and triggering factors, natural and anthropogenic risks, geological and geomorphological mapping, soil erosion, preservation of historical and archaeological sites, enhancement of degraded areas, geo-touristic use, and the protection of the landscapes. He is the author of about 150 scientific publications in national and international journals, monographs, book chapters, and conference proceedings concerning applied geology, geomorphology, dynamics of artificial reservoirs, soil erosion, landslides, geoarchaeology, hydrogeological instability, natural hazards, monitoring, cultural landscape, UNESCO Heritage, geoarchaeology, and geo-tourism.

Meet the Volume Editor

Mohammad Mokhtari, a highly accomplished geophysicist, was born in Nosara, Neyshabur. He holds a BSc, MSc, and Ph.D. from Azarabadegan, Southampton, and Bergen Universities, respectively. His expertise extends to Utrecht University, where he conducted research, and his role as a principal geophysicist at Norsk Hydro (Norway) and NIOC (National Iranian Oil Company). With an impressive portfolio, he has made significant contributions as the Director of SRC(Seismological Research Center) at IIEES (International Institute of Earthquake Engineering and Seismology) and a Member of the Board of Directors. Notably, he established the NBSN (National Broadband Seismic Network), served as a co-founder and Director of NCEP and the Risk Management Excellence Center, and was part of the Passive Seismic Equipment Expert Panel for CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization). Moreover, he has contributed to GSA as a visiting researcher and the Indian Ocean Tsunami Hazard Assessment. He has also served as an advisory board member for IntechOpen publications. Currently, he is chairman of ICG/NWIO-WG(Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System/Working Group for the North-West Indian Ocean), is a founding member of TERC(Tsunami and Earthquake Research Centre), and serves as the Director of the Maga Makran project at Hormozgan University and the VP of the SPIRM Institute. Throughout his career, he has supervised 32 MSc and 14 Ph. D. students, published over 95 papers, delivered 120 conference presentations, and authored 11 books.

Contents

Preface

The world today faces an unprecedented array of challenges as natural hazards and environmental changes continue to shape the landscapes we inhabit. From the intricate dynamics of climate variability to the sudden devastation wrought by seismic and tsunami events, our understanding of these phenomena is critical to building a resilient and sustainable future. The chapters in this book offer a multifaceted exploration of these hazards, presenting a blend of scientific rigor, community-focused strategies, and innovative solutions.

This book explores the complex interplay between climate variability and community resilience, particularly in regions like Nabiswera Sub-County, Uganda, and Northern Nigeria. It highlights how climate-smart agricultural practices and local knowledge can mitigate the vulnerabilities rain-fed farming communities face. By presenting these case studies, we hope to inspire new approaches to empowering vulnerable populations and creating adaptive strategies.

Equally vital are the contributions to seismic risk assessment and tsunami preparedness. Applying machine learning to seismic hazard analysis and using microtremor HVSR (Horizontal-to-Vertical Spectral Ratio) techniques for micro-zonation exemplify how advanced methodologies shape our capacity to predict and prepare for disasters. Tsunami inundation mapping, as demonstrated by the study of Jask Port, Iran, underscores the importance of localized action within globally coordinated frameworks like the Community Tsunami Ready Program, initiated by UNESCO and its consequence Evacuation Mapping.

The human dimension of disaster recovery emerges strongly in this book, mainly through reflections on post-disaster recovery in Chimanimani District, Zimbabwe, and the socio-economic impacts of the 2004 tsunami in Galle City, Sri Lanka. These chapters remind us that resilience is not only a matter of infrastructure but also one of equity, inclusivity, and survivor agency.

Emerging frontiers in risk assessment, such as earthquake nowcasting methods in North China, demonstrate the transformative potential of integrating traditional analyses with modern computational tools. These innovations represent a leap forward in mitigating risks and safeguarding lives and livelihoods.

The insights and research presented in this book prove the necessity of global collaboration and localized action. Together, they paint a compelling picture of humanity's capacity to adapt, innovate, and thrive in the face of uncertainty. We hope this book serves as both a resource and an inspiration to all those committed to addressing the unseen hazards of our world.

May this exploration of natural hazards serve as a stepping stone towards a future where we can effectively navigate the challenges, minimize risks, and build a safer and more sustainable environment for future generations.

Before I conclude, I want to mention that the presented chapters have been peer-reviewed and accepted for publication. Hence, I express my heartfelt gratitude to all the authors who have contributed their expertise and insights to this book. Their dedication and passion for understanding and addressing the hazards we face have been instrumental in shaping this comprehensive exploration.

Finally, I also want to extend my appreciation to the IntechOpen publication for initiating this book and for their invaluable support and guidance throughout the publication process. Their commitment to disseminating knowledge and encouraging scholarly works has been pivotal in bringing this book to fruition.

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Section 1

Climate Variability, Resilience, and Adaptation

Chapter 1

An Exploratory Analysis of Climate Variability and Its Effects on Community Resilience in Nabiswera Sub-County of Nakasongola District, Uganda

Wonder Mafuta, Lydia Mazzi Kayondo, Lilian Oryema and Victor Onama

Abstract

Climate variability and change are fundamental global challenges that pressure society's social, economic and environmental dimensions. The study examined how climate variability affected community resilience in Nakasongola District's Nabiswera sub-county from 1984 to 2016. Geospatial vulnerability and regression analysis tools were used to assess climate variability and establish the relationship between climate variability and community resilience. Results showed a significant change in rainfall and temperature patterns over 30 years (1984–2014). Climate variability significantly affected community resilience ($F = 18.266$ and $p = 0.000$). The change in climatic conditions exposed all social groups' resilience within the pastoral communities, as most depend on rain-fed agriculture. The paper mainly focused on the longitudinal effects of temperature and rainfall variability and further research is recommended to identify coping strategies for climate variability. It is recommended that early warning and early action systems be established to ensure that households are prepared for disasters and that resources are available to respond when shocks occur.

Keywords: climate variability, community resilience, rainfall analysis, temperature analysis, extreme weather

1. Introduction

Climate variability and change continue to be a fundamental global challenge exerting pressure on society's social, economic and environmental dimensions [1–4]. Climate variability presents severe challenges to rain-fed agricultural economies, resulting in crop destruction, failure and the subsequent loss of coping capacity due to shocks. The global mean surface temperature will rise from 1°C to 6°C by 2100 [5, 6].

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The United Nations Development Programme (UNDP) 2003 affirmed that recent natural disasters in East Africa have been related to climate change and variability. Climate variability and change severely affect the poor due to their limited adaptive capacities and systems about education, technology, functional institutions and access to financial assets [7–9]. Climate variability remains a significant challenge because the linkage between failed crops and changing weather patterns has not been established [10–12].

Uganda projected a change between 1.5°C and 4.30°C by the year 2100 (source). The semi-arid regions of Uganda, particularly the cattle corridor of Nakasongola, received erratic rainfall and temperature rises [13–16]. The precipitation intensity is, on average, expected to increase mainly in tropical and high-latitude regions [17]. According to Panagos et al. [18], the annual rainfall amounts are projected to increase by 10% and 20% by 2050 and 2100, respectively. These changes will undoubtedly impact crop yields. When planted, croplands experience too much rainfall, crop damage, soil erosion and the inability to cultivate land due to waterlogging of soils may become inevitable [19]. The damages to crops result in food insecurity [20]. Climate variability and change also result in droughts, landslides, famine, windstorms and epidemics [21]. Uganda is among the grossly affected vulnerable countries to the impacts of climate change and disasters due to the physical, social, economic and environmental factors [22, 23] that influence people's capacity to protect their livelihoods. Flooding in Uganda in the past years resulted in a surge of malaria, cholera, dysentery and respiratory diseases [24–29].

The cattle corridors in Uganda, characterised by poor rainfall distribution, prolonged dry spells and flash floods, are the most vulnerable areas [30–33]. The frequent occurrence of these hazards has eroded the productive assets and the coping strategies of the communities to support their livelihoods (source). This study's main objective was to establish the extent to which climate variability affects community resilience.

2. Materials and methods

2.1 Study area

Nabiswera sub-county is located within Uganda's cattle corridor, which is characterised by poor rainfall distribution, prolonged dry spells and flash floods [34]. The frequent hazards have eroded the productive assets and communities' coping strategies to support their livelihoods. Nabiswera relies on natural resources such as Lake Kyoga to sustain its people's food income demands. In the past, charcoal production was a major commercial enterprise in the District.

2.2 Data collection and management

Establishing the relationship between climate variability and community resilience required adopting a quantitative and geospatial vulnerability analysis approach. A longitudinal study design was adopted using both quantitative and qualitative techniques. Three hundred eighty-seven respondents administered the questionnaire survey. The data from the survey guided the development of questions for the Focus Group discussions. The FGDs collected data on opinions, attitudes, perceptions and knowledge on climate variability and change, coping mechanisms and adaptation strategies. A total of 6 FGDs (1 per parish) were conducted for each category of respondents. Quantitative data collection was leveraged on smartphones using the Open Data Kit (ODK) platform with a Global Positioning System (GPS) facility to support geo-referencing survey locations and geospatial analysis of results.

Desktop reviews were conducted to collect historical climate data to determine the changing trends and better understand variability and change. The climate data on rainfall and temperature from 1984 to 2014 was obtained from the Uganda National Meteorology Department (UNMA). An assessment period of 30 years was considered since cycles of climate variability can best be understood at different time scales of at least more than a decade, as asserted by Grimm [35] and IPCC [36]. The rainfall and temperature data determined the study area's trends, variability and climate change. Monthly and annual temporal scales were reviewed for rainfall. Minimum, average and maximum temperatures were also recorded. The temperature data time scale was also monthly and yearly. The Rainfall Anomaly Index (RAI) was calculated to normalise rainfall values based on the annual rainfall data from 1984 to 2014. The positive and negative anomalies were computed using the formula below:

$$\mathrm{RAI} = 3\left[\frac{\mathrm{N}-\overline{\mathrm{N}}}{\overline{\mathrm{M}}-\overline{\mathrm{N}}}\right], \text{For positive anomalies}$$

$$\mathrm{RAI} = -3\left[\frac{\mathrm{N}-\overline{\mathrm{N}}}{\overline{\mathrm{X}}-\overline{\mathrm{N}}}\right], \text{For negative anomalies}$$

Where:

N = the yearly rainfall data used to generate the rainfall anomaly index (mm).

Ñ = yearly average rainfall of the historical series (mm);

$\overline{\mathrm{M}}$ =average of the ten highest yearly precipitations of the historical series (mm);

$\overline{\mathrm{X}}$ = average of the ten lowest yearly precipitation of the historical series (mm).

Positive anomalies have higher values above average, and negative anomalies have values below average. **Table 1** presents the classification of rainfall anomalies for purposes of visualisation.

Survey data was downloaded from ODK aggregate and analysed using Statistical Package for Social Scientists (IBM SPSS version 25.0) and ArcGIS software. Regression analysis identified the relationships between multiple resilience models: total vulnerability (dependent variable) was influenced by total income and dietary diversity.

RAI range	Classification
Above 4	Extremely humid
2 to 4	Very humid
0 to 2	Humid
−2 to 0	Dry
−4 to −2	Very dry
Below −4	Extremely dry

Source: Van Rooy [37]; adapted by Freitas [38] and Araujo et al. [39].

Table 1.
Yearly rainfall anomaly classifications.

According to Birkmann [40], Vulnerability = (Exposure) + (Resistance) + (Resilience). It encompasses the degree to which a system is susceptible to and unable to cope with climate change's adverse effects, including climate variability and extremes. The analysis of exposure involved temperature and rainfall data. Sensitivity analysis focuses on examining the rate of change in the climate parameters of temperature and precipitation. Lastly, the adaptive capacity involves analysing socioeconomic and household demographic profiles, livelihood strategies and social networks. To compute the Vulnerability Index (VI), the expression; Vulnerability = Exposure + Sensitivity-Adaptive capacity was applied. The exposure parameters included rainfall and temperature.

The sensitivity parameters included the rate of change in the annual and monthly precipitation and the yearly average minimum and maximum temperature range. For each sampled household, a weight of 0-1 was assigned based on exposure to temperature and rainfall values changes. Therefore, households with a weight of 0 were less exposed than those with a weight of 1. The Inverse Distance Weighted (IDW) technique in ArcGIS software was used to code and weigh household-specific temperature and rainfall data index. The geospatial data has been interpolated to provide a better visualisation. Thematic analysis was conducted using Nvivo 12 to analyse community opinions, attitudes, perceptions and knowledge relating to variability and change in climate, coping mechanisms and adaptation strategies.

3. Results

3.1 Climate variability

More than three-quarters (76.2%) of the respondents had witnessed a variation in rainfall. 89.7% of the respondents reported extreme weather events such as fluctuations in rainfall patterns, frequent droughts, more hot days and delays in rainy seasons, while only 8.3% reported that they had not experienced extreme weather events; 2.1% were not sure if they had experienced extreme weather events in the past.

> *'We can no longer tell when the rainy season begins and ends. Even when you expect the usual rainfall, it does not happen; things have changed-Said a focus group participant in Kyamukonda'.*

Overwhelmingly, 98.6% of the respondents reported that they had experienced drought conditions, and 76.5% reported experiencing frequent droughts over the past 30 years.

3.2 Variability in rainfall

The historical rainfall data from Uganda National Meteorology Authority revealed that the study area's rainfall varied from 896 mm to 1594 mm, averaging 1336 mm per annum. The average rate of change in the annual rain was 4 mm per annum. The yearly rainfall oscillating between 896 mm and 1594 mm resonated with survey findings, where 76.2% of the respondents reported rain fluctuations over the years. The seasonal mean rainfall was 28 mm, with a Standard Deviation (SD) of 17 and a

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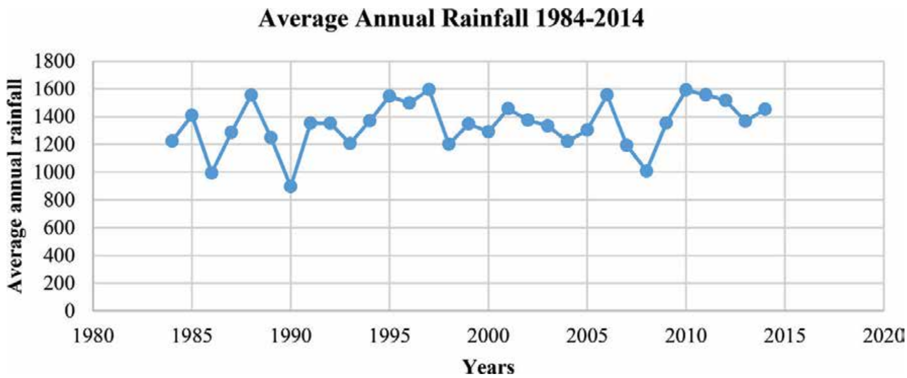

Figure 1.
Rainfall patterns in Nakasongola.

0.6 Coefficient of Variation (CV). A low CV depicts a slight variation observed in the seasonal rainfall patterns in the study period. **Figure 1** presents the rainfall pattern in the Nakasongola sub-county from 1984 to 2014.

As shown in **Figure 2**, the yearly rainfall anomaly index ranged from 0 to 1.2, with the highest reported in 1986, 1990 and 2008. The years 1991, 1992, 1999, 2003, 2009 and 2013 had 0.0 rainfall anomaly. The results imply that the study area has continued to be humid despite the variations in climate parameters.

Over the years, Nabiswera has continued to experience isolated outbreaks of showers and rainfall. Annual and seasonal rainfall peak was observed in 1988, 1995, 1997, 2006, 2010 and 2011. The lowest rainfall patterns have been in 1990 and 2008. Near normal

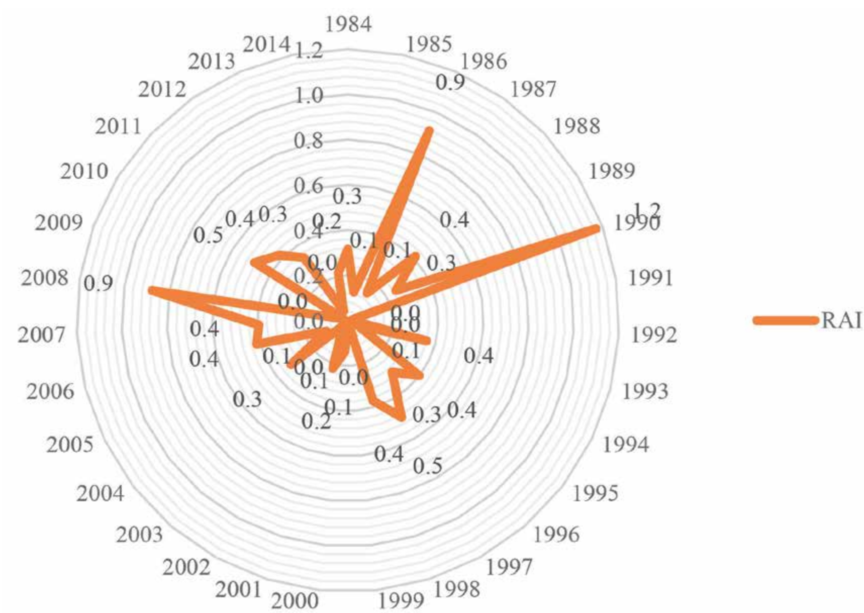

Figure 2.
Yearly rainfall anomaly index (RAI).

(average) to above normal (above average) rainfall conditions are expected to prevail over the study area. The results imply that Nabiswera will continue to experience a drop in rainfall patterns, likely affecting the community's capacity to respond to shocks.

3.3 Variability in temperature

The annual minimum temperature rapidly varied from 21°C to 24°C, while the average maximum temperature ranged from 23°C to 46°C. Uganda's minimum temperature was highest (26.5°C) in February of 2005 and lowest (21°C) in December of 1860. The recorded average maximum temperature of 46°C in 1995 could be an outlier that could not be triangulated and confirmed with the available data. A coefficient of variation for the season temperature data was analysed to understand the mean value's temperature dispersion. The results indicate that the coefficient of variation for temperature was at 3 between December and February. The coefficient of temperature variation was reported at 2 between June and August. Therefore, with a CV of 3 and 2 noted, there is not much variation in minimum and maximum temperatures from 1984 to 2014. **Figure 3** presents the average annual minimum and maximum temperatures.

Figure 3 shows the minimum and maximum average temperature in Nabiswera from 1984 to 2014.

Kalengedde and Namasa experienced an average minimum temperature of 19 and 19.5°C, while other parts experienced a lower minimum average temperature between 18.5 and 19°C. The Eastern parts of Nabiswera sub-county-towards Lake Kyoga experienced a higher maximum average temperature of 30.5–31°C than the western part, experiencing a slightly lower average maximum temperature of 30–30.5°C between 1984 and 2014. The higher temperatures around the lakeside result from the sun's heat retained in the ground and water.

The Eastern parts of Katubba, Kalengedde, experienced higher average temperatures of 25–26°C. Mulonzi, Kyangogolo, Migeera and Namasa experienced an average temperature of 24–25°C. The Western parts of Kyamukonda-towards Nakaseke district experienced an average temperature of 23–24°C. These findings resonate with Sierra [41], who noted that temperatures decrease by an average of 6.5°C per rise of one thousand meters (1 km). Therefore, Kalengedde and Katuba lie at a lower altitude than Kyamukonda. The nearer the lake, the lower the altitude and the higher the temperature. Conversely, the further from the lake, the higher the altitude and the lower the temperature.

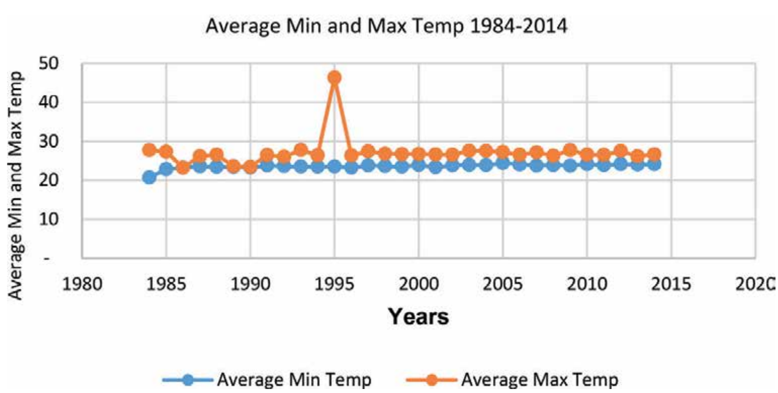

Figure 3.
Average annual minimum and maximum temperature.

3.4 Effects of climate variability on community livelihoods

62.8% of the respondents reported a loss in agricultural production, while 20.7% reported a loss in livestock. Similarly, 3.5, 4.6 and 3.7% of respondents reported property damage, loss of income sources and lack of potable water, respectively.

Table 2 presents the effects of climate variability on communities in Nabiswera.

Regression analysis determined the extent to which climate variability affects community resilience and adaptive capacity. The R^2 results of 0.418 in the regression analysis in **Table 3** indicate that the overall variance in community resilience explained by climate variability is 41.8 (4.18*100). Notwithstanding the R-square's value of 0.418 (presumably low), the results show that the regression model has statistically significant explanatory power. With guidance by Neter et al. [42], a small R^2 still generates lots of data since we do not expect social sciences to include all the relevant predictors to explain an outcome variable. Therefore, it is worth noting that the results imply that climate variability affects community resilience by 41.8%, and the remaining 58.2% is attributable to other variables not part of the study. A further statistical analysis using the ANOVA test affirms the results.

The ANOVA results indicate that climate variability significantly affects community resilience, with F = 18.266 and p = 0.000. Climate variability significantly determines community resilience changes in Nabiswera sub-county in Nakasongola (**Table 4**).

The regression analysis results in **Table 5** reveals that temperature change is negatively significantly related to community resilience (β) = −0.131, and the p-value of 0.028 is less than the chosen alpha (α) level of 0.05. It means that temperature change significantly negatively affects community resilience in Nabiswera. The results

Response	Frequency	Percentage (%)
Damage to property	12	3.5
Loss in livestock	72	20.7
Loss in crop production	218	62.8
Loss in income	16	4.6
Health hazards	5	1.4
Lack of water	13	3.7
Other	10	2.9
I don't know	1	0.3
Total	347	100

Source: Field data.

Table 2.
Effects of extreme climates events.

Model	R	R^2	Adjusted R^2	Std. Error of estimate
1	0.418[a]	0.175	0.165	0.72498

[a]*Predictors: (Constant), change in temperature, change in rain.*

Table 3.
Regression analysis.

Model	Sum of squares	df	Mean of square	F	Sig
Regression	38.403	4	9.601	18.266	0.000[a]
Residual	181.333	345	0.526		
Total	219.736	349			

[a]*Predictors: (Constant), change in temperature, change in rain.*
[b]*Dependent variable: community resilience.*

Table 4.
Anova[b].

Model	Unstandardised coefficients		Standardised coefficients		
	B	**Std. error**	**Betta (β)**	**t**	**Sig.**
(Constant)	1.737	0.214		8.101	0.000
Change in temperature	0.140	0.63	−0.131	−2.211	0.028
Change in rainfall	0.291	0.61	−0.254	−4.758	0.000

[a]*Dependent variable: community resilience.*

Table 5.
Coefficients[a].

practically imply that community resilience deteriorates with changes in climate variables. A change in rainfall is negatively considerably related to community resilience (β) = −0.254, and the p-value of 0.000 is less than the chosen alpha (α) level of 0.05. The results revealed that change in rainfall significantly negatively affects community resilience in Nabiswera sub-county (**Table 5**).

3.5 Community vulnerability index

The results indicate that Namasa, Migeera, Kyamukonda and Kyangogolo were more exposed to shocks. This implies that urban households are more vulnerable to shocks than rural households. In rural setups, most families depend on rain-fed agriculture for their livelihoods, yet urban households have minimal access to land as a resource for production.

Furthermore, the rate of change in annual and monthly rainfall and average yearly minimum and maximum temperature values were considered when assessing sensitivity. The weighting of 0–1 was considered in computing sensitivity. A higher weight depicted a higher sensitivity and vice versa. The results indicate that Namasa was the most sensitive parish, followed by Kalengedde and Migeera. A higher sensitivity means that the households are more exposed to challenges associated with climate variability, and the community's vulnerability is higher. This is because poor communities, particularly those concentrated in high-risk areas, can be especially vulnerable. They tend to have more limited adaptive capacities and depend more on climate-sensitive resources such as local water and food supplies.

3.6 Adaptive capacity

The paper also computed the adaptive capacity of each sampled household. The adaptive capacity was based on vital socio-economic indicators, including access to health services, education, safe water and financial services. The higher the adaptive capacity, the lower the household vulnerability. Conversely, a lower adaptive capacity implied a higher susceptibility to exposure. The results indicate that Migeera, Namasa and Kyamukonda were more adaptive than other parishes where the study was undertaken. It should be noted that enhancing community resilience requires building their adaptive capacity and reducing people's vulnerability to the observed changes in climate variables such as temperature and rainfall. Although it may be argued that adaptive capacity does not necessarily translate into measures that reduce vulnerability, it is worth noting that it dramatically influences community adaptation to climate change.

Parts of Namasa, Kyamukonda and Migeera were found to be the most vulnerable locations in the Nabiswera sub-county. Surprisingly, many respondents from Migeera were the most susceptible despite their proximity to the Migeera town council. On the contrary, Kyamukonda, Kyangogolo and Kalengedde were less adaptive to respond to shocks' occurrence. According to the Focus Group Discussion participants, this was due to multiple livelihood opportunities around the lake shores, including fishing.

While community members have been affected by extreme weather events, the majority (68.2%) have taken actions to adapt or cope with the changes, although 25.6% could not manage. Nevertheless, 6.2% of the respondents were unaware of efforts to cope with climate change or extreme climate events in their communities. Unfortunately, those who cannot cope with the changes are particularly vulnerable to climate change since their livelihoods mainly depend on resources that are heavily influenced by the changes in rainfall.

> *We plant crops, but when they fail, we try to engage in other alternative activities as much as possible. The problem is that most alternative activities still depend on rain, reported a focus group participant from Migeera.*

Although the pastoralist community has demonstrated considerable effort in adapting to climate variability in the past, their capacity to cope with the continued variability in temperature and rainfall remains doubtful. The respondents are reported to have adopted various coping strategies in reaction to the extreme climate events, as observed in earlier studies [43–45].

4. Discussions

The findings on rainfall changes affirmed earlier studies by [46–50]. 64.3% of the respondents reported delays at the start of the rainy season. The results depict that with the change in rainfall patterns, community members cannot engage in agricultural production, dramatically affecting their capacity to bounce back during shocks. The results are comprehensible compared to other studies that revealed a rise in temperatures by 0.70C during the twentieth century, while changes in rainfall patterns saw reduced precipitation [51, 52]. Similarly, the results corroborated with studies that reported that a 1.50C shift in temperature is critical for agriculture [53, 54]. Extreme weather events will likely induce new and persistent shocks, such as crop pests and livestock epidemics common among pastoralist communities, mainly from rainfall deficiency. Extreme climate events will potentially risk community resilience, as Uganda Meteorological Unity observed in 2011.

The study results affirm the findings from other studies that projected a rise in the global mean surface temperature by 1.00C-060C by the year 2100 [36, 55–58]. A further analysis conducted by IPCC [36] projected an increase from 1.8°C to 4.0°C by the year 2100, with tropical regions experiencing the most significant increments because of prolonged droughts, dry spells and direct exposure of the area to the sun's rays throughout the year. The exact change in temperature has been observed [59–61], who affirm that temperatures will continue to change by 1.50C to 4.30C by 2050. While most scholars' projections in temperature fall in the same range of 1.50C to 4.50C, Alexander [62] projects even a higher rise by 40C–60C by 2080-above, the global average, thereby posing a significant threat to community resilience in the Nabiswera sub-county.

The findings corroborated with the Uganda Office of the Prime Minister study that rain-fed agriculture forms a significant food and income source in Uganda. The OPM study further noted that drought severely affects communities' welfare. Rautenbach [63] noted that extreme weather events have increased and become more severe in recent years. Similarly, Shi and Tao [64] said that Uganda is one country experiencing the highest impacts of drought and changes in climatic patterns. The findings imply that the community's capacity to withstand climate variability shocks will continue deteriorating.

The study results agree with an analysis by other authors that concluded that risks from extreme weather events have been increasing and becoming more severe [63, 65, 66]. Shi and Tao's [64] study of African Country data since 1960 placed Uganda among the countries with the highest drought impacts on community resilience. Papalexiou and Montanari [67] also noted that extreme weather events have increased recently, and droughts are becoming more frequent and severe in the community.

Therefore, the unfolding change in temperature and rainfall places most families at high risk. The results align with earlier findings that large-scale subsistence agriculture, and the ability to generate agricultural export earnings in rural areas should make them relatively less vulnerable to food insecurity [68]. The same study found acute vulnerability to food insecurity in low-income urban households due to their exposure to shocks and climate-related challenges.

The findings corroborate a study conducted by Schneider et al. [69], where he argues that there is evidence of an adaptation deficit [70]. Hepworth and Gouden [71] noted that Uganda has the least adaptive capacity, making location-specific adaptation the most immediate priority.

5. Conclusion

Changes in rainfall and temperature patterns have occurred across Nakasongola, as characterised by extreme weather events such as fluctuations in rainfall patterns, frequent droughts and delays in the usual rainy seasons. Extreme weather events will likely induce new and persistent shocks, such as crop pests and livestock epidemics common among the pastoralist communities, mainly from rainfall deficiency. Climate variability exposes women more than men since society excludes them from socioeconomic activities and mostly depends on rain-fed agriculture for basic sustenance. Enhancing community resilience requires building their adaptive capacity and reducing vulnerability to the observed changes in climate variables such as temperature and rainfall. Although adaptive capacity does not translate into measures that minimise exposure, it is worth noting that it greatly influences community adaptation to climate change. Urban households have minimal access to land as a resource for production.

6. Recommendations

The unfolding change in temperature and rainfall increases the risk for urban dwellers. It is recommended that early warning and early action systems be established to ensure that households are prepared for disasters and that resources are available to respond when shocks occur. Various social institutions' capacity must be strengthened through training and financial support to enhance adaptation to climate variability and change.

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Chapter 2

Changing Paradigms in Addressing Climate Shocks among Pastoralists and Women Farmers in Northern Nigeria

Sidiqat Aderinoye-Abdulwahab, Akeem Rabiu Ganiyu and Halimah Egbewole

Abstract

African farmers and pastoralists practice rain-fed agriculture that predisposes them to natural hazards in the form of climate change impacts and shocks. 'Shocks,' by implication, already connote unexpectedness, high damage, vulnerability, and low resilience. Moreover, natural hazards have the potential to become disasters in the absence of mitigation measures. Climate-induced hazards have impacts on the livelihood of families linked with farming, while pastoralist women also suffer great losses given that they depend on the milk from husbands' herds as their major source of sustenance. This chapter presupposes that the hazard was the Boko-Haram elements, while insurgency is the disaster waiting to occur in northern Nigeria. This has indeed happened, and Nigerians are now left to deal with the shocks. Women were more vulnerable because they were exposed to greater risks, and as such, they felt greater impacts. Hence, after the Boko Haram insurgency, the internally displaced camps (IDP) were filled with more women and children. This chapter will therefore explore how to strengthen the coping capacity of farmers, pastoralists, and women given the impacts of climate change.

Keywords: rain-fed agriculture, mitigation, coping capacity, productivity, vulnerable groups, climate-smart practices

1. Introduction

Agricultural sector is widely recognized as one of the major contributors to climate change [1], while it is known that most African farmers and pastoralists practice rain-fed agriculture with worsening situations due to erratic rainfall patterns [2] amidst exacerbating changes in climatic conditions. Farmers and most women farmers are adversely impacted and unable to plan adequately for their planting operations. Agricultural productivity is also known to be sensitive to climate change-induced effects [1, 2], and it has impacts on the livelihood of families linked with farming. Pastoralist women also suffer great losses given that they depend on the milk from husbands' herds as their major source of sustenance [3]. Thus, it is important to understand the gravity of the disaster, the level of farmers' vulnerability to climate-induced shocks, what coping strategies exist for farmers, and what mitigating strategies farmers and pastoralists deploy in the case of climate shocks.

Globally, extension services remain one of the panaceas for sustainable agricultural practices as well as food and environmental security attainment. Farmers are in dire need of technical information to overcome the challenges associated with climate change impacts and to boost agricultural production using available resources. To ensure that proper and adequate technical information reaches farmers, extension officers need to have updated knowledge through regular and constant training in the form of capacity building. Hence, this chapter seeks to inform experts in the field of agricultural extension to foster the capacity of field officers as well as to enlighten the entire populace on how to address and mitigate the impacts of climate shocks. Although extension practitioners are a major beneficiary of the chapter, personnel working in agriculture and other related disciplines would also find it useful. Farmers will equally benefit, while the cited illustrations and examples will go a long way in awakening agricultural students and farmers alike. We will proceed to explore closely related terms related to *shocks:* climate change, hazard, vulnerability, risk, impact, coping strategy, disaster, mitigation, and resilience.

1.1 Climate shocks-related terminologies

Hazard: an extreme geophysical event that can cause a disaster (4). A hazard is a threat but not an actual event.

Vulnerability: the quality or state of being exposed to the possibility of being attacked or harmed, either physically or emotionally (4, 5). It is the degree to which a system or human is adversely affected by the occurrence of a hazardous event and the capacity of the system/human to absorb and recover from the hazardous event. Vulnerability can be viewed using three lenses: exposure, sensitivity, and adaptive capacity. It is a complex outcome of many events, such as education, affluence, gender, demography, technology, environmental hazards, and preparedness. Location can also act as a vulnerability factor, for example, people and farmers living near a topography that is prone to erosion or drought will be more vulnerable to flooding and desertification, respectively. In this context, farmers and pastoralists can be exposed to both physical harm and emotional harm. Their vulnerability can be linked to the vagaries of climate change indices such as droughts, heavy rainfall, high sun intensity, drylands, and lack of pasture [4]. Pastoralists, who hitherto live on the margins of their environment, can be vulnerable to emotional hazards such as lack of education [3], poor infrastructure, and gender discrimination.

Risk: the magnitude or probability of a dangerous event occurring [4, 5]. In other words, how likely is it that one is inflicted by harm or danger? Risk is a potentially occurring event that can damage well-being or inflict unpredictable harmful fluctuations to life and productivity. Risk = (hazard probability) (vulnerability) *OR* hazard probability + vulnerability. Farmers and pastoralists can therefore be said to be high-risk people because of their vulnerability to environmental hazards.

Disaster: a sudden calamity, an event bringing great damage, loss, and injuries to property and/or life [5]. Examples of disasters are erosion, climate change impact, tornadoes, tsunamis, deaths, car and road accidents, and wars.

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Coping capacity: the capacity of humans to respond to or recover from extreme events or shocks. A system or human can recover from the effect of stress [6] with the use of available skills and resources. Coping strategies are deployed to manage adverse conditions, risks, or disasters.

Mitigation: policies and activities that attempt to reduce and/or eliminate individual and/or community vulnerability to damage from future disasters. Mitigation seeks to address hazards such that they impact humans or communities to a minimal degree [5, 6]. Natural hazards have the potential to become disasters in the absence of mitigation measures. For example, where there is no drainage (mitigation), heavy rain (hazard) has the potential to cause flooding or erosion (disaster).

Resilience refers to mitigating hazards, recovering from the impact of disasters and coping capacity, containing or restricting the effect of disasters, and reducing vulnerability [7]. It is the ability to withstand external, social, economic, or political shocks. Resilience is more encompassing than coping capacity. One is said to be resilient when people find it easy to cope well with the shocks, and the disaster no longer tends to impact their well-being [8]. Hence, farmers and pastoralists would be resilient when climate change no longer tends to impact their livelihoods. For example, pastoralists from arid and semi-arid regions have consistently migrated to savannah areas to circumvent droughts and their effects (lack of pasture). In the course of their sojourn, they have learned to diversify their economy and incomes by engaging in agropastoralism so that they are still able to navigate both occupations as the climate demands.

1.2 What are climate shocks?

Shocks are the realizations of highly unexpected events that cause welfare losses. In other words, risks are prospects of a shock, or shocks can be thought of as the realization of risks [4, 5]. 'Shocks,' by implication, already connote unexpectedness, size, high damage due to concentration on persons with high vulnerability and low resilience, exogenousness in the source, and physical or psychological strain to one or more individuals due to that stress. Thus, the term climate shock would be termed a natural disaster: those events that outstrip the capacity of a society to cope with it.

1.2.1 Case analysis of climate shock: an indigenous illustrative evidence from Nigeria

The majority of pastoralists in Nigeria are situated in the arid and savannah regions and are highly vulnerable to shocks brought about by the impact of climate change [3]. Water and pasture for livestock are particularly scarce in these areas especially during the dry season making the pastoralists relocate with their herds [2, 3]. Moreover, desertification, low rainfall, and prolonged shortage of water and pasture because of impact of climate change have necessitated relocation of pastoralists, in large numbers, from the arid to the Guinea Savannah and rainforest regions. In addition, pastoralists who live within this geographic domain have limited access to social, health, processing, preservation, and infrastructural facilities necessary for developing the value chain activities of their milk products. The vulnerability indices and resultant effects on the pastoralists include wastage and loss, which further exacerbate their poor economic livelihood, low yield in terms of milk production and cheese processing, poor nutritional content of the milk following the inadequate processing methods being used by the women, lack or inadequate intervention from extension agents, low income, and unsustainable livelihoods. Climate change impact has necessitated that pastoralists relocate from their original domain, and this has further escalated into farmer-herdsmen crises. The intensity and regularity of farmer/herder crises have maintained a steady crescendo engulfing most of the central and southern regions of Nigeria. According to the global terrorism index, over 1200 people were killed by different Fulani herdsmen in 2014. A non-governmental organization, the Coalition on Conflict Resolution and Human Rights in Nigeria reported that over 2000 lives were lost to clashes between the herdsmen and farmers in Benue, Taraba, Plateau, Adamawa, Kogi, and Nasarawa States in 2017 [9]. Amnesty International also reported 168 deaths in Adamawa, Benue, Taraba, Ondo, and Kaduna States in January 2018 alone. Of all the states affected, Benue communities were reported to have been brutally attacked and emptied out [10]. Oyo and Ondo States in southwest Nigeria have also reported grave cases of farmer/herdsmen crises in recent times [9].

These events, which largely were occasioned by the vagaries of weather and climate, have resulted in a hazardous event and might have further plunged the northern region of the country into a vulnerable situation. The hazard was the Boko-Haram elements, while the insurgency was the disaster waiting to happen. This has indeed happened, and Nigerians are now left to deal with the situation. Women were more vulnerable because they were exposed to greater risks, and as such, they felt greater impacts. Hence, the IDP camps in Nigeria after the Boko Haram insurgency were filled with more women and children. After the occurrence of disasters, women tend to be more strongly affected than men [11, 12].

1.3 What are the climate change problems or shocks faced by women farmers and pastoralists?

1. High temperatures during the dry season, coupled with a drastic reduction in the amount of rainfall. The global impacts of climate change have further increased the drudgery of the inhabitants of dry and tropical regions, especially women. During the past 5 years, a large chunk of cultivable land has remained barren because of the changing micro-climatic conditions [13, 14] as well as the insecurity ravaging the country. People have been forced to auction their milk-yielding animals due to the unavailability of sufficient fodder. This, in effect, has translated into farmers/herdsmen crises over the years, especially in the northern region.

2. Extended dry seasons have forced households to change their eating and drinking habits.

3. Long periods of drought have put an extra strain on already overburdened women. They must travel long distances in search of water, fodder, and fuel/firewood for cooking at home.

4. Resowing is becoming a common phenomenon in agriculture because seeds fail to germinate due to insufficient moisture in the soil. This is yet an impact of climate change.

5. Erosion, flooding, landslides, and earthquakes have become very common and frequent [14] not only near dams but also in other parts in the communities. They not only destroy the fields but also make the lives of the inhabitants even more difficult by blocking the motor road, which might be the only way to reach the nearest market or health center. As is common across sub-Saharan Africa, women in Nigeria represent the main agricultural workforce [15], while they face

arduous circumstances to include enormous domestic responsibilities, which include cooking food, looking after kids and animals, collecting fodder, water, fuel, and working in the fields.

6. Climate change adversely affects the health of human beings, especially women, children, and elderly people. Emissions are increasing daily due to agricultural production, increase in the number of automobiles, and the free grazing of cattle. All these greatly affect human lives with an increase in the incidence of respiratory diseases [16, 17].

2. Changing paradigms: what needs to be done for women to enjoy a better life devoid of climate shocks?

Rural women already experience the effects of climate change in their daily lives. They can see weather patterns changing and previously dependable crops no longer thrive. They are having their livelihoods wiped out by extreme weather events [18]. With less access to resources than men, they have a harder time bouncing back. They are at greater risk of gender-based violence [19] due to climate disasters (e.g., they stay longer on farms because of changes in weather episodes and become exposed to the risk of gender-based violence when returning from farms). They often feed the households [18], so they notice when a variety of nutritious food is no longer affordable or available. To address these vulnerabilities, there is a dire need to recognize that rural women hold the keys to climate resilience for themselves, their families, and those people living in localities surrounding their environment. Hence, there is a great need for a paradigm shift so that women can be allowed to lead the way. In changing the paradigms, it is important to:

1. *Listen to women*: Women make up almost half the world's agricultural workforce [19], and they have good knowledge of the local landscapes and resources, including the wealth of biodiversity available. Therefore, listening to women leads to more effective, comprehensive, and inclusive solutions.

2. *Promote women's leadership and participation in decision-making at all levels*: Improving women's access to decision-making opportunities will make them equal partners of men in climate change and disaster risk reduction efforts. Unfortunately, they are not allowed to contribute to decision-making even in their households. However, if women are allowed to contribute to decisions, their households and communities will cope better with the changing climate given their wealth of knowledge on how to manage climate change impacts. When considering matters of equality and justice, women's voices and opinions must be represented. Hence, the involvement of women in leadership positions can lead to more resilient solutions.

3. *Invest in women's economic growth:* The consequences of economically empowering women have far-reaching implications. First, the benefits would not be for women only as they would also extend to their households and communities. Empowering women increases and diversifies incomes and protects against financial crises and environmental shocks. With improved access to inputs and knowledge of climate-smart practices, empowered women are also better equipped to protect natural resources and prevent land degradation.

4. *Increasing initiatives that support women's growth and development*: There are existing social, structural, and legal barriers that prevent women from achieving their full potential. Roughly 95 percent of the world's economies have at least one law restricting economic equality for women. This is why the International fund for Agricultural Development's (IFAD) initiatives to secure land rights for the poorest rural people focused on women [20]. Insurance policies are another way to provide financial stability in the face of climate risks, incentivize climate-smart agriculture and unlock other financing options. IFAD, for example, is already helping women grow their businesses; likewise, many non-governmental organizations (NGOs) are promoting access to insurance for women farmers.

5. *Reducing women's workloads:* Rural women bear the brunt of responsibilities, both on the farm and at home, without receiving full credit or compensation for their labor. These daily chores leave women with little time or energy to grow a business or take part in decision-making. A remedy is to promote equipment and techniques that reduce the time and effort needed to perform laborious tasks so that women can invest more in agricultural and productive activities [21]. These include the use of graters in place of manual grinding stones, the use of blenders in place of graters, and the use of industrial grinding machines in place of blenders. It should, however, be noted that these technologies have disadvantages and potential risks that increase climate shocks. Hence, there must be other mitigating measures to reduce the impact on women and farmers generally. Ultimately, it is about trading off; if machines reduce the processing time from days to a matter of hours, then one would consider what matters to them the most in deciding whether to use the technology or not. One tends to believe that women would find these technologies useful, and the use of the equipment will boost their production capacities and marketing skills, thereby resulting in increased incomes, better-connected communities, increased cultivation of indigenous food crops, and improved resilience.

6. *Break the barriers holding rural women back:* Bringing down barriers and ending power imbalances for women require nothing less than a social transformation—a complete rethinking of the discriminatory social and cultural norms that hold them back. Measures should be taken to help women and girls make informed decisions, deal with climate-induced pressures on their lives, and be recognized as fearless agents of change. There is a need to address women's practical needs by improving their technical knowledge and skills and increasing their access to productive resources (land, liquid assets, and decision-making capacities). There is also a need to promote the use of participatory methodologies such as focus group discussions, gender analysis mapping, and participatory appraisals to help women and men talk about—and question—traditional gender norms. Through these dialogs, families come to better understand women's contributions to the household and discuss how they divide household tasks and their rewards more fairly.

3. Changing paradigms: adopting climate-smart agricultural practices (CSAPs) to reduce climate shocks

Climate-smart agricultural practices (CSAPs) are a set of agricultural practices designed to sustainably increase productivity, enhance resilience, and reduce greenhouse gases (GHGs) [4, 7]. They aim at ensuring food safety and quality, environmental sustainability, economic profitability, and social and economic equity. Climate-smart agriculture is not a solution to climate change but rather a solution to many of the secondary challenges caused by climate shocks. The practices span pre-planting operations such as soil management and seed selection, the growing phase, postharvest handling, processing, packaging, and storage. CSAPs operate on three pedestals:

- Increased productivity for better food security for farmers, pastoralists, their families, and the entire populace.
- Reduced vulnerability so farmers, pastoralists, and the entire populace can better cope with and are better prepared to handle the current and future effects of climate change.
- Reduced GHG emissions to promote a sustainable and safer environment.

Some of the CSAPs that can be used to change the paradigm for increasing resilience to climate shocks include the following:

3.1 Conservation and biodiversity

Conservation tillage, crop, and pasture diversity can be used to address wind and water erosion by covering the soil with vegetation and limiting the number of tilling operations. Some crops have large leaf surface areas for absorbing atmospheric carbon for photosynthesis, thus reducing the amount of carbon in the atmosphere, while others help to fix nitrogen in the soil [14]. For effective tillage and cropping operations, proper timing for field operations should be determined and observed depending on the soil type. For example, clay soil is better tilled after harvesting, while other types of soil are better tilled before seeding. No-till farming will assists in soil conservation. This means planting seeds in crop residue with minimal disturbance. The no-till conservation approach implies that plants and their root systems are kept in place because the ground is not left bare. Uncovered areas are highly susceptible to erosion, and vegetation accumulates moisture for future crops.

3.2 Cover-cropping

Planting cover crops, such as legumes (melons, groundnuts, cowpea, etc.), helps to fix nitrogen [8, 14], thereby improving soil fertility and preventing weed growth. Cover crops serve as forage for cattle, provide green manure, assist in weed control, retain moisture, ensure a natural environment for microorganisms and minor animals, and balance nitrogen concentrations (either releasing or accumulating it with certain plants).

3.3 Grassland intensification

Women can engage in grassland intensification; therefore, cultivating massive amounts of natural grassland is more climate friendly. This will aid carbon sequestration by reducing the amount of carbon released into the atmosphere, consequently reducing the climate change impact.

3.4 Carbon capture

Carbon capture happens especially in segregated areas (grazing reserves) where cattle are being raised to avoid the mingling of herders' activities with farmers and other people in the communities. This would mean women and farmers would be less impacted by the greenhouse gas emissions.

3.5 Management of manure

By reducing N_2O while also helping to reduce atmospheric emissions generally, climate-smart agriculture will also decrease fossil fuel use, as this tends to increase CO_2 emissions.

3.6 Carbon trading

This can be employed to cushion the effect of climate shocks on women. Currently, men dominate the business where it exists, but women can become involved so they can also have access to the benefits accruable. This will boost their economic base and strengthen their empowerment level.

3.7 Use of alternative energy sources to reduce emission of greenhouse gases

Instead of using charcoal and firewood, efforts should be geared toward alternative sources such as solar-powered technologies. This will preserve our forests, enhance a greener environment, increase cleaner air, and reduce climate change impacts. Women can also use solar-powered pumps instead of electric/emission-generating sets for irrigating home gardens and even farm plots.

3.8 Agroforestry

Agroforestry is a sustainable land management practice that integrates trees and shrubs with crops and/or livestock production systems. This approach enhances biodiversity, improves soil health, and provides various ecosystem services. Agroforestry is a versatile strategy that can be adapted to suit a wide range of agricultural landscapes and environmental conditions.

3.9 Organic amendments

The use of organic amendments such as natural manure, compost manure, and farmyard manure can improve soil health, fertility, and structure. Additionally, it boosts nutrient content and improves water retention.

3.10 Water management

- *Rainfall harvesting:* Climate change refers to extremes of intense rainfall at times or longer dry periods at other times. This led to either too much or too little water. The collection and storage of rainwater from roofs or other surfaces for irrigation can supplement the water supply during dry periods. This reduces the dependence on groundwater and enhances water security. Such water can be stored in water tanks, storex, and water wells.

- *Mulching:* Dry season farming comes with a singular, most threatening challenge, heat! To increase the chances of crop survival, adequate irrigation water must be provided. Efforts must also be put in place to ensure that the water in the soil stays considerably for longer periods before the next irrigation day. Mulching is a practice in which either natural or synthetic materials are used to cover the beds or portions around the plant to limit the amount of water evaporating from the soil surface. It helps to retain soil moisture and reduce temperature extremes (**Figures 1**–**3**).

3.11 The use of drought-resistant varieties

Crop varieties that are resilient to drought conditions can ensure productivity even in water-scarce environments.

Figure 1.
Irrigation practices. Source: https://www.fao.org/platforms/water-scarcity/Knowledge/knowledge-products/detail/rainwater-harvesting-and-agroecological-irrigation-make-farmers-more-resilient-in-senegal/en

Figure 2.
Mulching practices. Source: https://ifdc.org/2023/04/21/mulching-a-win-win-for-the-earth-the-farmer-and-the-food-consumer/

Figure 3.
Crop-Livestock integrated practices. Source: https://sites.bu.edu/croplivestock/image-gallery/

3.12 Integrated crop-livestock management

This approach maximizes resource use efficiency by combining crop and livestock production, such as using wastes from livestock as fertilizer and crop residues to feed livestock [1]. Integrating livestock into cropping systems helps to reduce the risk of raising a single product, increase resistance to soil erosion, and increase soil organic compounds.

3.13 Livestock grazing management

This involves preventing soil overgrazing, shifting cultivation practices, and controlling grazing to maintain soil health, reduce erosion, and promote carbon sequestration.

3.14 Bio-pesticides

Natural materials such as plant extracts and beneficial microorganisms are used to control pests and diseases.

Other common CSAPs to increase production include the following:

1. Postharvest management: to improve the quality of harvested crops and diversify family's diets.

2. Reduced food loss and waste.

3. Stop deforestation.

4. Embrace public walking, biking, and public transport to reduce carbon emissions.

5. Low-carbon emitting devices can be used by embracing solar-powered technology and vehicles, as is the case in some states of the country, for example, Borno State.

6. The resilience of vulnerable people (i.e., empowered women) should be strengthened so that they can adapt better to climate change impacts.

7. Ameliorate poverty and other inequalities that increase vulnerabilities.

8. Investing in disaster risk reduction.

9. Guaranteeing these changes on a long term by instituting policy reforms.

10. Use of bioresources: Women can increase the use of green leaves instead of plates and plastics to reduce the amount of chemicals inhaled by using leaves to wrap *moin-moin* (bean puree), *pap* (corn puree), etc.

11. Adopting gender smart agriculture: This is a bid to reduce the risk of women having to deal with arduous activities. Private and public climate investments can be targeted toward women who need them most.

12. Climate finance or assistance must be directed toward the worst impacted women and men in the most affected regions. Efforts should be made to identify climate-agriculture-gender inequality hotspots where climate hazards are rampant and where women participating in food systems are largely concentrated. Once this is ascertained, it becomes easier to determine/isolate where to invest scarce resources to the benefit of need-is-greatest populations, including women. In addition, channeling climate finance to promote adoption and mitigation efforts has been shown to foster gender equality and women's empowerment and has led to climate-resilient development.

13. Make productive resources and labor-saving technologies available across gender roles: Climate adaptation mechanisms that reduce workloads can increase production, reduce negative impacts on health, and allow more time for other activities, such as education or businesses, that can increase people's resilience. For example, the use of climate-smart technologies such as direct-seeded rice, green manuring, and laser land leveling not only improved productivity and incomes but also showed the potential to reduce drudgery. Addressing gendered constraints that hamper women from accessing basic agricultural technologies can help boost their adaptive capacity.

14. Design climate information services to reach and benefit women: Women need information if they are to cope with and manage climate risk and variability but often have fewer options for accessing information than men do. Evidence has shown that women have less access to climate information *via* mobile phones than men and that even when women receive climate information, other resource constraints limit their ability to apply climate information to farming practices [22]. Therefore, designing climate information services to take women's situations and context into consideration is essential for increasing women's knowledge and adoption of climate-smart practices to increase their adaptive

capacity. Successful strategies for reaching women include using intermediary organizations as platforms for communication and using a combination of channels such as radio, TV, and mobile phones.

15. Use of precision farming tools can interface with global positioning systems (GPS) and other sensors to provide site-specific advice on crop management, helping farmers apply the right inputs at the right place and time. This precision approach minimizes the environmental impact while maximizing crop yields. Expert guidance on crop management, pest and disease control, and soil health is available through mobile apps. This includes recommendations on the optimal use of inputs such as fertilizers and pesticides, which will contribute to more efficient and sustainable farming practices.

16. The use of information communication technology (ICT) in agriculture: The use of ICT in implementing climate-smart agriculture practices—is a transformative approach to enhancing agricultural productivity, resilience, and sustainability. ICT tools facilitate the collection, processing, and dissemination of timely and precise information, enabling farmers to make informed decisions that align with climate-smart objectives.

17. Weather forecasting and climate information apps provide real-time weather updates and long-term climate forecasts [22], enabling farmers, pastoralists, and women to plan and adjust their farming season and practices accordingly. This information is crucial for timing, planting, and harvesting.

18. Support women's collective action for increased resilience: Working with women's groups and collective action can be effective in identifying and delivering capacity-building activities tailored to women's needs and constraints [23], and these groups can serve as platforms for women to exercise authority in implementing climate adaptation strategies. Social networks and groups are especially important for accessing the information, resources, and economic opportunities needed to respond to climate change.

19. Collect gender-disaggregated data: Many data on climate change impacts and policies are being collected by governments, often with support from development funders. More gender-disaggregated data are needed to better understand the gender-differentiated impacts of climate change and to implement gender-responsive measures.

20. NGOs should become involved by taking action: Along these lines, NGOs can use participatory approaches to develop and adapt climate-smart agriculture tools and technologies to meet women's needs.

4. Barriers to the adoption of climate and gender smart practices

4.1 Technical barriers

These are physical and environmentally relevant factors that may hinder the adoption of CSAPs. Examples include rocky soils that may hinder proper crop growth and soil health, and incorporation or limited access to alternative resources/technologies (e.g., mechanization). Limited access to technology and innovation can create difficulty in accessing and adopting new technologies, such as precision agriculture and renewable energy [24]. Similarly, capacity and skills gap can also limit technical and managerial capacity to implement climate and gender smart practices.

4.2 Social barriers

These are problems that may emanate due to organizational structures and government policies. For example, labor competition at a specific period and the organizational capacity of a given community for collective action. The lack of awareness, knowledge, and limited understanding can make it difficult for women farmers and pastoralists to be aware of the benefits of CSAPs [25] and, hence, limit their adoption of such practices. Socio-cultural norms, deep-rooted gender roles, stereotypes, and societal expectations can influence behavior and decision-making [26], making it difficult to adopt gender-smart practices that challenge these norms. Gender roles and expectations may limit women's participation in CSAPs' decision-making and implementation. For example, women may be expected to focus on domestic duties rather than livestock management. In the same vein, infrastructure and resource limitations such as inadequate access to essential resources like water, energy, markets, and transportation can make it difficult for women farmers and pastoralists to implement climate-smart practices.

4.3 Institutional barriers

These are problems related to institutions or systems. Perchance, public policy makers are less aware of the reaps of CSAPs and the capability of the initiative to transform the economic landscape of society. Consequently, governments do not place a premium on employing and training extension service workers who are expected to engage women pastoralists and farmers on CSAPs. For example, the lack of supportive policies, laws, and regulations can create uncertainty and discourage the adoption of climate and gender-smart practices [27]. Weak institutions, corruption, and lack of effective governance can hinder the adoption of climate and gender-smart practices.

4.4 Economic barriers

Economic barriers are related factors that may not be affordable due to high costs. In settings where CSAPs are highly needed, resource limitations are a major factor in gender-sensitive smart practices. Without dedicated efforts aimed at empowering women pastoralists and farmers, the dividends of CSAPs will remain a mirage in communities greatly in need of help except when stakeholders are willing and ready to commit the required resources. Economic barriers may include perceived risks and uncertainty about the effectiveness and potential impacts of climate and gender smart practices can make individuals and organizations hesitant to adopt them. Financial constraints may also limit access to funds and resources; consequently hindering the adoption of climate and gender-smart practices.

5. Conclusions

We stressed the significance of the agriculture sector in climate change impacts and explained the relevant terminologies before delving into what climate shocks are, how they are mitigated, and what women should do differently to minimize the impact of climate shocks. We have been able to establish that there are several opportunities for women to mitigate the impact of climate shocks while boosting their resilience. Efforts should be made for women to support climate action so that their vulnerability level can be minimized while reducing their level of risk. We have shown that CSAPs help to increase productivity, protect the environment, reduce vulnerabilities and risks, conserve soil, and preserve nature. Hence, the adoption of climate-smart agricultural practices will help women farmers and pastoralists increase their productivity, enhance their resilience, and reduce GHG emissions into the environment.

Women are responsible for mitigating livelihood vulnerabilities that affect individuals and households around the world. The results of empirical studies have shown that exposure to agricultural extension and training programs has a positive influence on choosing appropriate coping mechanisms, but female farmers have poor access to these resources. The government, on its part, should listen to women, engage them, and support their actions to enhance their decision-making capacities to collectively boost their resilience to climate shocks. There should also be a concerted effort from women, the government, and other stakeholders to remove the identified barriers that prevent women from adopting gender and climate-smart practices.

Conflict of interest

The authors declare no conflict of interest.

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Section 2

Seismic and Tsunami Hazards: Assessment and Preparedness

Chapter 3

Machine Learning and Seismic Hazard: A Combination of Probabilistic Approaches for Probabilistic Seismic Hazard Analysis

Roberto Ortega

Abstract

Probabilistic seismic hazard analysis (PSHA) integrates seismology with invitation of civil engineering. Allin Cornell's 1968 work, developed with Dr. Emilio Rosenblueth and Dr. Luis Esteban Maraboto, revolutionized earthquake engineering by making seismology practical for construction. Cornell's deterministic equations, once valued for their elegance and simplicity, can now be enhanced with modern tools. Today, probabilistic seismic hazard analysis (PSHA) is evolving by integrating both deterministic and nondeterministic models, leveraging machine learning (ML) techniques such as Random Forests, Support Vector Machines, Neural Networks, Reinforcement Learning, and Bayesian Inferences. This chapter explores the future of PSHA through these advanced methods. While ML offers powerful solutions, it is crucial to recognize that it is not a one-size-fits-all answer. The optimal approach involves using a hybrid ensemble of systems, each designed to address specific challenges in detail.

Keywords: probabilistic seismic hazard analysis (PSHA), ground motion prediction equations (GMPEs), deterministic models, Bayesian inference, machine learning

1. Introduction

The study of probabilistic seismic hazards is one of the most prolific in engineering. It connects seismology with civil engineering needs. Allin Cornell's work in 1966 and published in 1968 [1] changed earthquake engineering, making seismology practical for construction. Cornell's paper, partly written during a stay at the National Autonomous University of Mexico with invitation of Dr. Emilio Rosenblueth [2] and supported by Dr. Luis Esteban Maraboto [3], is highly cited in earthquake engineering. It is important to review its origins and impact, especially the role of geometric probability [3]. Cornell's paper emphasizes the probability of distance distribution based on area geometry. However, seismologists later focused on ground motion prediction equations (GMPEs) [4]. These equations, which are studied and cited

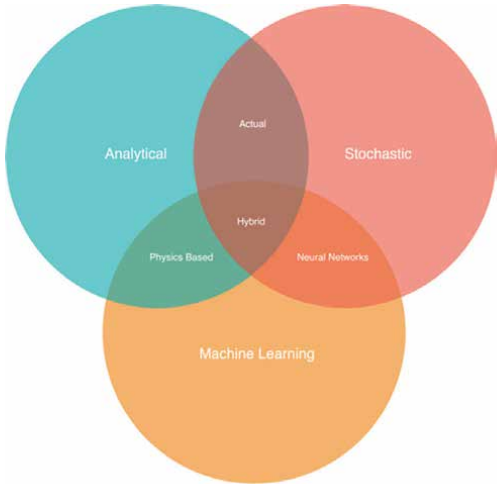

Figure 1.
Three probability approaches currently used in probabilistic seismic hazard analysis (PSHA): the actual maps are based on stochastic and analytical approximations. Meanwhile, the machine learning approach is evolving toward hybrid and more robust methods.

extensively [4–14], map logarithmic scale problems to linear values for construction, complicating solutions to probabilistic seismic hazard problems [5].

Dr. Cornell's idea was to present an analytical problem with clear formulas. His deterministic equations outperformed Monte Carlo algorithms based on Markov chains. At the time, there were two main approaches: seeking elegant analytical solutions or using computational models for complex equations. Over time, solving nondeterministic probability problems with stochastic processes, which do not require strict definitions in the equations, has been developed. This includes Bayesian inference, using a priori and a posteriori probability distribution linked by a likelihood distribution.

This approach is praised and discussed for its ability to learn from previous data and adjust parameters by trial and error to solve complex problems. It has led to the development of artificial intelligence and machine learning, which generate equations fitting inferences to established patterns.

Figure 1, represents a simple figure with three probability approaches that are currently used in PSHA; as expected, the best option is that of a hybrid approach that takes advantage of the different advances in methodologies.

2. Machine learning

Currently, artificial intelligence is booming, and all lines of thought are trying to solve problems using this new paradigm [15]. Probabilistic seismic hazard is no exception, and new attempts in this area combine deterministic and nondeterministic models. In this chapter, I will present the combination of both approaches to envision the future of probabilistic seismic hazards through the new resources offered by machine learning.

In the difficult art of solving technical and scientific problems, we are left with the idea of trying new techniques, and many of them are complicated. Sometimes, it is several years to several generations of PhDs. Neural networks and other ML techniques are powerful tools, but they are not suitable for all problems. Their greatest success is in image recognition, speech recognition, and generative text and audio tasks. The real question is, how much of a substitute can PSHA be for the huge breakthrough it has? The reality is that in solving most of the PSHA problems, very ingenious solutions have been chosen and many of them are a breakthrough. But there are others that have not yet been explored, and AI has come to the rescue. One of them is the tree decision problem.

The decision tree is a classic problem in computational science, which has evolved into Random Forests [16]. Decision trees play a crucial role in allowing the modeling of uncertainties and the combination of multiple sources of information. However, conventional decision trees can be limited due to their tendency to overfit and their sensitivity to variations in the input data. This is where Random Forest, an advanced extension of decision trees, provides a significant improvement.

Random Forest is particularly useful in PSHA for integrating and analyzing complex data, such as ground motion prediction equations (GMPE). In a GMPE context, where multiple models are considered to predict ground motion intensity as a function of variables such as earthquake magnitude, distance to the epicenter, and ground characteristics, Random Forest allows combining these multiple GMPEs in an efficient

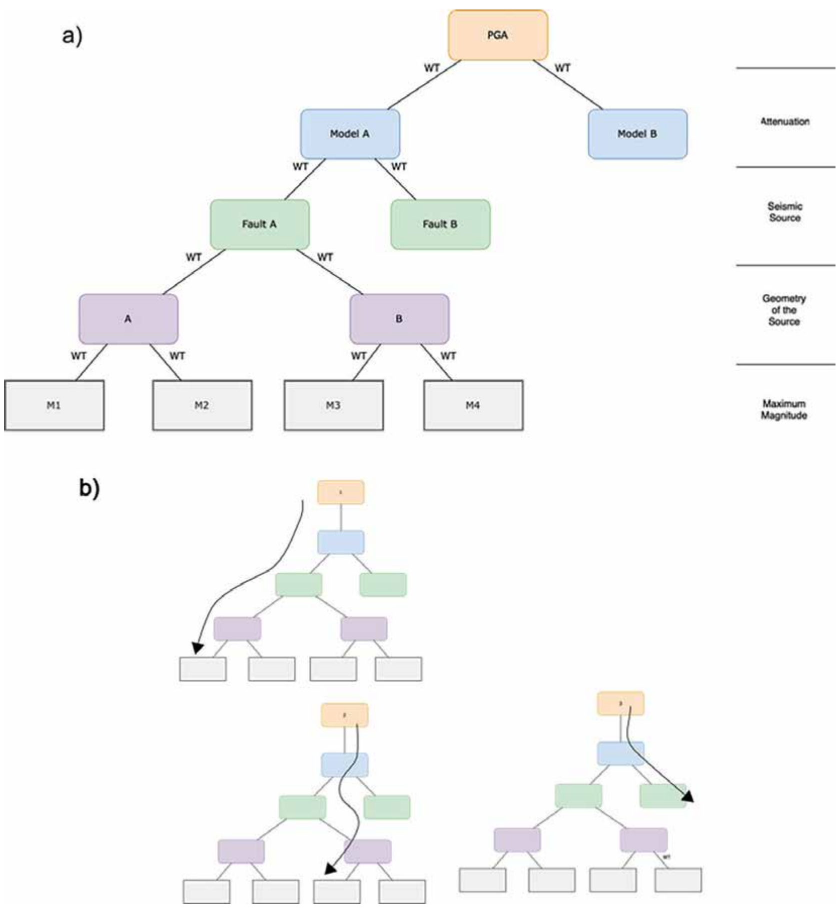

Figure 2.
(a) Schematic representation of a decision tree in PSHA and (b) the natural extension of Random Forest. In general, Random Forest allows combining these multiple GMPEs in an efficient manner.

manner. By creating a set of decision trees, each trained with different subsets of data and features, Random Forest can capture the variability and uncertainty inherent in individual GMPEs, providing more robust and accurate ground motion predictions. **Figure 2** presents the decision tree and the random forest in the context of PSHA. Note that the Random Forest approach optimizes the decision tree. The decision tree (**Figure 2a**) is a simple probabilistic combination in ML and is also called as ensemble. A Random Forest (**Figure 2b**) is the optimal consequence using ML techniques.

In terms of seismic risk assessment, a crucial aspect is the estimation of Value at Risk (VaR) values, which represents the expected loss in each period due to seismic events. Random Forest can improve these estimates by combining multiple scenarios and seismic data sources. Each decision tree in the forest can represent different seismic hazard scenarios and their impact on b-values. By averaging the results of these multiple trees, Random Forest provides a more reliable and less biased assessment of seismic risk, incorporating uncertainty more effectively.

In addition, the ability of Random Forest to assess the importance of each feature is especially valuable in PSHA. For example, they can identify which factors are most influential in predicting ground motion and estimating b-values. This allows engineers and scientists to focus on the most critical parameters and improve the accuracy of their seismic models.

3. Catalogs and statistical seismology

The elaboration of catalogs represents a significant technological advancement in seismology within the field of machine learning. Less than a decade ago, catalogs contained information on a few tens of thousands of events within a regional network. Today, millions of data points with magnitudes of less than one is detected. Although classic PSHA studies typically consider minimum magnitudes of around 4.5, the extensive information from these catalogs profoundly enhances our understanding of seismic activity. This growth in data and techniques is propelling the development of new big data paradigms [17–26].

The most important parameter in statistical seismology is what we call the b-value [27], which represents the relationship between events of smaller magnitude and events of larger magnitude. In general, this b-value is used for a probabilistic analysis in the distribution of magnitudes in such a way that it compensates for the number of events of a destructive magnitude in a large period. This value is very important because by defining long periods of time, we can estimate the moment at which we will have destructive magnitudes.

However, in the final stage of PSHA, this distribution is combined with another discrete distribution, which assumes that the events in time have a Poisson distribution, when we think that the occurrence of an earthquake is simply limited to an average value of events in 1 year, in which is once eliminated the relation of its aftershocks we assume that all events are independent. That is to say that the events have no memory in the sense that a seismic event does not depend on any other event in a long period. This assumption is incorrect, and we are facing a huge challenge to find an adequate probabilistic model where to integrate medium- and long-term seasonal changes with non-homogeneous Poisson distributions integrating large-scale knowledge of the physics of rupture coma of geology and the transfer of stresses that occur when triggering large magnitude seismic events. A typical Gutenberg-Richter relationship (**Figure 3**) is a linear trend with a slope equal to the b-value. It starts

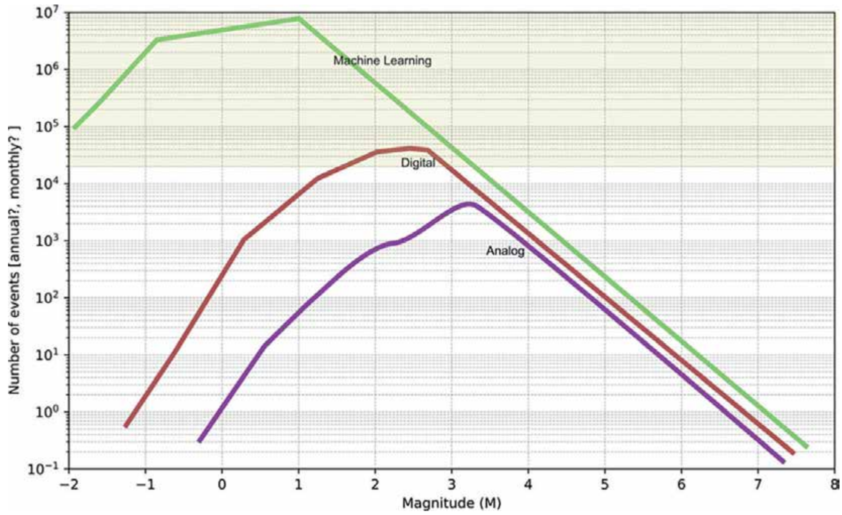

Figure 3.
Three different examples of Gutenberg-Richter distributions, depending on technological limitations. In the analog period, Mc was about 3. Nowadays, with the use of machine learning algorithms, it is expected to be less than 1 with millions of data.

from the cut magnitude (Mc). Due to the limitation of data, Mc varies depending on the technological limitations. In the analog period (about 1950–1970), Mc was about 3. Nowadays, with the use of machine learning algorithms, it is expected to be less than 1. At the same time, this amount of data is situated where a Poisson process goes beyond the number of the annual cumulative events and can reach new thresholds, such as monthly or even daily measurements with statistical significance. This opens new perspectives in homogeneous, no-homogeneous Poisson distributions [28–30].

Analyzing these events temporally is perfect for unsupervised machine learning problems, which analyze clustering and will allow us to search for spatial and temporal relationships. At the same time, it is possible to create new complex and realistic models with new conditions. For example, the non-scientific but valid observation that there are regions that seasonally experience earthquakes [31–35], such as September in the case of central Mexico, or the interactions between earthquakes [36].

4. Site effects

Site effects are not always part of the PSHA study *per se* but are part of the site-specific analysis study. When the PSHA maps have been elaborated, each construction then studies the specific conditions of the site, for example, the type of soil and sediments that amplify the seismic waves, and seismic design spectra are constructed that include the site amplification. However, in places like Mexico City, this phenomenon is very complex and must be addressed from the beginning as the most important phenomenon.

In Machine Learning, there are many ways to tackle the learning process. Data-driven and physics-based are two different ways to predict earthquake site response [37]. Data-driven seems to be more adequate because it has more variability and better suits the site effects phenomena [38]. However, there is still a long way to go to understand the details of this complex problem.

Figure 4 shows some of the problems of using GMPE and side effects. A big regression between observed peak ground acceleration (PGA) is performed. The final curve is a parametric function that predicts the PGA given distance. Also, it is important to estimate uncertainties and correct them for a specific site. Usually, a specific site is given in shear wave velocity, which in turn represents rigidity and is a good comparison to correlate seismic wave amplification. The specific site is commonly 720 or 750 m/s.

The primary challenge lies in effectively integrating the Ground Motion Prediction Equation (GMPE) with a design spectrum in such a way that it virtually eliminates false negatives. This means that the design should ensure that no buildings sustain damage during seismic events. Achieving this goal requires a robust approach that accounts for various factors influencing ground motion and building response.

The GMPEs are mathematical models used to predict the expected ground motion intensity (such as peak ground acceleration or spectral acceleration) at a given site based on parameters such as earthquake magnitude, distance from the fault, and local site conditions. GMPEs are usually isolated and should be integrated into the design spectrum. The design spectrum is a crucial tool in seismic design, representing the maximum expected response (acceleration, velocity, or displacement) of a building to ground motion across a range of frequencies. It is derived from GMPEs and other seismic data to ensure that buildings can safely absorb and dissipate seismic energy. The future should involve ML, which integrates GMPE and design spectrum in the same framework. However, this is not the only problem, as every site is different, and so should be every construction.

Figure 5 shows a simple representation that should perform integrating site effects and GMPE to estimate the design spectrum using data-driven and physics-based hybrid ensembles.

A challenge today is to distinguish the types of problems that machine learning helps us with without being tempted to use it for everything. The advantage of this

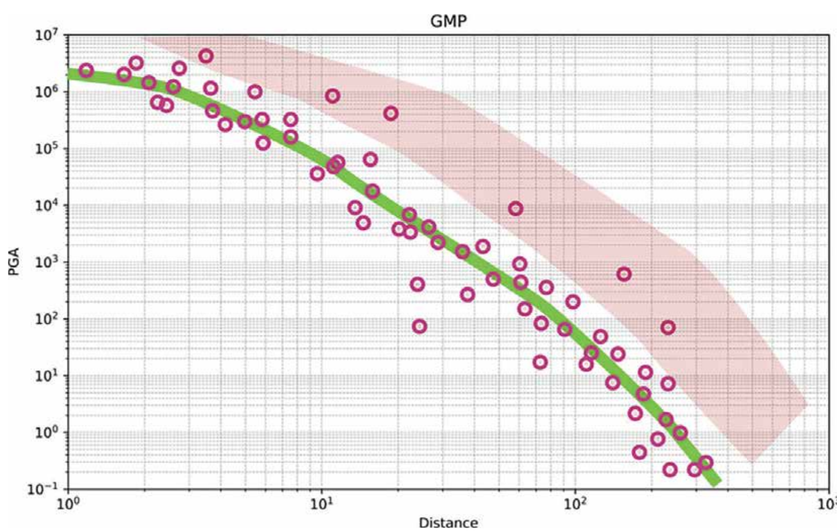

Figure 4.
Graphical sketch of a ground motion prediction. The equation is a parametric representation that simplifies the prediction. However, the real challenge is that outliers in the upper region need to be studied comprehensively so that site amplification provides a real prediction of a GMP.

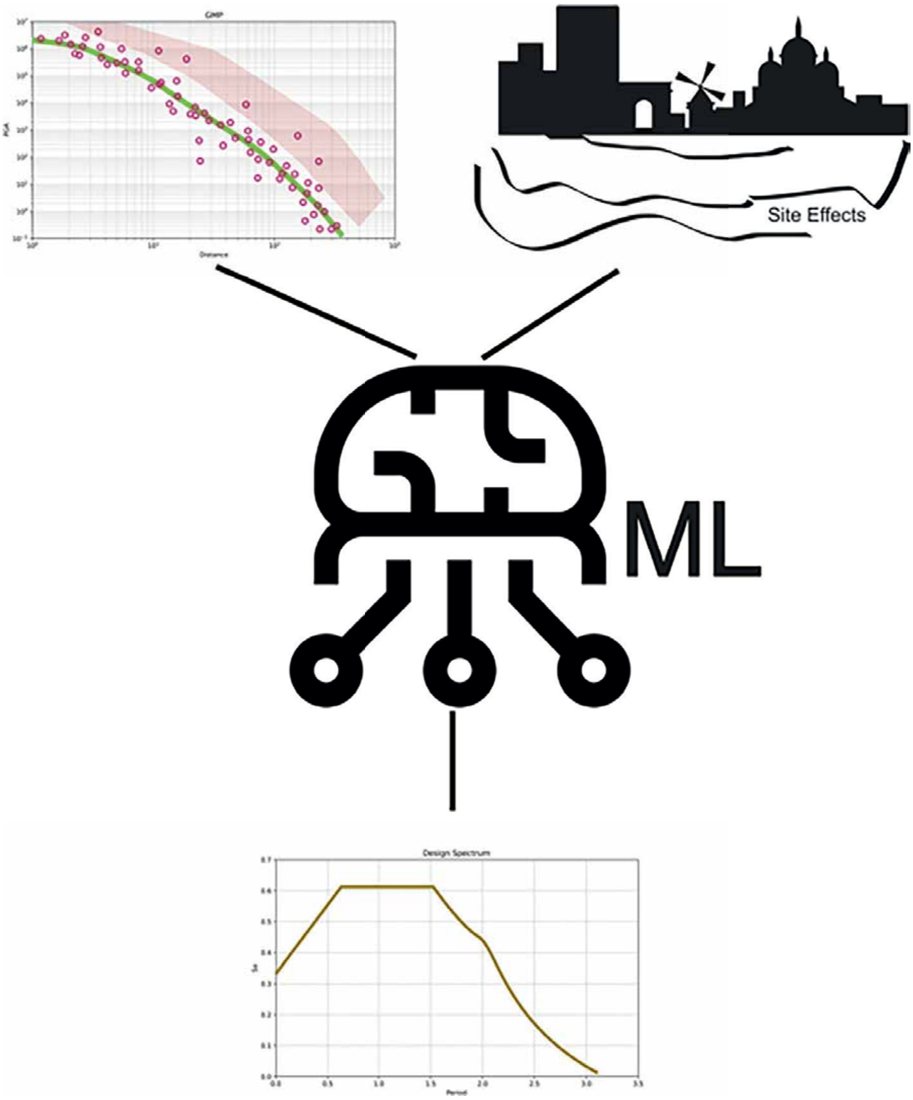

Figure 5.
Machine learning should be performed integrating site effects and GMPE to estimate the design spectrum using data-driven and phyisics-based hybrid ensembles.

paradigm is the enormous amount of data that can be processed in a short time and finding ways to solve more specific problems.

5. Conclusions

The integration of machine learning into probabilistic seismic hazard analysis (PSHA) marks a significant advancement in the field. By combining deterministic and nondeterministic models, machine learning provides robust methods for analyzing and predicting seismic activity. One prominent application is the use of Random Forests, an advanced form of decision tree, which enhances the modeling of uncertainties and integrates multiple sources of information. This approach is particularly effective for ground motion prediction equations (GMPEs), enabling the combination of various models to yield more accurate predictions of ground motion intensity. Additionally, Random Forests help identify the most influential factors in predicting seismic activity, thus improving the overall accuracy of seismic models.

Despite these advancements, several challenges remain, particularly in integrating GMPEs with design spectra to ensure that buildings can withstand seismic events without damage. This requires a comprehensive understanding of site-specific conditions and the ability to process vast amounts of data efficiently. Machine learning's capability to handle big data and uncover spatial and temporal relationships offers new perspectives, especially in creating realistic models that account for complex phenomena like seasonal seismic activity. However, distinguishing the appropriate applications of machine learning and addressing the unique characteristics of each site and construction remain crucial. The future of PSHA lies in leveraging machine learning to develop integrated frameworks that combine GMPEs and design spectra, ultimately enhancing the resilience of structures against earthquakes.

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Conflict of interest

The author declares no conflict of interest.

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Chapter 4

Microtremor HVSR Technique for Seismic Risk Vulnerability Studies and Microzonation of Site Materials

Malik Miezah-Adams, Ferguson K. Torvor, Ebenezer Ansah, Emmanuel K. Boateng and Anthony Ewusi

Abstract

The microtremor HVSR, also known as Nakamura's approach, is an empirical technique that is becoming more suitable for site response analysis. The main goal of this research is to develop microtremor zonation (microzonation) of the study area to examine the potential risk of blast and other vibration sources, determine the seismic vulnerability indices of the area based on the site response parameters, and develop the distribution of the site response parameters. Surface waves were recorded at 34 locations using a three-component geophone to obtain the microtremor data. According to the site response parameters, the natural peak frequency varied from 2 to 5 Hz, the maximum period was less than 0.5 seconds, and the maximum amplification factor (H/V ratio) was 5.50. Of the 34 locations, 26 recorded low vulnerability indices (K_g) in the range of 0.27 to 4.82 and, thus, classified as Zone 1 materials. This indicates that K_g is typically low throughout the research area, except for a few areas that had extremely high vulnerability. The high vulnerabilities can be attributed to dense, loose soils in the vicinity, which amplify ground vibrations. Since the average natural period is less than 0.5 seconds, a seismic event's impact would not be felt for a longer time unless it occurred in a region with extremely low frequencies ($F_0 \leq 1.0$ Hz).

Keywords: microtremor, microzonation, site response parameter, vulnerability index, HVSR model

1. Introduction

Microtremor analysis (MA) is a geophysical method that assesses near-surface engineering characteristics of soils without invasive procedures. It provides valuable insights into soil texture, structure, porosity, compaction, moisture content, and organic matter content [1]. This non-invasive approach is widely used in geotechnical and civil engineering to understand soil properties before the construction and implementation of infrastructural projects. It assesses soil stiffness, damping characteristics, and stratification [2]. The MA technique has several advantages over traditional invasive techniques and it is more efficient than traditional invasive methods such as the standard penetration test (SPT) and dynamic cone penetration test [3]. According to Refs. [4, 5], the MA technique's relatively affordable cost and flexibility in terms of spatial and temporal constraints have made it the most utilized method for studying site effects across various applications.

The Horizontal to Vertical Spectral Ratio (HVSR) analysis uses the MA technique to evaluate the seismic vulnerability of sites by measuring ambient ground vibrations and analyzing their spectral ratio [5]. The HVSR is a quantitative measure of the spectral ratio between the horizontal and vertical components of surface waves recorded using a three-component (3C) geophone. The technique detects microtremors with low energy and amplitude levels caused by various sources, such as earthquakes, traffic, and blasting from mining operations [5]. The spectral ratio is established between the horizontal (H) and vertical (V) components of motion (surface waves) recorded using a properly calibrated 3C geophone at a single station [6]. Also, the HVSR analysis helps determine the site's fundamental frequency and amplification characteristics. Nakamura [7] introduced the seismic vulnerability index (K_g) as a means to evaluate the probability of encountering severe ground movements or significant shear strains in a specific region during earthquakes. The Kg combines the amplification factor (A) and predominant natural frequency (f_o) using the H/V spectral ratio from the HVSR analysis.

Several studies have demonstrated the effectiveness of the HVSR technique. According to Refs. [8–10], the HVSR technique can effectively be utilized in site response studies and determining the liquefaction potential of site materials. Refs. [11, 12] also posited that the HVSR is the most effective in the determination of the fundamental or resonant frequency (f_r) of soft deposits. The HVSR method has been used in several countries, including Japan, Italy, and Indonesia, to assess the seismic vulnerability of different structures such as schools [13], historical buildings [14], and bridges [15]. Ewusi et al. [10] made a joint use of both active MASW and HVSR techniques for seismic site classification and established the effectiveness of these techniques in the determination of the dynamic geotechnical parameters and seismic vulnerability of site materials. Aside from its numerous advantages, including being non-invasive, low-cost and time efficiency, the results obtained from the HVSR analysis can be used to develop appropriate disaster risk management and resilience strategies [16–18]. Thus, the HVSR method may prove valuable for microzonation investigations owing to its rapid data acquisition, minimal equipment and personnel needs, and reliable outcomes [19].

The Abonko area of the Mfantsiman District is currently undergoing a series of exploration exercises toward the exploitation of lithium in the next few years. It is significant to investigate the soil conditions in the area and characterize the site materials to assess the potential seismic risk in the area due to future mining operations such as blasting. In this chapter, we discuss the vulnerability of the site materials to seismicity based on the site response parameters recorded at the study area. An idea of the site response characteristics (or vulnerabilities) can be utilized in proper design and implementation of infrastructural projects.

2. Study area

2.1 Location and size

Abonko is a small community located in the Mfantsiman Municipality of the Central Region of Ghana. It is located along the Atlantic coast and at the east of Cape

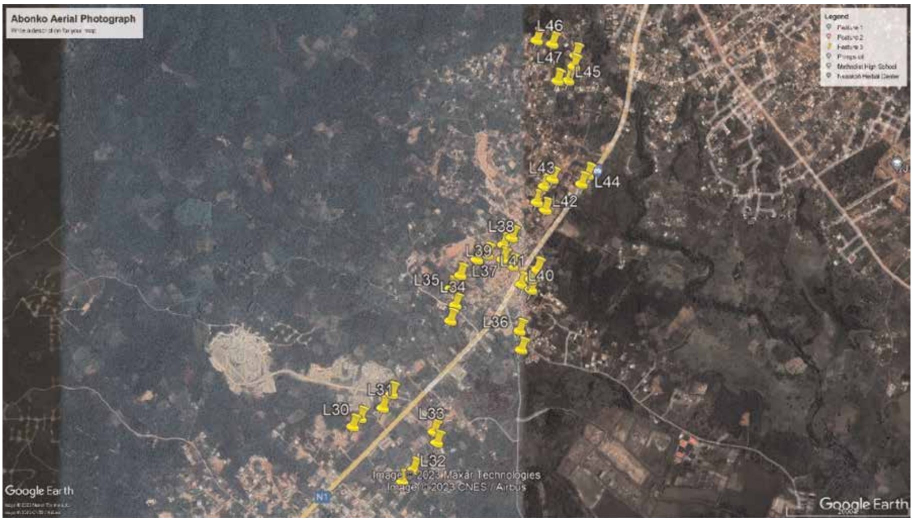

Figure 1.
Microtremor recording stations.

Coast which is the capital for the Central Region [20]. The community is situated approximately 4.55 km north of Saltpond and about 5.5 km southwest of Mankessim, with coordinates of latitude 5°14′21″N and longitude 1°01′46″W.

The Mfantsiman Municipality covers about 662 km^2, which represents about 6.1% of the total land area of the Central Region. The Abonko community occupies only about 0.06 km^2 of the area covered by the Mfantsiman Municipality, making it a relatively small area compared to the overall size of the municipality [10]. The Abonko community shares borders with Anokye to the east, Afrengwa to the west, and Baifikrom to the north. **Figure 1** is a Google Earth map of Abonko showing the survey points, areas where the microtremor data were taken.

2.2 Geology of the study area

The geology of the study area comprises the volcano-sedimentary basin of the Birimian Supergroup of Proterozoic age (**Figure 2**). Most of the area is occupied by predominant rocks such as biotite-rich granitoids of basin-type (Cape Coast granitoids) [21]. These vary in composition from intermediate granodiorite with a medium-grained texture to felsic leucogranites with a coarse to pegmatoidal grain size [10, 21]). It is worth noting that biotite-rich granitoids are commonly associated with spodumene mineralization at contacts between the granitoids and the pegmatites.

There are two main types of pegmatites found in the study area: the barren pegmatites with no mineralization and spodumene-bearing pegmatites with mineralization of lithium. The pegmatites that are in contact with the granitic rocks and other rocks in the area occurs generally as sub-vertical dykes. They exhibit two dominant trends: (1) striking north-northeast (Ewoyaa) and dipping sub-vertically to moderately southeast to east-southeast, and (2) striking west-northwest (Abonko, Kaampakrom, and Ewoyaa Northeast) and dipping sub-vertically northeast [10]. Metamorphic rocks, such as schist, have undergone regional metamorphism due to tectonic activity and the intrusion of granitoids. The schist is characterized by the

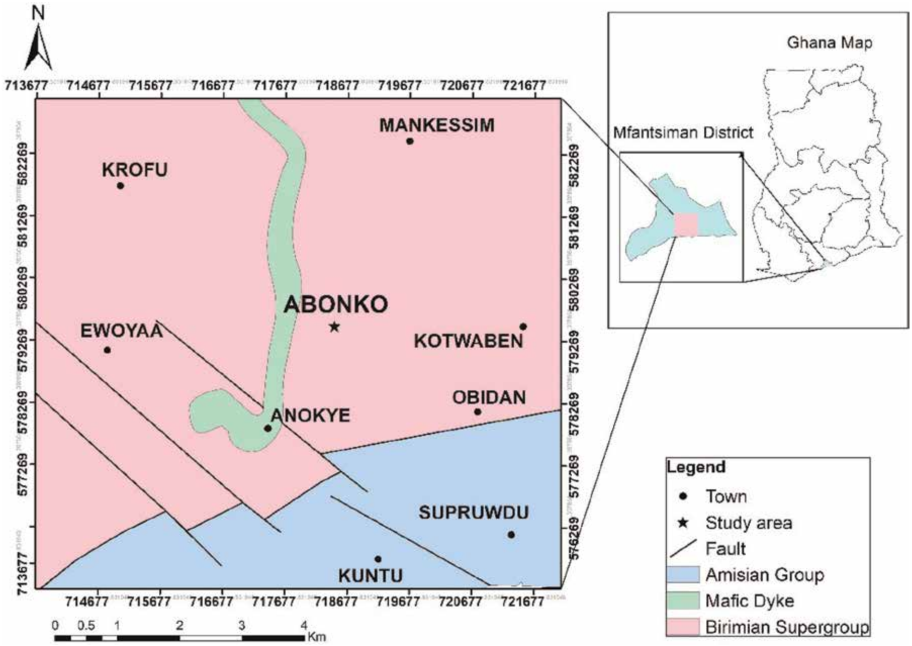

Figure 2.
Geology of the area of study.

presence of garnet, mica, and staurolite, and has been observed to be weathered in some locations within the area [22, 23]. There are also numerous massive quartz veins found in the area, which can be attributed to the presence of intrusions in the area. **Figure 2** shows the geology of the study area.

3. Materials and methods

3.1 Microtremor data acquisition

The Horizontal to Vertical Spectral Ratio (HVSR) data acquisition involves collecting passive seismic data to analyze the ratio of horizontal to vertical ground motion. It relies on ambient noise or natural seismic signals instead of actively creating seismic sources. In this study, thirty-four sites were selected for conducting microtremor measurements to evaluate the site response parameters of soil deposits. Each recording lasted for 20 minutes at a sampling rate of 128 Hz, which was later re-sampled to 64 Hz for analysis.

The recording was done using a calibrated Holi 3C geophone, installed in close contact with the ground, and isolated thermally well against temperature changes and wind motion (**Figure 3**). The Holi 3C geophone was well fixed with the bubble centered and was positioned such that its north arrow aligns with the North magnetic pole of the Earth. This is then connected to the seismograph, and the seismograph is then connected to a computer. The recorded data is stored on a computer for later analysis.

The HVSR data acquisition utilized natural frequencies of the subsurface and was analyzed enabling the collection of seismic data using natural signals that can then be analyzed and interpreted using this systematic approach. All experimental conditions

Figure 3.
Microtremor HVSR data acquisition.

for this study are governed by the precautions of the European SESAME research project [24].

3.2 Data processing

The following approach was utilized to calculate the H/V spectral ratios. Raw data from the study area were analyzed using HoliSurface 2019 software utilizing the flowchart illustrated in **Figure 4**. The data was first converted from nanometric to Seg2 format. The Holi 3C geophone axes of the three columns are first column (vertical component), second column (NS component), and third column (EW component) channels that were used, and the unit of measurement was indicated as mm/s. A frequency range of 0.5–20.0 Hz was considered for the analysis.

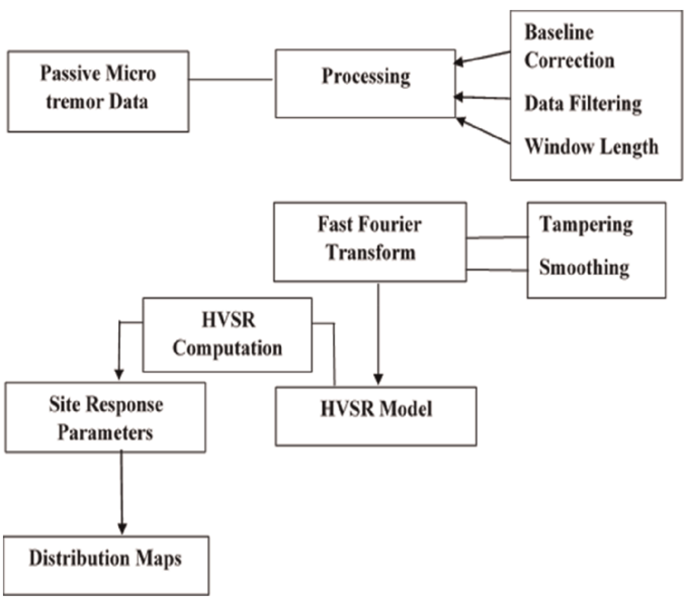

Figure 4.
Flowchart of the method used.

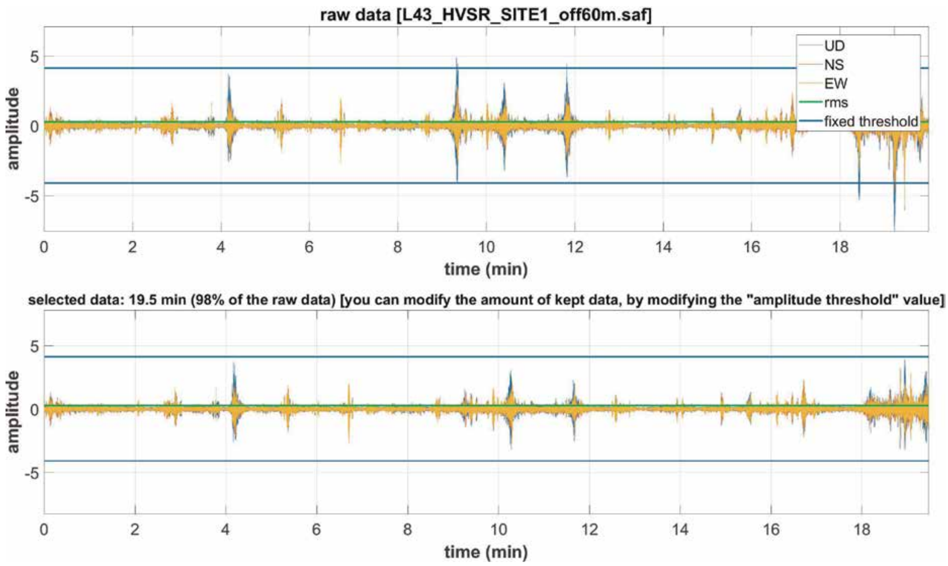

Figure 5.
Passive data smoothing: (a) raw data with transients and (b) smoothen data without transients. This step is necessary before computing the H/V spectral ratio.

Specific events (signals) or industrial noise was removed before the analysis (before calculating the H/V spectral ratios) (**Figure 5a** and **b**). According to Ref. [25], a routine was developed to separate windows with high and low levels of ambient noise, since the ratios computed with different noise levels were deviant, especially when there was a low-frequency peak present.

The amplitude spectra of the horizontal and vertical components were calculated using a Fast Fourier Transform (FFT). The obtained curves underwent smoothing employing Konno and Ohmachi's algorithm, incorporating a 5% cosine taper and a smoothing parameter set at 15. As highlighted by Molnar et al. [26], this smoothing technique stabilizes HVSR curves and prevents the appearance of excessive peaks (transients) caused by industrial activities and traffic.

The amplitude spectra for each component were calculated by utilizing the Fast Fourier Transform on every 20-second segment (**Figure 6a**). Subsequently, the averaged horizontal components were divided by the vertical component within each selected time window, resulting in multiple curves. The standard deviation for each frequency was determined by averaging these curves (**Figure 6b**). This procedure enabled the identification of the fundamental frequency and its associated amplitude across the entire study area.

The generated curves were examined to determine which noise sources were natural or industrial. Using a directional test of the HVSR peaks, it was possible to detect the presence of strong sources during ambient noise measurements. For this test, the two horizontal components were rotated in the range of 0° to 180° degrees to check for azimuthal rotation (**Figure 7**), suggesting that there is human activity in the vicinity of the seismic recording station. By increasing the smoothing value, these peaks could be detected, particularly when industrial sources were present.

According to Refs. [19, 27], an impulse test around the suspicious frequency is detected using a random decrement technique. In this case, the industrial peak, having

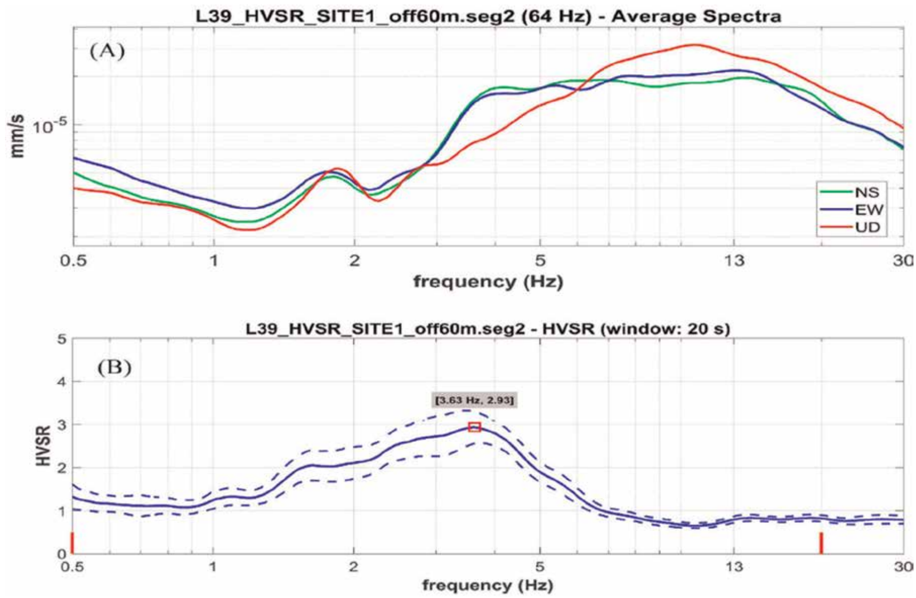

Figure 6.
(a) The amplitude spectrum of the three components. (a) The H/V spectral ratio curve of the amplification at the fundamental frequency.

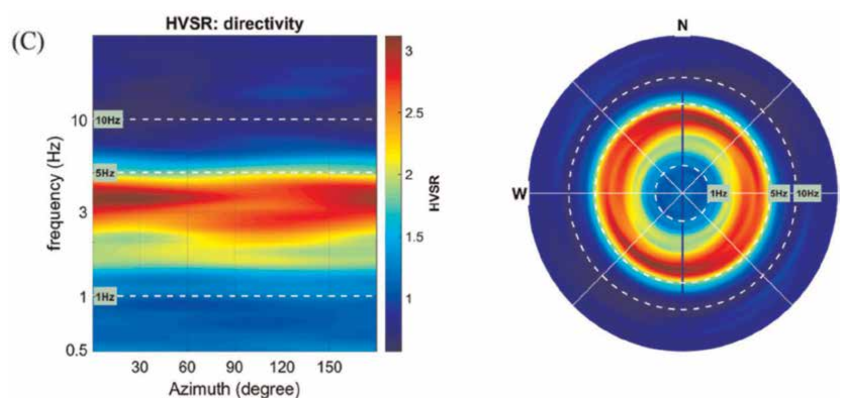

Figure 7.
H/V rotation with Azimuth degrees.

a damping (Z) value less than 1%, will be discarded. In this study, the presence of industrial peak frequencies was not observed.

3.3 Geospatial distribution

In developing the study area's microzonation distribution map, the ESRI ArcMap computer application was used utilizing the IDW algorithm. This approach estimates values at unknown locations based on values and distances of the known (measured) points. In microzonation studies, IDW is commonly used for developing microzonation maps due to its ability to capture spatial correlation and uncertainty [28, 29]. For earthquake microzonation, IDW can provide more reliable estimates of ground shaking intensity, considering the spatial autocorrelation and variability in the data [30]. IDW can account for factors such as local geological conditions, topography, and other variables to produce a more accurate and detailed microzonation map and can identify areas with vulnerability characteristics and delineate zones with varying degrees of vulnerability. Mathematically, IDW is computed using the expression in Eq. (1):

$$Z_{(u)} = \frac{\sum_{i=1}^{n} W_i . Z_i}{\sum_{i=1}^{n} W_i} \quad (1)$$

Where $Z_{(u)}$ is the estimated value at the unknown location u, Z_i represents the known values at the same points, Wi is the weights assigned to each sample point based on their distances from the unknown location, and n is the number of sample points. The weightings are calculated using the inverse of the distances between the unknown location and each sample point as depicted in Eq. (2).

$$W_{(i)} = \frac{1}{d_i^p} \quad (2)$$

Where d is the distance between the unknown location and the i-th sample point and p is a parameter that controls the rate at which the weights decrease with distance. This can be 1, 2, or 3 depending on the application.

3.4 Seismic vulnerability computations

Nakamura [7] introduced the vulnerability index (K_g value) as a method for assessing the magnitude of liquefaction. He suggested utilizing the K_g to indicate the extent to which a location or region might encounter intense ground movement or significant shear strain in the event of an earthquake. Hence, the K_g serves as an index for assessing the ease with which measured points deform, providing valuable insights into identifying weak spots in the ground. For areas where more deformation took place, K_g-values are higher. The Kg value is simply derived from strains of ground and structures [19]. This is computed using Eq. (3) as:

$$\mathrm{K_g} = \frac{\mathrm{A}^2}{\mathrm{f_o}} \quad (3)$$

Where:
K_g = seismic vulnerability index.
A = amplification factor of the site (H/V ratio), and
f_o = peak natural frequency (Nakumura [7]).

4. Results and discussions

4.1 Horizontal to vertical spectral ratio (HVSR)

One of the frequently used methods for assessing seismic vulnerability and microzonation is the use of site response characteristics, such as natural ground frequency, natural period, and amplification, determined from site response assessments using HVSR (micro-tremor data). These site response parameters at the location are used to identify locations with high seismic risk during seismic events [8, 31]. These response parameters are presented in selected the HVSR curves in **Figures 8**–**11**.

Table 1 represents the statistical summary of site response parameters recorded at 34 stations in the study area. The natural peak frequency ranges from 0.50 to 20 Hz with a mean of 3.93 Hz and standard deviation of 3.68 Hz, the site amplification factor ranges from 1.10 to 13.15 with a mean of 4.09 and a standard deviation of 2.62, and the period ranges from 0.05 to 2.0 seconds with a mean 0.49 seconds and a standard

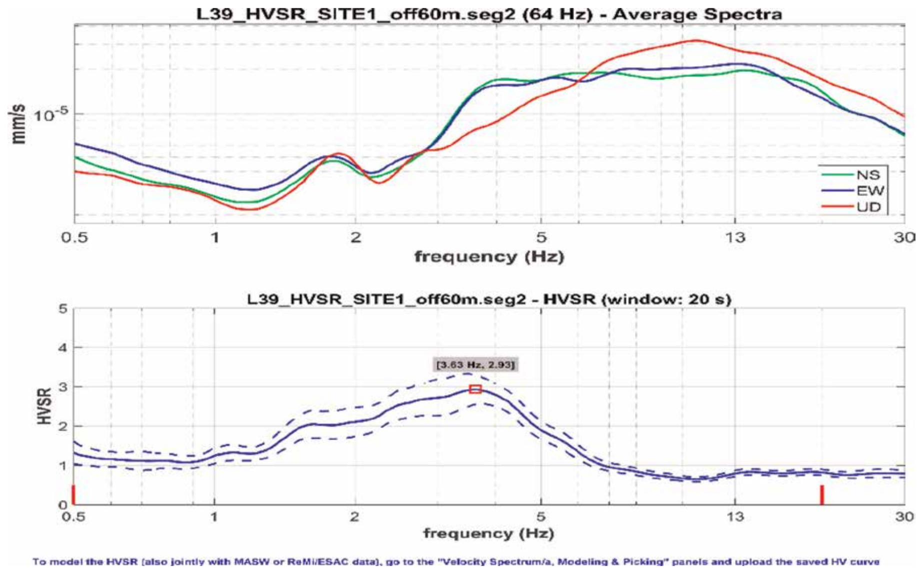

Figure 8.
Horizontal-to-vertical spectra curves for site 1 on L39.

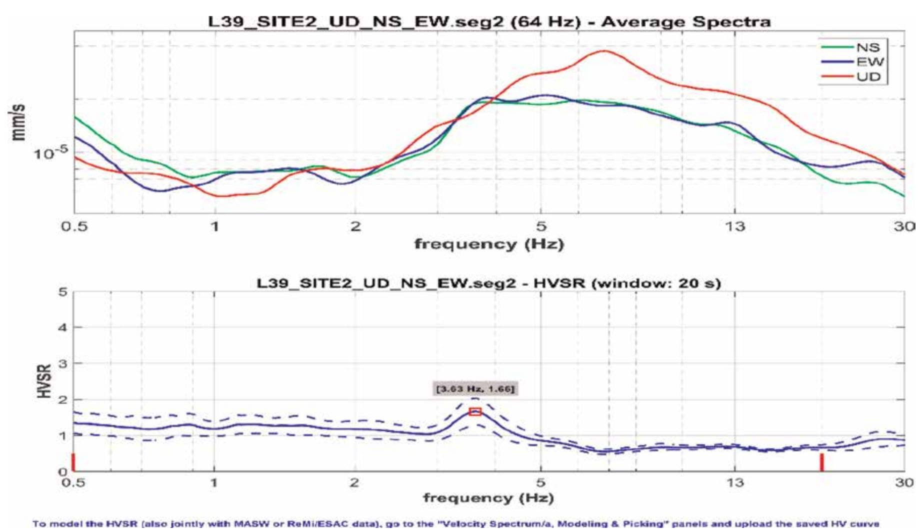

Figure 9.
Horizontal-to-vertical spectra curves for site 2 on L39.

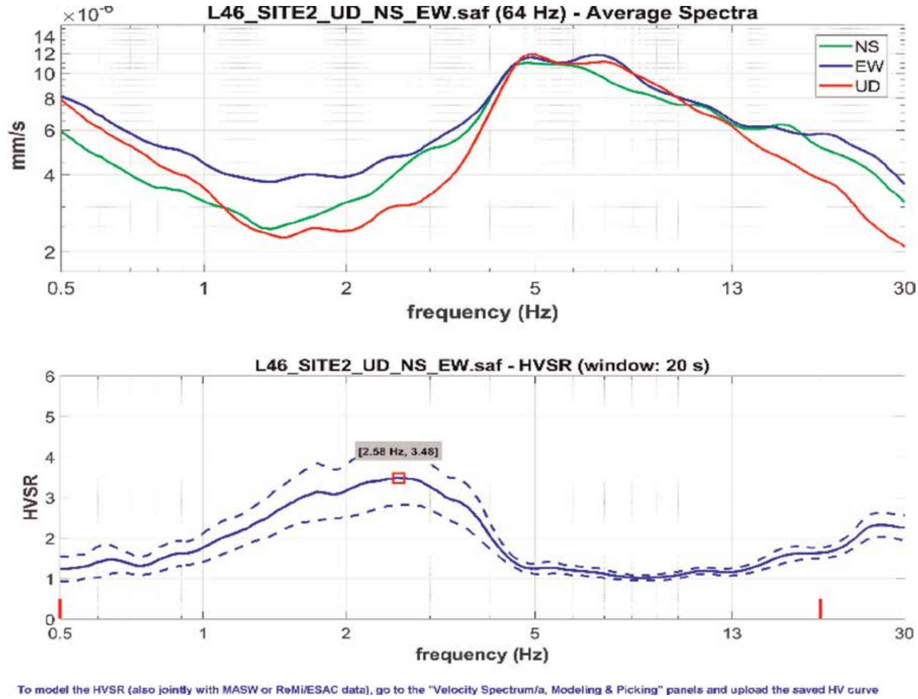

Figure 10.
Horizontal-to-vertical spectra curves for site 2 on L46.

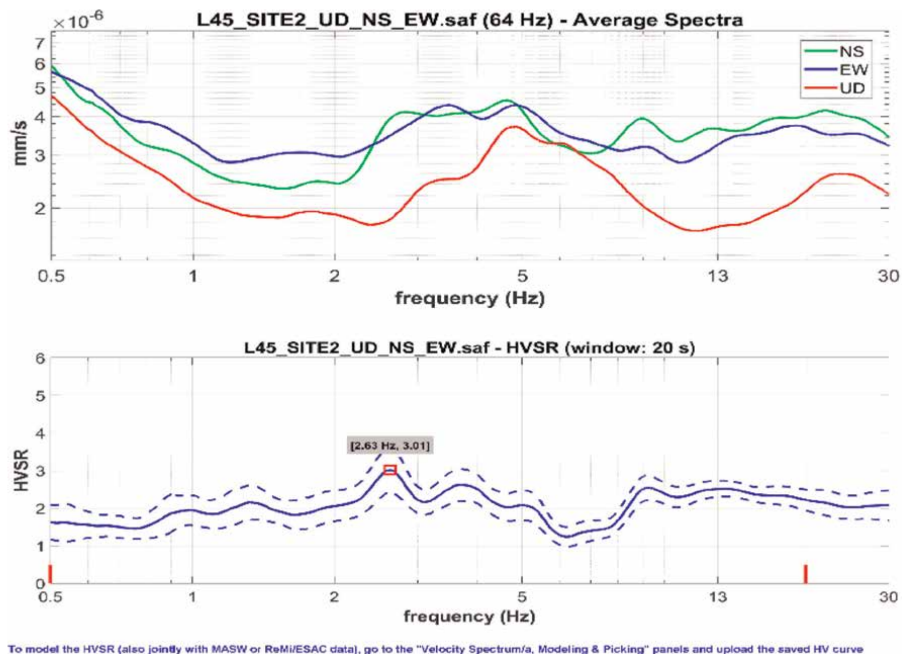

Figure 11.
Horizontal-to-vertical spectra curves for site 2 on L45.

Parameter	Minimum	Maximum	Mean	Std. deviation
Amplification (A_o)	1.10	13.15	4.09	2.62
Frequency (F_o)	0.50	20.00	3.93	3.68
Period (T)	0.05	2.00	0.49	0.47
Vulnerability index (K_g)	0.27	129.05	13.02	26.35

Table 1.
Statistical summary of the site response parameters for the study area.

deviation of 0.47 seconds. The estimated vulnerability indices (K_g) range from 0.27 to 129.05 with a mean of 13.02 and a standard deviation of 26.35 (**Table 1**). The minimal amplification is a result of little seismic impedance contrast due to the thin sedimentary layer covering the competent bedrock.

4.2 Seismic microzonation and classification

The study area is characterized into three significant zones based on the Kg values determined from the analysis of soil and rock conditions, which are categorized on a scale from low to high (**Table 2**). These are zone 1 with K_g values ranging from 0.27 to ≤4.82, zone 2 with K_g values ranging from 9.60 to ≤13.47, and zone 3 with K_g ranging from 21.49 to ≤129.05 (**Table 2**). According to Ref. [32], the greater the K_g value, the greater the seismic event will cause more detrimental damage. A high seismic vulnerability index is found in areas of the weaker zone, while it indicates a low seismic vulnerability index in areas of the stronger zone. Changes in the seismic vulnerability indices are closely related to the geological and lithological attributes of the nearby region.

The results revealed that the trend of the datasets majorly displayed lower values (**Table 3**), suggesting the competency of the rocks and soils in the area. However, a

Zone	Vulnerability index	Classification	Locations	Description
1	0.27–4.82	Low	26	Thin sedimentary layer covering the competent bedrock.
2	9.60–13.47	Moderate	4	Surface sediment thickness is about 5–10 m. It may consist of gravels and medium compacted cohesive materials
3	21.49–129.05	High	4	Thick loose sedimentary overburden. Thickness greater than 25 m

Table 2.
Microzonation and classification of site materials.

HVSR site	H/V ratio	Peak frequency (Hz)	Natural period (s)	Vulnerability Index (Kg)	Remarks
30_S1	7.73	2.78	0.36	21.49	Moderate
30_S2	3.10	2.47	0.40	3.89	Low
31_S1	5.49	0.50	2.00	60.28	High

HVSR site	H/V ratio	Peak frequency (Hz)	Natural period (s)	Vulnerability Index (Kg)	Remarks
31_S2	1.30	0.50	2.00	3.38	Low
32_S1	1.10	0.67	1.49	1.81	Very Low
32_S2	2.71	8.83	0.11	0.83	Very Low
33_S1	3.26	5.06	0.20	2.10	Low
33_S2	3.92	3.19	0.31	4.82	Low
34_S1	4.54	1.53	0.65	13.47	Low
34_S2	2.82	4.97	0.20	1.60	Very Low
35_S1	4.36	1.98	0.51	9.60	Low
35_S2	3.75	2.38	0.42	2.38	Low
36_S1	3.06	1.95	0.51	4.80	Low
36_S2	3.00	11.3	0.09	0.80	Very Low
37_S1	3.26	3.52	0.28	3.02	Low
37_S2	2.38	3.52	0.28	1.61	Very Low
38_S1	13.15	1.34	0.75	129.05	Very High
38_S2	2.36	3.61	0.28	1.54	Very Low
39_S1	2.93	3.63	0.28	2.36	Low
39_S2	1.66	3.63	0.28	0.76	Very Low
40_S1	3.94	1.28	0.78	12.13	Low
40_S2	2.93	8.94	0.11	0.96	Very Low
41_S1	5.14	6.13	0.16	4.31	Low
41_S2	4.52	6.13	0.16	3.33	Low
42_S1	3.29	4.14	0.24	2.61	Low
42_S2	2.37	1.28	0.78	4.39	Low
43_S1	11.30	3.39	0.29	37.67	High
43_S2	2.07	3.83	0.26	1.12	Low
44_S1	4.29	4.44	0.23	4.15	Low
44_S2	2.53	4.88	0.20	1.31	Low
45_S1	9.75	1.15	0.87	82.66	Very High
45_S2	3.01	2.63	0.38	3.44	Low
46_S1	2.32	20.00	0.05	0.27	Very Low
46_S2	3.48	2.58	0.39	4.69	Low
47_S1	6.06	1.44	0.69	25.50	Moderate
47_S2	4.27	1.70	0.59	10.73	Low

Table 3.
Site response parameters and vulnerability index for the study area.

small fraction of data, particularly from sites like L31 site 1, L38 site 1, L43 site 1, and L45 site 1, depart from this pattern by showing extreme K_g values. The higher Kg values in the Abonko area depict the presence of weaker and loose site materials in these zones (Zone 3 materials). During seismic events like earthquakes and blasting activities, such weak zones that are associated with loose materials have the potential to cause significant structural damage. Researchers have previously determined that

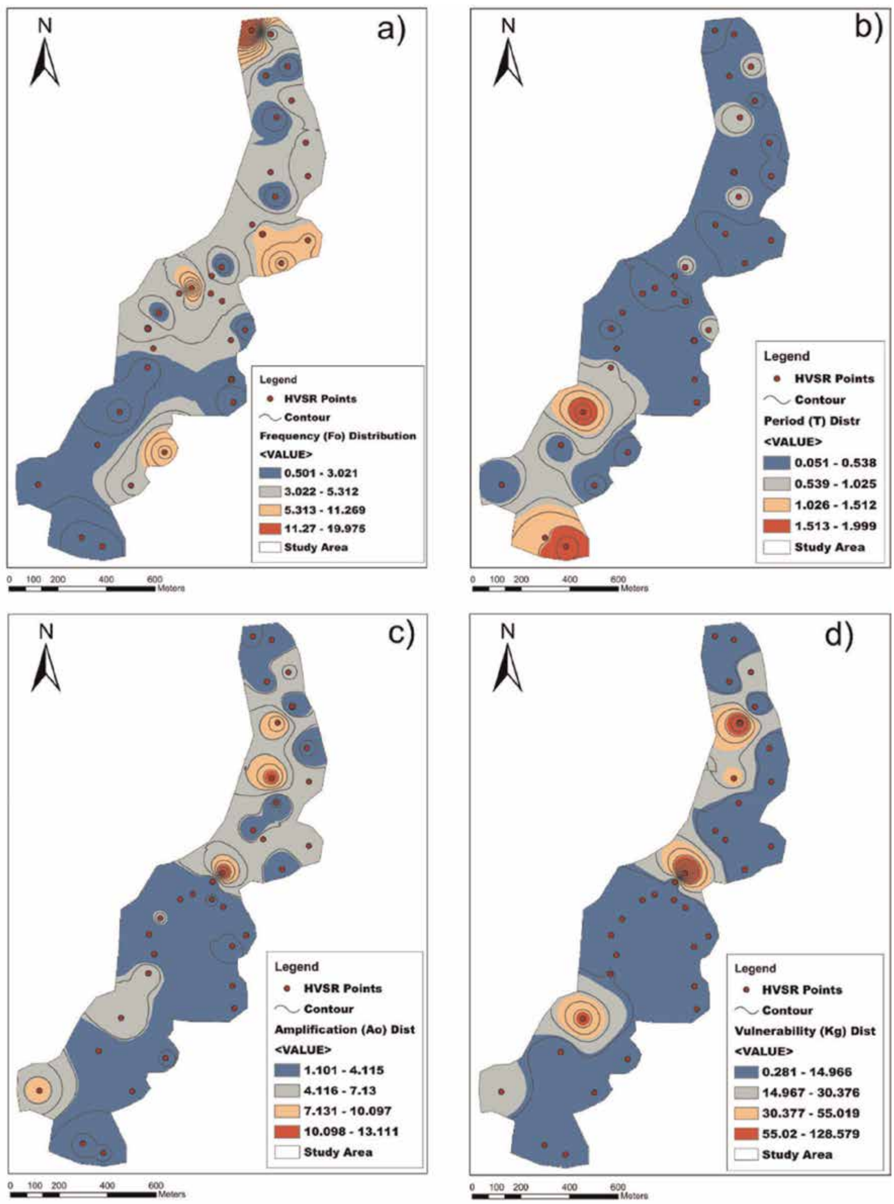

Figure 12.
Spatial distribution of response parameters: (a) frequency, (b) period, (c) amplification, (d) vulnerability index.

as the vulnerability index rises, the probability of liquefaction and resulting damage also increases, for example, [33–37].

4.3 Spatial distribution of site response parameters

The spatial distribution of the seismic site response parameters, that is, predominant natural frequency, natural period, amplification factor, and vulnerability index were plotted using the ArcMap application of GIS. These are presented in **Figure 12** (**a**–**d**) respectively. The distribution of the predominant natural frequency (**Figure 12a**) generally depicts low-frequency values except for lines L32_S2, L36_S2, L40_S2, and L46_S1 (red and reddish-brown colored) that recorded high values (i.e., 8.83, 11.30, 8.94, and 20.00 Hz, respectively) as seen in **Table 3**. The resulting natural periods were generally less than 1 sec, except for a few stations such as L31_S1, L31_S2, and L32_S1 that recorded values greater than 1 sec (i.e., 2.0 and 1.49 sec respectively). The distribution of the natural periods is shown in **Figure 12c**.

Similarly, the spatial distribution amplification factor (H/V ratio) and the seismic vulnerability index exhibited the same pattern (**Figure 12b** and **d**). Stations such as L30_S1, L38_S1, and L45_S1 have appreciably high H/V ratios (7.73, 13.15, and 9.75 respectively) as seen in **Table 3**. The site material study area generally had low Kg values, except locations such as L30_S1 and L47_S1 which recorded moderate values of 21.49 and 25.50, respectively. Also, lines L31_S1, L43_S1, L45_S1, and L38_S1 recorded higher K_g values of 60.28, 37.67, 82.66, and 129.05 respectively. The results revealed that areas that recorded higher amplification values and lower values of the natural frequency are the highly vulnerable areas to seismic activities, as exhibited by their K_g values.

5. Conclusions and recommendations

5.1 Conclusions

Data from microtremor measurements taken at 34 different sites were included in the analysis. These measurements produced trustworthy H/V spectral ratio charts with distinct peaks. These peaks are important because they make it easier to determine each site's fundamental periods and amplification factors. It is crucial to remember that this thorough determination was only possible at a select few spots because of curve instability and flatness. A thorough analysis of the site response parameters for the local area, as shown in **Table 3**, reveals a natural peak frequency range of 0.5 to 20.00 Hz. This is followed by an average natural period that lasts less than 0.5 seconds. The highest observed amplification factor is 13.15, as well. It should be noted that this amplification factor is judged insufficient to pose a seismic risk resulting from occurrences like earthquakes or blasting activity.

Values for the vulnerability index (K_g) range from 0.27 to 129.05. The convergence of data within this confined time can be attributed to the minimal differences in the near-surface geological conditions that exist within the investigation area. Based on the prevailing pattern, most of the surveyed region is characterized by a predominant frequency peak ranging from 0.50 to 5.38 Hz. It is intriguing to see those regions with natural frequencies similar to or below 2.0 Hz exhibit enhanced sensitivity, which could lead to various levels of amplification. When compared to regions whose natural frequencies are higher than the 2.0 Hz cutoff, this sensitivity stands out noticeably.

Zone 1 elements are identified in 26 of 34 locations and have a K_g range of 0.27 to 4.82. This indicates that, except for a few areas that had extremely high vulnerability, K_g is typically low throughout the research area. This might be due to the presence of dense, loose soils in the vicinity, which amplify ground vibrations. Given that the average natural period is less than 0.5 seconds, only regions with extremely low frequencies ($F_0 \leq 1.0$ Hz) would have a longer effect time during a seismic event.

5.2 Recommendation

The continuous monitoring of the site response parameters and seismic vulnerability of the local site materials within the study area is recommended, especially during the period of mining operations. This will help to create awareness of the people in that area and serve as a criterion to make informed decisions as far as the safety of the residents is concerned.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 5

Tsunami Inundation and Evacuation Mapping for Jask Port, Iran: Advancing the Tsunami Ready Program

Amin Rashidi, Mohammad Mokhtari and Mehdi Masoodi

Abstract

This chapter presents a study on high-resolution tsunami inundation and evacuation mapping for the Jask port in Iran, focusing on a potential tsunami scenario generated by the Makran megathrust in the Gulf of Oman. Using a recent numerical model and high-resolution topographic data, the study aims to provide detailed information on the potential extent of tsunami inundation and evacuation routes in the Jask port area. Through the analysis of various tsunami scenarios, valuable insights are offered for disaster preparedness and mitigation efforts, emphasizing the implementation of the Tsunami Ready Program to enhance community resilience. The inundation map for Jask port reveals the extensive reach of tsunami waves, with inundation distances up to 2 km and run-up heights reaching 6 m. This underscores the critical importance of detailed site-specific data and the consideration of factors such as coastal structures and vegetation in tsunami hazard assessments. The study highlights the potential impact on critical infrastructure, including schools, hospitals, main roads, and airports, demonstrating the need for comprehensive evacuation and mitigation plans supported by the Tsunami Ready Program. The findings of this study are essential for decision-makers and emergency planners, providing actionable guidance for developing effective evacuation strategies and strengthening tsunami preparedness through initiatives such as the Tsunami Ready Program, which plays a vital role in reducing the impact of tsunamis on the Jask port and surrounding communities.

Keywords: tsunami, Jask, Makran subduction zone, inundation, evacuation

1. Introduction

Tsunamis are one of the most destructive natural disasters, often leading to tragic loss of life and severe damage to communities and the environment. In Iran, the coastal areas around Jask Port are particularly at risk due to their location along the tectonic boundaries of the Arabian and Eurasian plates, especially in the Makran subduction zone (MSZ). This study aims to assess the potential areas that could be flooded by a tsunami around Jask Port and create an evacuation plan to improve preparedness and response efforts.

To start, we will take a closer look at Jask Port and emphasize the crucial need for readiness and quick action when faced with tsunami threats. We will explore the methods used in tsunami modeling, including the selection of a tsunamigenic scenario. The findings from this model will help us understand how far water might reach during a tsunami in Jask, highlighting areas that are most at risk and need more focus. In addition to mapping out flood zones, this study will also work on developing a practical evacuation map. This means evaluating the current infrastructure, identifying key facilities, and suggesting improvements to ensure the safety of both residents and visitors during a tsunami. We will stress the importance of involving the community and providing education as essential parts of the evacuation strategy to build resilience among locals.

Ultimately, this research aims to support broader efforts in disaster risk reduction by offering actionable insights and recommendations for policymakers, emergency responders, and community leaders in Jask Port. By deepening the understanding of tsunami risks and enhancing evacuation preparedness, we hope to reduce the potential impacts of future tsunami events, helping to protect lives and property in this vulnerable coastal region.

2. Study area

Jask Port, situated on the southeastern coast of Iran, plays a crucial role as a maritime hub for trade and transport, especially for important commodities like oil and petrochemical products. However, this strategic location also brings significant challenges, particularly from natural disasters like tsunamis. This coastal city, with a population exceeding 17,000, is geographically connected to the mainland solely from the north, creating an island-like appearance. Its low elevation relative to sea level renders it highly susceptible to flooding, even with minimal rainfall, as sea waves can inundate the entire residential area. Reports from the Integrated Coastal Zone Management (ICZM) by the Management and Planning Organization (MPO) of Iran indicate that the entire residential area of Jask is situated within a marine hazard danger zone. For Jask Port to continue functioning safely and efficiently, it is essential to understand the potential impacts of these events and to develop effective strategies to mitigate risks.

The port's location near seismic fault lines, combined with various geological and environmental factors, means that a thorough risk assessment of coastal infrastructure is necessary. A tsunami could have devastating effects on Jask Port, resulting in loss of life, significant damage to infrastructure, interruptions to shipping, and long-term economic consequences. While many structures at the port, such as docks, warehouses, and operational facilities, are designed for typical maritime conditions, they may not be equipped to withstand the immense forces of tsunami waves. The intense, cyclical wave actions and the resulting flooding pose substantial risks not just to permanent buildings but also to temporary assets.

Additionally, there may be a lack of accurate mapping of local seismic and tsunami hazards, which can leave communities unprepared. Investing in advanced early warning systems that quickly detect seismic activity and predict potential tsunamis is essential. Collaborating with regional seismic monitoring networks can ensure that port operators receive timely alerts. Tsunamis can also severely impact the surrounding environment, harming coastal ecosystems. Beyond the physical destruction of infrastructure, pollution from industrial spills and debris can create long-lasting ecological challenges that complicate recovery. The economic consequences of a tsunami at Jask Port could be far-reaching. Disruptions in trade operations might lead to significant financial losses, particularly since the port is a critical point for oil and gas exports. Recovery times can vary greatly depending on the extent of the damage and how effectively response measures are implemented. Although Jask Port has the potential to be a key player in Iran's trade, it faces serious challenges from natural hazards like tsunamis. A proactive strategy that combines engineering solutions, advanced technologies, community involvement, and environmental care will not only strengthen Jask Port's resilience against tsunamis but also reinforce its importance as an economic asset in the region. Ongoing research and collaboration are vital for improving our understanding of these natural threats and enhancing preparedness.

The main tsunami threat to the Jask port comes from the Makran subduction zone (**Figure 1**). The Makran subduction zone (MSZ) is a significant geological feature located along the coastlines of Iran and Pakistan, where the Arabian plate is subducting beneath the Eurasian plate [2]. This region has garnered considerable attention due to its complex tectonic dynamics and the uncertain tsunamigenic and seismogenic potentials associated with it. The MSZ is characterized by a low rate of seismic activity, which has led to debates regarding its capacity to generate large earthquakes

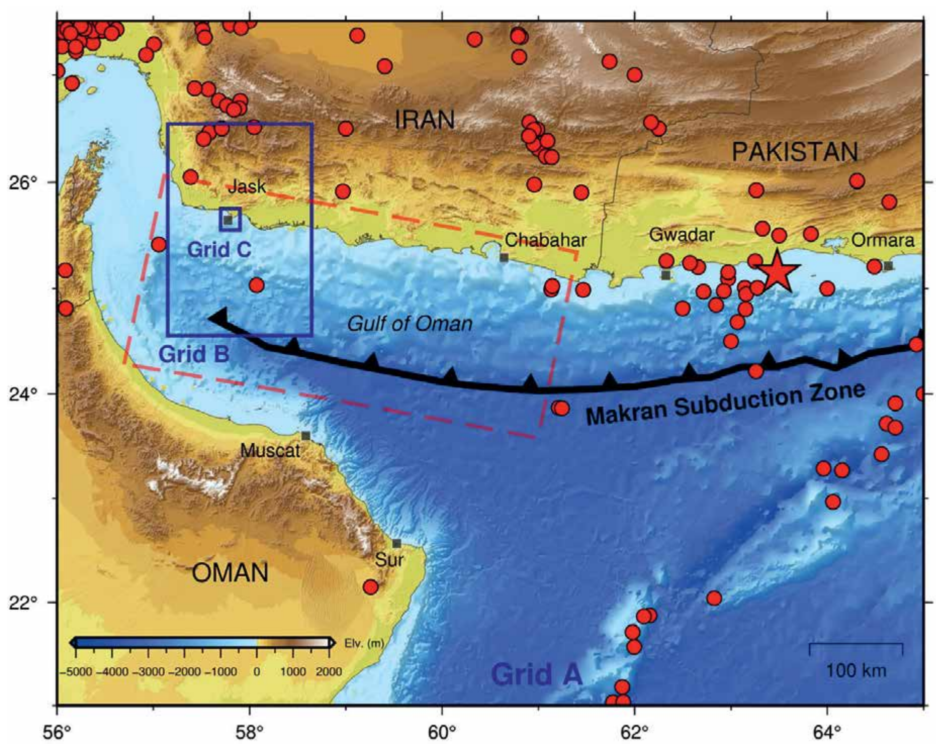

Figure 1.
Location map of the Makran subduction zone, the nested grids (blue outlines) employed for tsunami inundation modeling, and the western Makran rupture area (dashed red lines). Red circles represent earthquakes (M ⩾ 4.0) after the 1926 from the ISC catalog [1]. The star shows the 1945 Makran tsunamigenic earthquake (M_w 8.1).

and tsunamis [3]. Historical records indicate that the region has experienced notable tsunamigenic events, including the devastating tsunami triggered by the 1945 earthquake and the landslide tsunami in 2013, which highlighted the potential risks posed by this subduction zone [4]. Historical records indicate that the region has experienced at least six significant tsunamis over the past two millennia, with a mean return period for tectonic tsunamis estimated at around 800 years [5, 6].

The historical tsunami events date back to 326 BC, 1008, 1524, and 1897. The earthquakes of 1945 (Mw 8.1) and 2013 (Mw 7.7) stand out as the only two tsunamis in the area that have been captured by modern instruments. For the 1945 event, researchers estimate that the earthquake caused a rupture approximately 70 to 100 km wide [6]. Some researchers believe that the main shock triggered a submarine landslide, which could explain the delayed arrival time and the powerful waves of the tsunami, a disaster that claimed a couple of hundred lives [7]. Looking at the 2013 earthquake, it is important to note that while it did not directly cause a tsunami, it may have initiated a submarine slump that played the main role in generating the small tsunami waves that followed [4].

The eastern segment of the MSZ is relatively active (**Figure 1**), while the western segment has shown little seismicity in recent centuries. This discrepancy raises questions about the potential for future large earthquakes in the western segment, which may be locked and accumulating stress. Geological evidence suggests that the western segment of the MSZ, despite its current low seismicity, may have the capacity to generate large earthquakes and tsunamis [8]. This potential is supported by paleotsunami research, which indicates past tsunami events that could have originated from this segment [9]. The tsunamigenic potential of the MSZ is further complicated by the presence of local sources such as splay faults and submarine landslides, which can contribute to tsunami generation independently of the main subduction thrust [6, 10, 11].

In summary, the Makran subduction zone is a critical area for studying the relationship between tectonic activity and tsunami hazards. As research progresses, it becomes increasingly important to assess and monitor both the tsunami and earthquake risks associated with the MSZ to protect the densely populated coastal areas nearby.

3. Methodology

3.1 Earthquake source

To set the stage for tsunami modeling, we must first calculate how the seabed displaces during earthquakes. For our simulations of tsunamis caused by earthquakes, we assume that the seabed displacement translates directly to the initial elevation of the water surface [12]. We utilize the well-established Okada solution [13] to determine these co-seismic seabed displacements.

In this study, we focus on the western Makran source model put forward by Rashidi et al. [12], which is based on the rupture scenario introduced by Smith et al. [14]. The location of the western Makran source model is shown in **Figure 1**, with its parameters detailed in **Table 1**. The average slip value for this model is set at 3 m, as indicated by Smith et al. [14]. With a shear modulus of 30 GPa [14], we calculate the moment magnitude (M_w) for the western Makran source to be 8.5. This decision was based on several critical considerations:

Source parameter	Value
Length (km)	450
Width (km)	210
Focal depth (km)	25
Strike angle (°)	280
Dip angle (°)	7
Rake (°)	90
Mean slip (m)	3
Moment magnitude M_w	8.5

Table 1.
Details of the western Makran source model utilized in this research.

Severity and preparedness: An earthquake of magnitude 8.5 represents a severe and realistic worst-case scenario. Preparing for such an event ensures that response plans and mitigation strategies are robust enough to handle significant impacts.

Historical data and geological evidence: Historical records and geological studies indicate that the region has the potential to experience seismic events of this magnitude. Therefore, planning for an 8.5-magnitude earthquake is both prudent and necessary.

Impact assessment: Modeling of the 8.5 magnitude scenario shows extensive inundation and potential damage to infrastructure and communities. Addressing this scenario allows for comprehensive planning and resource allocation to mitigate these impacts.

Community and infrastructure protection: Selecting the 8.5 scenario ensures that critical infrastructure, such as hospitals, schools, and evacuation routes, is adequately protected and that the community is well-prepared for evacuation and emergency response.

Given the uncertainty surrounding the Makran subduction zone's potential maximum magnitude, we have decided to adopt a more conservative mean slip compared to the scenarios outlined by Smith et al. [14].

It is important to note that the tsunami community often overlooks the variability of slip along the fault. Assuming a uniform slip distribution can lead to significant uncertainties. In reality, variations in slip can greatly influence the tsunami wave heights in the near field. To address this slip heterogeneity, we draw upon the methodology implemented by Rashidi et al. [15] and previously used by both Rashidi et al. [16] and Zafarani et al. [17]. We utilize a random k^{-2} stochastic slip model [18, 19], where k represents the wavenumber. Tsunami modeling is a complex process that significantly relies on the expert judgment for various aspects. Much of it involves a trial-and-error approach to selecting the appropriate source for simulation [20]. In our study, we test 10 randomly generated stochastic source models, aiming to concentrate the along-dip slip asperities in the shallow-to-intermediate sections of the fault, as inspired by Refs. [21–23], and to determine the preferred slip model. The distribution of these asperities differs across subduction zones and seems to be linked to their geological characteristics [24]. The resulting slip model, along with its static seabed deformation field, is illustrated in **Figure 2**. The maximum initial sea level rise computed for our scenario is about 3 m.

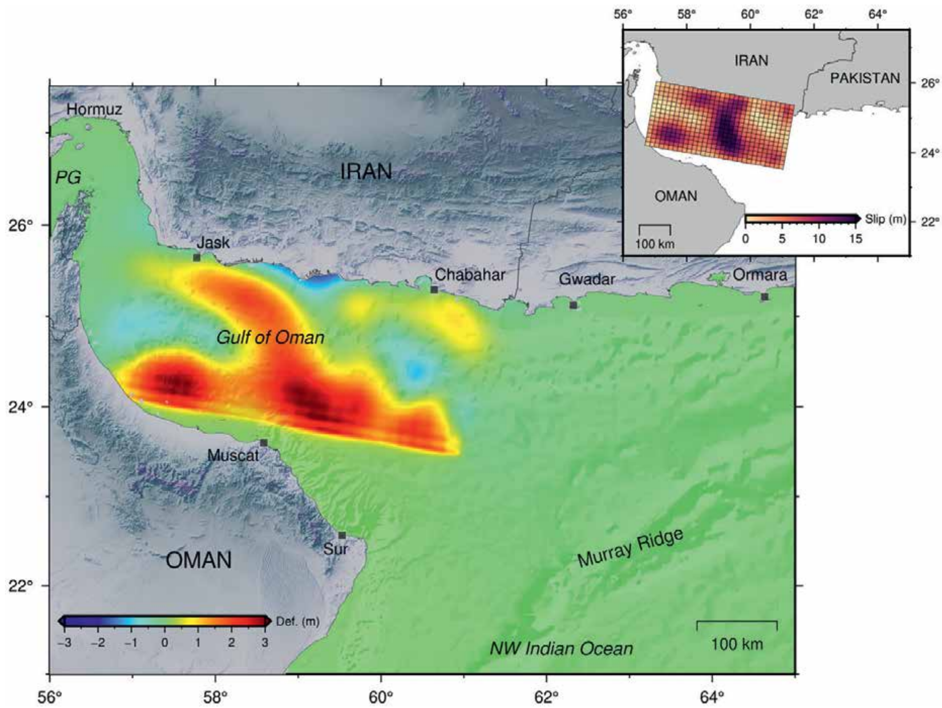

Figure 2.
Slip distribution (inset map) and resulting seafloor deformation of the western Makran M_w *8.5 scenario.*

3.2 Inundation modeling

Tsunami numerical simulations are conducted utilizing the model established by Wang and Liu [25], which supports nonlinear shallow water equations. This model employs an explicit leapfrog finite difference scheme to discretize these equations, incorporating a staggered and nested grid framework. To enhance the accuracy of tsunami wave height estimates in shallow water regions, a moving boundary scheme is implemented. The simulations account for tsunami inundation through a system of three nested grids, as illustrated in **Figure 1**. For the outermost grid (Grid A), we utilize bathymetric data from the 15-arcsec General Bathymetric Chart of the Oceans (GEBCO; http://www.gebco.net). The intermediate grid (Grid B) has a finer resolution of 3 arcsec, while the innermost grid (Grid C), which zooms in on Jask port, comes with a resolution of 1 arcsec. This smallest grid integrates data from the Global Multi-Resolution Topography (GMRT) synthesis (http://www.geomapapp.org), local datasets, and the Shuttle Radar Topography Mission (SRTM) 1 arcsec dataset (available at https://earthexplorer.usgs.gov).

Our computational domain, as depicted in **Figure 1**, spans from 56°E to 65°E and from 21°N to 27.5°N. The time steps employed for the simulations are 1 second for Grid A, 0.5 seconds for Grid B, and 0.25 seconds for Grid C. Open boundaries are treated using radiation boundary conditions, and our simulation applies a constant Manning's roughness coefficient of 0.025, with a tsunami simulation duration of 5 hours.

3.3 Evacuation mapping

Developing a tsunami evacuation map/plan involves several key steps to ensure the safety and preparedness of communities in the event of a tsunami. The essential steps reviewed at this study include Risk Assessment, Public Education and Awareness, Evacuation Routes and Areas, Infrastructure and Signage, Communication Systems, Evacuation Procedures, Training and Drills, Coordination with Agencies, Review and Improvement, and Community Involvement.

Several field visits have been conducted to review the inundation map, assess evacuation zones, identify evacuation areas and buildings, and screen potential tsunami evacuation buildings. During these visits, low-lying areas prone to inundation during heavy rainfall and marine storms are thoroughly inspected. These inspections are informed by data from officials and input from residents and are compared with existing inundation map data to verify accuracy. Additionally, the team carefully examined coastal lines, coastal roads, main urban traffic routes, city exit routes, and both natural and man-made obstacles. Future urban development plans, including projected paths for streets and boulevards, were also considered to ensure that evacuation strategies align with the city's growth.

Based on the information gathered and technical input from city officials, the pilot area is divided into four zones, numbered 1 to 4 from south to north. Low-lying areas identified as vulnerable to inundation during heavy rainfall and marine storms are thoroughly examined during the field visits. These areas are selected based on detailed input from city officials and residents who have firsthand experience with flooding events. The on-site inspections are then cross-referenced with the inundation map data to verify accuracy and identify any discrepancies. The purpose of these comparisons is to assess the reliability of the existing inundation maps in predicting flood-prone zones and to update them if necessary. This process is critical for ensuring that evacuation plans are effective and that resources are allocated to the most at-risk areas.

4. Results

The research findings are illustrated in **Figures 3**–**6**, each providing valuable insights into various aspects of tsunami behavior and risk in the region. Starting with **Figure 3** depicts the distribution of maximum tsunami amplitudes in the northwestern Indian Ocean. The results highlight a significant local risk to the coasts of Iran and Oman, indicating a potential for considerable impact in these regions. Interestingly, there is a notable difference in the maximum tsunami amplitudes between the Gulf of Oman and southern Pakistan, where the tsunami hazard zone is much narrower and concentrated near Pakistan. Within the study area, tsunami wave amplitudes from the seismic source range from 0 to 13 m, showing varying levels of risk along different coasts. For instance, along the coastline of Pakistan, the maximum wave amplitudes are around 2 m. The scenario does not produce wave heights exceeding 2 m near the shore of Pakistan, as the tsunami waves lose most of their energy inside the Gulf of Oman before reaching other marine areas.

Figure 4 presents a map showing tsunami arrival times, along with computed time histories from six virtual gauge stations along the Makran coast. The initial tsunami waves reach most coastal areas of the Gulf of Oman, including Jask, within just 10 min. However, it takes about 30 min for tsunami waves to impact the entire

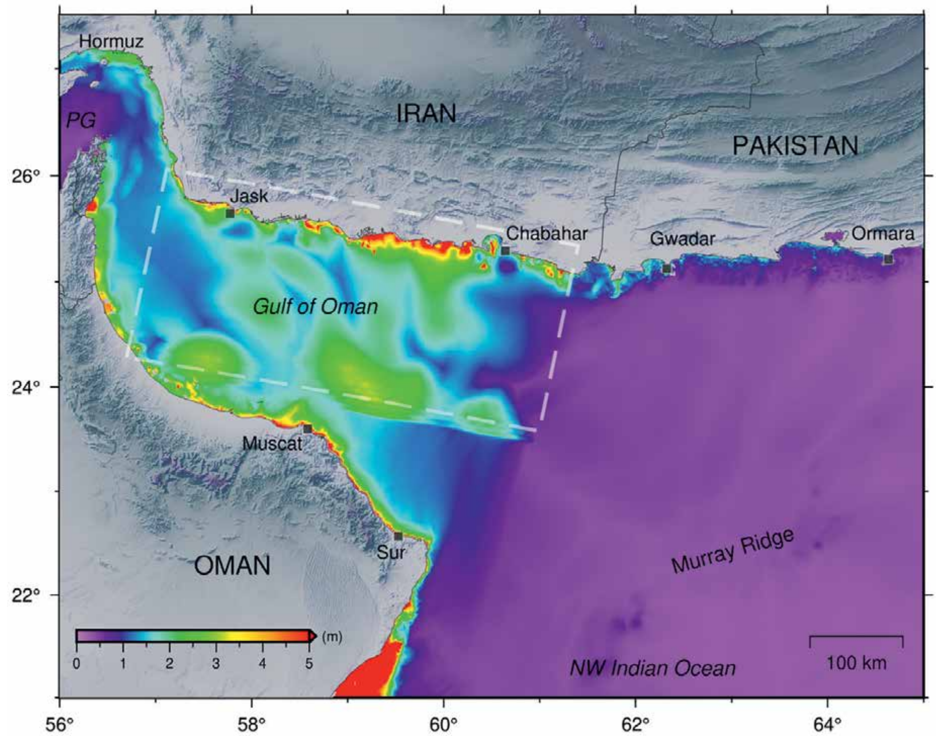

Figure 3.
Tsunami maximum wave amplitudes from the western Makran scenario in NW Indian Ocean. Dashed white lines represent the western Makran rupture area.

Jask coastline. In Muscat and Sur, the first tsunami waves arrive within 15 min of the event, with Sur experiencing a slightly delayed arrival compared to Muscat. Gwadar experiences its first wave in less than 30 min, while offshore Ormara encounters the initial wave almost 15 min after that. The tsunami waves take about 1.5 h to reach the Strait of Hormuz, located in the western part of the Iranian coastline, despite its proximity to the tsunami source (**Figure 4**).

To analyze the progression of these waves following the tsunami scenario, we set up six virtual gauges along the Makran coastlines, placed at an average water depth of about 100 m. The gauges are positioned offshore Jask and Chabahar in Iran, as well as Gwadar and Ormara in Pakistan, and Sur and Muscat in Oman (**Figure 4**). Muscat receives the tallest wave, reaching about 3 m, while Jask experiences a peak height of less than 2 m. After the initial wave, both Muscat and Sur experience significant damping, leading to lower wave heights. Ormara receives its first wave in about 45 min, with its highest wave occurring 30 minutes later.

Figure 5 focuses on the coastal amplitudes along the southeastern coast of Iran. The results show that the entire southeastern coastline of Iran is affected by all the tsunami scenarios examined in this study, highlighting the region's widespread vulnerability to tsunami threats. This underscores the importance of preparedness and response strategies for coastal communities. The maximum coastal amplitude is about 13 m near the Kereti coast. To the left side of the map, near the Strait of Hormuz, tsunami waves are attenuated due to changes in bathymetry, as the Persian Gulf is much shallower than the Gulf of Oman. Tsunami amplitudes also decrease toward the

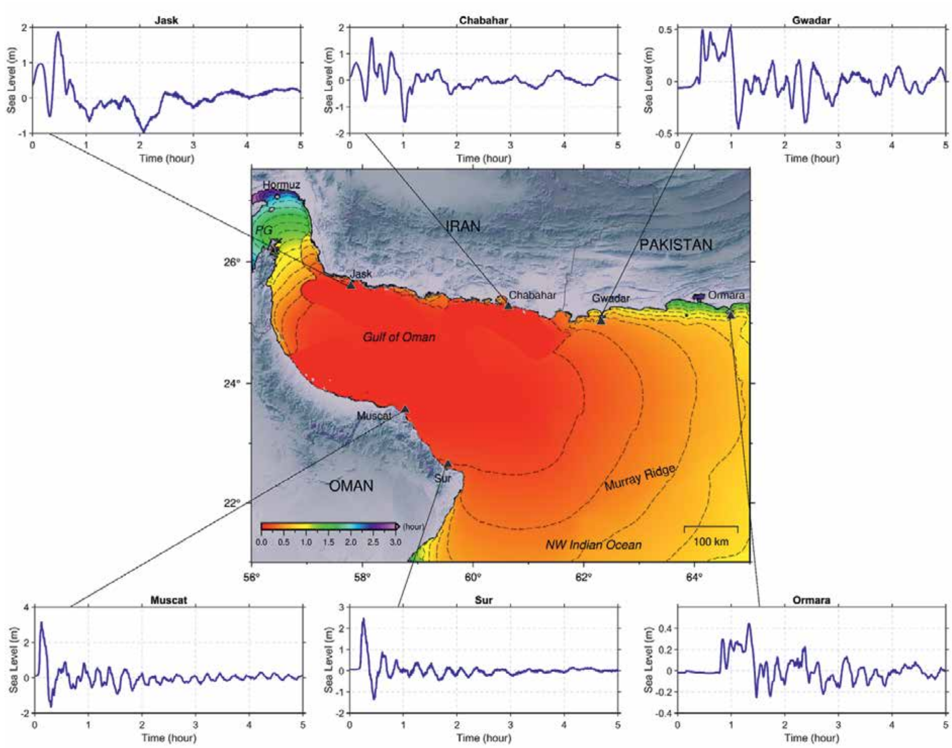

Figure 4.
Map of tsunami arrival times, featuring 10-min interval contours (dashed lines), along with computed time histories from six virtual gauge stations along the Makran coast.

Pakistan shoreline. Overall, these figures illustrate the complex dynamics of tsunami behavior in the northwestern Indian Ocean, revealing critical information about potential risks and energy distributions that could inform future mitigation efforts.

4.1 Inundation map

Inundation mapping is an interdisciplinary work that integrates geology, oceanography, engineering, computer science, and public policy to improve our understanding and management of tsunami risks. This complex field requires collaboration across various domains to develop accurate and actionable maps to inform and protect communities at risk of tsunami inundation. These maps are typically created for important ports and coastal segments to show how far a tsunami can penetrate inland. They are essential for tsunami hazard mitigation plans, helping to identify hazards, develop evacuation routes, and indicate relatively safer locations in coastal areas [26].

Tsunami inundation mapping and evacuation planning have been identified as priority topics for the five partner Member States in the NWIO region (India, Iran, Pakistan, Oman, UAE) of the UNESCO-IOC Intergovernmental Coordination Group for the Indian Ocean Tsunami and Mitigation System (ICG/IOTWMS) to improve tsunami preparedness at the community level. These are key steps toward making at-risk communities' tsunami-ready. The UNESCAP-funded Project TTF31 "Strengthening Tsunami Warning in the North-West Indian Ocean Through Regional Cooperation - Phase 2c" has supported its partners in strengthening their capacities for tsunami

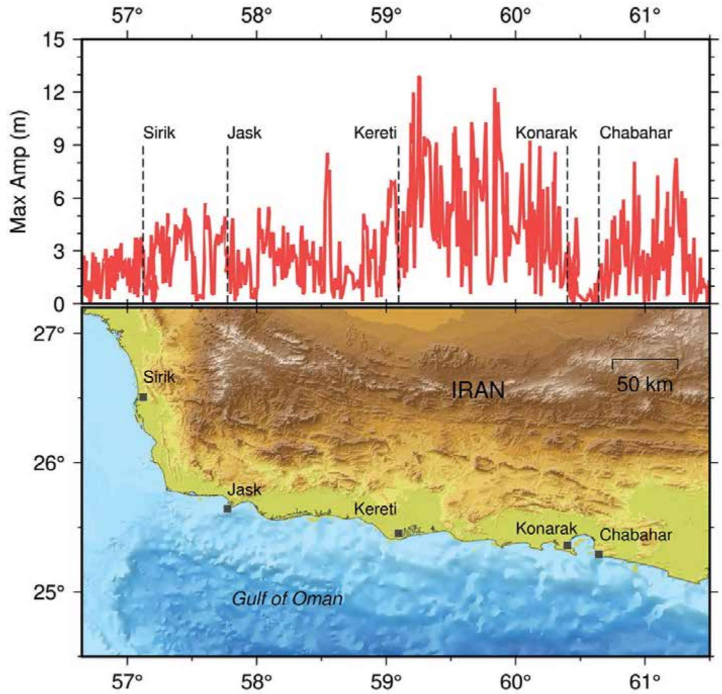

Figure 5.
Maximum tsunami amplitudes from the western Makran scenario along the Iran SE coastline.

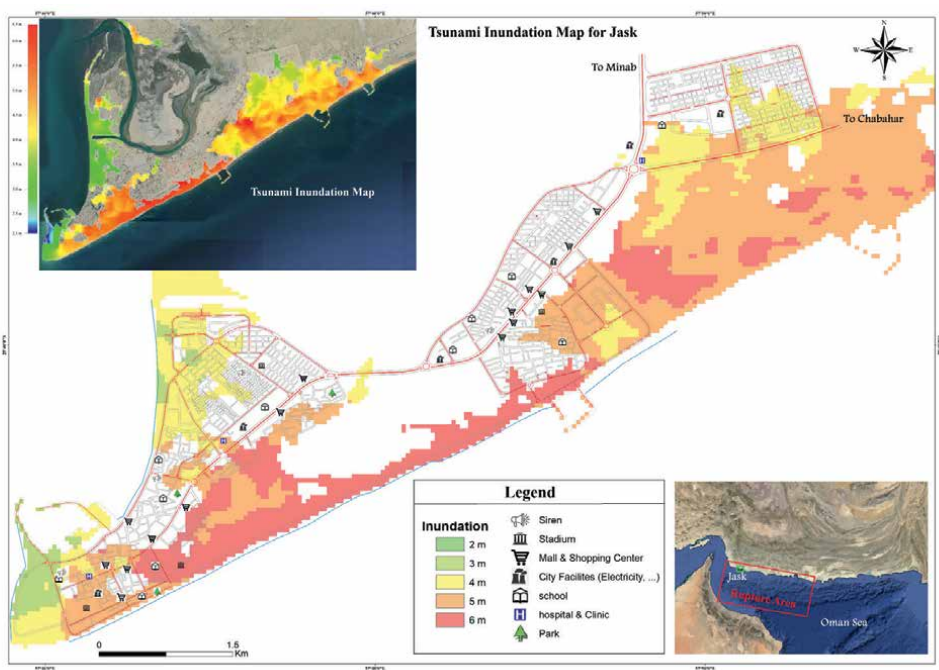

Figure 6.
Tsunami inundation map for Jask Port, Iran.

inundation mapping and evacuation planning. The main objective of the UNESCAP project was to support local coordination, capacity development, monitoring, and follow-up on the development of a tsunami evacuation plan for the selected pilot site/community. The adaptation, adoption, and improvement of a tsunami inundation map for Jask City are critical steps in enhancing the community's resilience to tsunami risks.

Figure 6 presents a tsunami inundation map for Jask port, based on tsunami modeling of a western Makran M_w 8.5 source model. **Figure 6** reveals that Jask Port is not immune to tsunami waves from the modeled scenario, as most areas are inundated. Only some locations at the western tip of the port are protected by barriers that prevent tsunami waves (**Figure 6**). The longest tsunami inundation distances are about 2 km, reaching a school and some city facilities in the north of the map. Tsunami waves can travel long distances along the east of Jask's port, penetrating the port and even reaching the Chabahar road. The tsunami run-up height reaches 6 m along the port. Notably, a coastal strip in the middle of the map, where Jask airport is located, is also affected and inundated by the tsunami waves (**Figure 6**). These findings highlight the potential tsunami inundation risks faced by Jask Port. For a more comprehensive discussion on tsunami inundation, it is essential to have more detailed site-specific topo-bathymetric data and consider the influence of coastal structures, land cover roughness, vegetation, and other relevant factors.

4.2 Evacuation map

- *Screening buildings for vertical evacuation:* As part of the screening process for vertical evacuation options, both existing and under-construction high-rise buildings have been assessed. Buildings with a minimum height of approximately 6 m are highlighted using color coding for easy identification (**Figure 7**). This visual system helps quickly identify suitable evacuation sites in the event of a tsunami or flood, ensuring that people can find safe refuge above potential inundation levels.

- *Evacuation zones and routes overview:* The boundaries for the four evacuation zones are clearly defined, and evacuation routes are carefully mapped out. Two key evacuation areas outside these zones are identified and named "Maskan Mehr" and "Bam." Zones 1 and 2 are located in the southern part of the city, while zones 3 and 4 are in the northern part, closer to the city exit (**Figure 7**). The maximum distance to reach the Maskan Mehr Evacuation Area from zones 1 and 2 is 1.3 km and 3.2 km, respectively (**Figure 7**). For zones 3 and 4, the maximum distance to the Bam Evacuation Area is 3.9 km and 1 km, respectively (**Figure 7**). Using the latest city map, all essential locations, including schools, hospitals, clinics, malls, and city facilities, are identified and marked. Main evacuation routes leading to the nearest evacuation area are determined, with an expected walking time of approximately 20 minutes. To prevent traffic congestion, it has been decided that the Maskan Mehr Evacuation Area would primarily serve residents from zones 1 and 2, while zones 3 and 4 would use the Bam Evacuation Area. Two evacuation areas have been designated for public safety. The first, the "Maskan Mehr Evacuation Area," is located within the urban zone (**Figure 7**). This newly built facility is well-equipped with modern amenities, ensuring it can effectively serve the community in emergencies. The second area, the "Bam Evacuation Area," is situated outside the urban zone. Although it offers more basic amenities, it includes several tents specifically set up for drills and emergency use. Consequently, the public is familiar with this area and well-informed about the access routes.

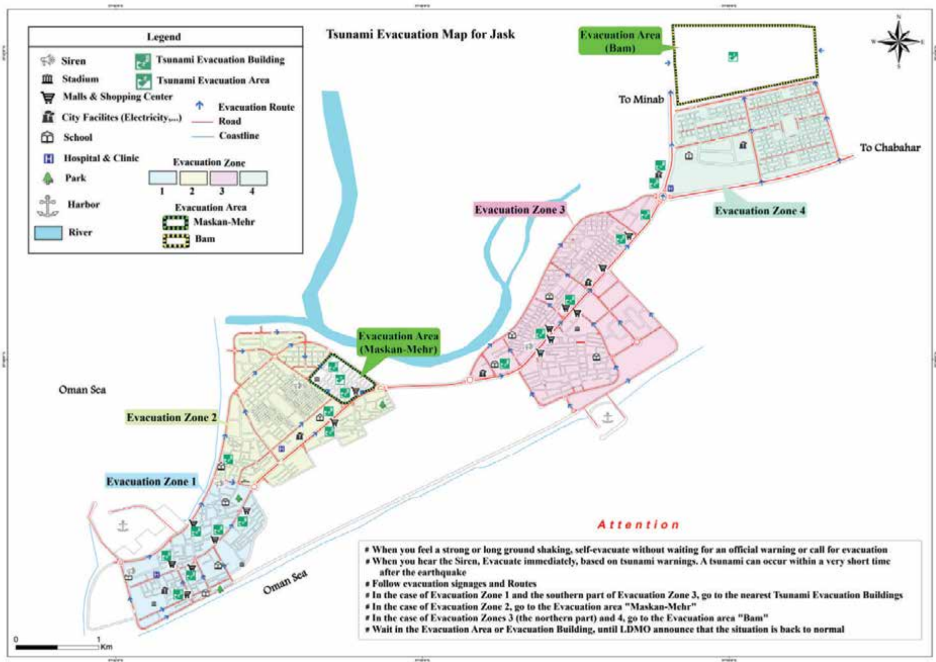

Figure 7.
Tsunami Evacuation Map for Jask Port, Iran.

5. Discussion

The results presented in **Figures 3**–**7** provide an insightful analysis of tsunami behavior and risk in the northwestern Indian Ocean, with a particular focus on the Jask coast, Iran. The significant local risk to SE Iran coasts, as highlighted by the distribution of maximum tsunami amplitudes, underscores the need for targeted mitigation strategies. The notable difference in tsunami amplitudes between the Gulf of Oman and adjacent areas suggests that local bathymetric and geological features play a crucial role in tsunami wave propagation and energy dissipation. The findings for the southeastern coast of Iran, particularly near the Kereti coast, indicate a maximum coastal amplitude of about 13 m, emphasizing the region's vulnerability. The attenuation of tsunami waves near the Strait of Hormuz due to shallower bathymetry further illustrates the complex interplay between underwater topography and tsunami dynamics. These insights are critical for developing effective preparedness and response strategies for coastal communities. The inundation map for Jask port reveals the extensive reach of tsunami waves, with inundation distances up to 2 km and run-up heights reaching 6 m. This highlights the importance of detailed site-specific data and the consideration of various factors such as coastal structures and vegetation in tsunami hazard assessments. The potential impact on critical infrastructure, such as schools, hospitals, main roads, and airports, underscores the need for comprehensive evacuation and mitigation plans.

It is crucial to highlight the importance of assessing the vulnerability of coastal communities in the Makran region, especially given the growing population and economic activities along these coastlines. Although the historical record of tsunamis in the Makran region is limited, it suggests a significant potential for future events. The 1945 tsunami, caused by a magnitude 8.1 earthquake, remains a vital case study for understanding the region's tsunami-generating behavior. The role of sedimentation in the Makran subduction zone (MSZ) is particularly important. Thick sediment layers can affect the seismogenic potential and the characteristics of tsunami generation. Therefore, understanding the sedimentary environment is essential for accurate tsunami hazard assessments. To improve our preparedness for future tsunamis in the Makran region, we need more comprehensive studies that integrate geological, geophysical, and historical data. These studies will help refine tsunami hazard models and enhance our ability to respond effectively to potential tsunamigenic events. Given the increasing population density and economic development along the coastlines, it is more important than ever to conduct thorough vulnerability assessments. These assessments can inform better planning and preparedness strategies, ensuring that coastal communities are well-equipped to handle the risks associated with tsunamis.

This study focuses on one selected scenario as an initial step. However, incorporating a broader range of scenarios is essential to accurately assess the variability in potential tsunami inundation patterns. A comprehensive scenario analysis enables a deeper understanding of how factors such as slip distribution, fault mechanics, and local topography interact to shape tsunami behavior. By capturing these complexities, we can ensure more robust and reliable predictions, thereby improving risk assessments and the effectiveness of mitigation strategies for vulnerable coastal communities. Expanding the analysis to include multiple scenarios will significantly enhance the applicability and relevance of the findings.

In addition to scientific research, community education and awareness programs are vital. By educating residents about the risks and proper response actions, we can build more resilient communities. Collaboration between scientists, local authorities, and international organizations can also play a key role in enhancing tsunami preparedness and response efforts in the Makran region. To reduce the risks of future tsunamis and protect people living along the Makran coasts, we need to combine scientific research, community involvement, and international cooperation.

5.1 Detailed process of evacuation mapping for Jask Port

5.1.1 Site assessment and risk analysis

The crucial information required is the topographic and bathymetric data. Given that Jask Port is relatively flat, one of the initial steps is gathering detailed topographic and bathymetric data for the region. A Digital Elevation Model (DEM) with fine resolution is crucial in this setting. Even small variations in elevation can affect how far inland tsunami waves will travel and which areas may serve as potential safe zones. The other important work that has been conducted was the Tsunami Hazard Zoning. For Jask, because even a tsunami with a wave height of less than 3 m could cause significant inundation in this region, hazard zoning must include the lowest wave heights. This means that evacuation maps must account for worst-case scenarios, even when the tsunami amplitude is small. The hazard zones have been divided into a high-risk zone which is the areas that will be immediately inundated in the event of any significant tsunami; moderate-risk zone the areas that are likely to experience inundation but with reduced severity compared to high-risk zones; and finally low-risk zones the areas that may not be directly affected by a tsunami but are vulnerable to secondary impacts such as flooding due to drainage system failure.

5.1.2 Identifying safe zones for evacuation

Safe zone selection in Jask is limited by topography, which restricts the availability of elevated areas, and there are few high-rise buildings available as vertical evacuation points. Therefore, evacuation mapping must rely on four pre-identified zones that are deemed safe for survival which are zone 1, a naturally elevated terrain or artificially raised land near the outskirts of the town. Even a slight elevation (2–3 m above sea level) can provide safety in this flat region; zone 2 is a reinforced structure specifically built for tsunami evacuation. Although Jask lacks high buildings, a structure or shelter designed to withstand a tsunami's force can serve as a refuge, and zone 3, where a location farther inland where evacuation routes converge. This area should be accessible within a short time frame and distant enough to be outside the tsunami's projected inundation area; and finally, zone 4.

5.1.3 Criteria for selecting safe zones

The main criteria used in Jask port were elevation that is the minimum safe elevation that should be determined based on the worst-case tsunami scenario. Although the waves may be small, even slight differences in elevation can provide protection. In addition to access and distance, since Jask has a flat terrain, safe zones must be located within a short travel time. The population must be able to reach these zones on foot, as traffic congestion could hinder evacuation. Safe zones should be distributed across the port area, ensuring that all residents are within 10–15 minutes of walking distance from a refuge point.

5.1.4 Evacuation route planning and optimization

In this regard, route selection is a vitally important contributor, which is the evacuation routes are the lifelines for the population during a tsunami event. Given that Jask lacks vertical evacuation options, all routes must lead to the three designated safe zones. The primary factors in route selection include the shortest Path: In a flat terrain like Jask, the shortest distance to a safe zone is critical. Routes should be as direct as possible, avoiding natural barriers such as rivers, canals, or flooded roads. In addition, crowd management that is again given the flat terrain, traffic congestion can become a significant issue. Evacuation routes should be designed to handle large crowds, with wide pathways or roads designated for pedestrian use during a tsunami evacuation. We found that each safe zone ideally should have multiple access routes to avoid bottlenecks. For example, if a main road is blocked or flooded, secondary paths should be available. The other significant action that was important for Jask to be followed was route marking and signage that clear signage should be installed along the designated evacuation routes, marking the direction toward the safe zones. In Jask, where there is limited infrastructure, mobile and digital solutions (e.g., mobile apps) can complement physical signage, providing residents with real-time updates and navigation assistance during an evacuation. Additionally, the map includes evacuation timing simulations, showing how long it would take the population to evacuate from various points in the port area.

5.1.5 Public awareness and drills

Education and awareness are crucial for the success of evacuation mapping in Jask, which will depend heavily on community awareness. Maps should be distributed widely, and education campaigns should ensure that residents understand the importance of reaching the safe zones in time. Regular drills and simulations should be conducted to familiarize the community with the evacuation routes and procedures. Vulnerable populations: Special attention should be given to the elderly, disabled, and children. These groups may require additional assistance during evacuation, and provisions for their safe transport should be included in the evacuation plan. Community-based organizations and local authorities should coordinate to ensure that everyone has access to safe evacuation.

5.1.6 Significance of evacuation mapping for Jask Port

The evacuation maps are not only a logistical tool but a life-saving resource for the population of Jask. Given the area's flat terrain and lack of natural high ground, the maps are crucial for minimizing casualties due to limited time to evacuate in the event of a tsunami, and these maps provide clear, efficient pathways to safety. For residents of Jask, understanding these evacuation routes is the most critical factor in surviving a tsunami. Another important element in this regard is the maps foster a culture of preparedness. Regularly updated and widely distributed, they ensure that the population is aware of the risks and knows exactly what to do when a tsunami warning is issued. Here, we should add also the evacuation mapping highlights the need for future infrastructural developments, such as reinforced shelters or elevated platforms, to compensate for the lack of natural or built vertical evacuation options in Jask.

6. Conclusions

The study provides valuable insights into the tsunami risk in the northwestern Indian Ocean, particularly for the coastline of Iran. The significant local risk identified in these regions calls for targeted mitigation efforts and the development of robust preparedness and response strategies. The varying tsunami amplitudes and inundation extents highlight the importance of understanding local bathymetric and geological features in tsunami hazard assessments. This study underscores the importance of proactive tsunami risk management for Jask Port. The inundation and evacuation maps developed in this research serve as vital tools for enhancing community resilience and ensuring the safety of residents and visitors.

In conclusion, the findings underscore the need for detailed site-specific data and the consideration of multiple factors in tsunami modeling to assess risks accurately and inform mitigation efforts. The potential impact on critical infrastructure and coastal communities necessitates comprehensive planning and the implementation of effective evacuation routes and safety measures. This study contributes to a better understanding of tsunami behavior and risk, providing a foundation for future research and mitigation efforts in the region.

The Makran subduction zone presents a complex interplay of geological factors that contribute to its tsunamigenic potential. Continued research is vital to mitigate risks and enhance the understanding of tsunami hazards in this vulnerable region. Moreover, the integration of findings into the Tsunami Ready Program is crucial for strengthening community preparedness and resilience. By promoting awareness, planning, and preparedness through this program, the region can take significant steps toward reducing the impact of tsunamis on vulnerable coastal populations and critical infrastructure.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 6

Socio-Economic Vulnerability in Tsunami Devastations: A Critical Review Based on Galle City, Sri Lanka

Udari Gunarathna, Chaminda Senarathna Bandara, Ranjith Dissanayake and Harsha Munasinghe

Abstract

With the Tsunami destruction in Sri Lanka in 2004, coastal communities became vulnerable to numerous environmental and socio-economic consequences. Besides, people tend to be more focused on the socio-economic impacts, as they suffer severely from that natural disaster. Consequently, this chapter comprehensively analyzes the socio-economic vulnerabilities caused by the Tsunami, focusing on the 2004 Tsunami incident in Sri Lanka, which created a disastrous situation among coastal communities. Moreover, it critically explains the integration between socio-economic aspects and the vulnerability of coastal communities during Tsunami events. With the devastation during the first event recorded in recent Sri Lankan history, Galle City was highlighted due to its extensive damage under different circumstances. Accordingly, the chapter evaluates the pre- and post-socio-economic conditions dominant in Galle City with the disaster recovery exertions. Further, different socio-economic perspectives on Tsunami vulnerabilities, including social cohesion, livelihoods, housing, and resource accessibility experienced by various community segments in the coastal areas of Galle City, are expansively defined with insights from urban planning, economy, sociology, and Tsunami-related reviews. Consequently, it provides potential improvements and novel pathways for future research focusing on resilience and sustainability in Sri Lankan coastal communities and beyond.

Keywords: coastal communities, disaster resilience, Galle City, socio-economic, sustainability, tsunami, vulnerability

1. Introduction

With the rapid increase of natural disasters, socio-economic vulnerability has become prominent, where community impacts can be seen from different perspectives [1]. Indian Ocean Tsunami devastation in 2004 has been one of the most catastrophic natural disasters in Sri Lanka's recorded history [2, 3]. The consequences of Tsunami disasters have highlighted the relationship between socio-economic factors and disaster resilience [4]. Accordingly, life, property losses, and destruction of social structures were the most significantly identified disasters caused by the calamity. Besides, these experienced widespread adversities, such as inequalities related to livelihoods, housing, social cohesion, and resource accessibility, intrinsically related to socio-economic aspects, further impairing the vulnerability of affected communities [5, 6].

In the aftermath of the disaster, many coastal cities were identified as critically damaged areas by the high-magnitude sea waves. Galle City became one of the most devastated cities because of its topology, urban landscape, and neighborhood development strategies [7, 8], and created a challenging experience for the community in the Galle coastal line. Consequently, this chapter extends a multidisciplinary approach integrated with economy, sociology, and Tsunami-related studies that comprehensively elucidate the relationships between Tsunami devastations and socio-economic vulnerabilities. As per [9, 10], economic disparities, social stratifications, and respective authorization malfunctions influenced the Galle coastal community to become more vulnerable to the Tsunami disaster. Thus, this chapter explores an all-inclusive perspective, with factors such as inequality, housing, poverty, social networks, and resource accessibility that influence the socio-economic vulnerability of Tsunami devastations based on the case of Galle City in the 2004 Tsunami event. Moreover, it emphasizes the effectiveness of post-Tsunami vulnerability from the socio-economic perspective while highlighting the governmental procedures, international initiatives, and community involvement with associated challenges of building back with better disaster resilience.

2. Socio-economic context of Galle City, Sri Lanka

Before the devastation occurred in 2004, Galle City was identified as a great historical city in Sri Lanka, which showed a diversified socio-economic landscape with its unique topological and cultural setting [11]. Sinhalese mainly inhabited Galle with minorities like Tamil and Muslim. Consequently, the city was identified as a melting pot, where the society consists of diversified ethnic, cultural, and racial groups. With a cohesive and unified community, the demographic mix of Galle City has been attractive and bustling over the past centuries (**Table 1**) [12].

From an economic perspective, the coastal belt of Galle City is one of the cornerstones of the Sri Lankan economy with fishing activities and tourism [13]. Before the Tsunami incident in 2004, the fishing industry was among the best sources of employment opportunities in Galle City, and it was expanded to include numerous supporting businesses and earning sources. According to Ref. [14], the population in agriculture and fisheries was 93,565, and the non-agriculture and non-fisheries were 225,115. Besides, tourism in Galle before 2004 was extremely prodigious due to the thriving tourist destinations in Galle City, such as the historic Galle Fort, a UNESCO World Heritage Site, which had colonial architectural features and rich cultural heritage [15]. The easily accessible roads supported this *via* the picturesque coastal railway from Colombo to Matara, making it a convenient and scenic destination for locals and foreign travelers.

Besides, the city's trade and commercial industry bloomed before 2004 due to the Galle port, with the local and international trade facilities supporting the Sri Lankan economy [16]. The critical infrastructure in Galle City, before 2004, was well maintained with its values due to its historical and touristic significance, especially the areas around

	2001	2021 E
Population	990,487	1,147,000
Sector		2012 C
Urban	109,921	133,398
Rural	863,308	911,159
Ethnicity		
Sinhalese	934,751	1,003,722
Tamil	20,354	20,099
Sri Lanka Moor	34,688	38,790
Other (Burgher, Malay, etc.)	694	723

Source: Department of Census and Statistics 2021.

Table 1.
Demographic profile in Galle City 2001–2021.

the Galle Fort. Consequently, the neighborhoods were also developed simultaneously, but with some inadequacy of transportation, housing, and sanitation facilities [17].

From an educational perspective, Galle City comprises several educational institutes, including schools, colleges, and universities, that provide a better-quality education regardless of income inequality. Before 2004, quality education was centralized in the city center with slight dissemination toward the peripheral areas like Hapugala. This was considered the foundation for developing the smart growth corridors in Galle City in order to equalize the city with disaster resilience features [18].

Socially, the community of Galle City had a strong bond even with several inequalities in socio-economic perspectives due to uneven wealth distribution [19]. Ref. [20] argued that traditional occupations in the Galle coastal area, such as fishing and small-scale trades, were the most common factors, enhancing the susceptibility to economic vulnerability. Moreover, the rich blend of colonial and Indigenous features in Galle City provided a vibrant, religious, traditional, and socially cohesive environment [16]. However, the city's dependence on susceptible economic sectors and existing poverty levels highlighted its vulnerability to the impacts of natural disasters, such as the 2004 Tsunami.

3. Socio-economic vulnerability exposed by tsunami

Socio-economic vulnerability refers to the economic and social exposure of communities, households, or individuals to the negative impacts of Tsunami disasters [21]. Often, these vulnerabilities occur as a combination of these factors, and it weakens the ability of said parties to recover from the hostile disaster conditions.

Since Galle is a city with a diverse socio-economic landscape [22, 23] relying on tourism and fishing industries, numerous factors could increase the socio-economic vulnerability in Tsunami disasters. Accordingly, socio-economic vulnerability can result from several factors, such as economic, social, demographic, geographical, institutional, governance, community, and cultural factors, as shown in **Figure 1**.

Economic Factors—Due to the low-income levels of many residents in Galle, who engage in fishing and tourism industries, these income groups are at a limited

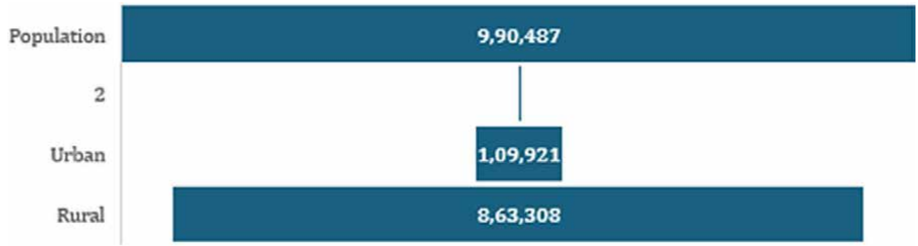

Figure 1.
Urban–rural population in Galle—2001 (Before Tsunami, 2004). Source: Created by the authors.

financial level to recover from disaster situations such as Tsunamis, which is highly vulnerable to property damages in the coastal belt of Galle City [24]. Besides, these employment groups severely impact their industries in disaster situations, and it can lead to a long-term economic downturn due to critical infrastructure failures in such calamities [25].

Social Factors—Residents in Galle coastal cities are mostly settled in poorly constructed or informal houses due to their lower income level and limitations in housing affordability [26, 27]. Consequently, these houses are highly vulnerable to Tsunami waves as they have not maintained the buffer zone requirements that local authorities have declared [13]. Further, the lack of resilient housing construction increases the risk of life and property losses and the impact of terrible debris (**Figures 2** and **3**).

Besides, limited and inadequate access to quality education and healthcare also distracts the Tsunami recovery process since the available healthcare institutes and schools are not adequately equipped to face emergencies, impairing the impacts of a Tsunami [28].

Demographic factors—As per the demography in Galle City during past census data, the city's female population is greater than the male population, and the elderly and child population is also considerably high [14]. This reflects that community groups are at great risk in Tsunami events as their specific needs and disabilities complicate the emergency evacuation and recovery process during and after Tsunami events [29]. Further, [30, 31] have stressed that the gender factor may have an additional impact on Tsunami disaster vulnerability due to gender-based roles in the community, which distract their minds from emergencies and warnings.

Geographical and environmental factors—Due to the topology of Galle, the city is highly prone to Tsunamis [16, 32]. In the narrow space between Galle Fort and the

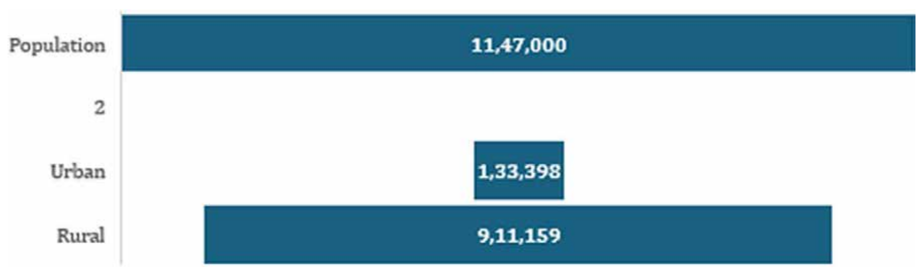

Figure 2.
Urban–rural population in Galle—2012 (After Tsunami, 2004). Source: Created by the authors.

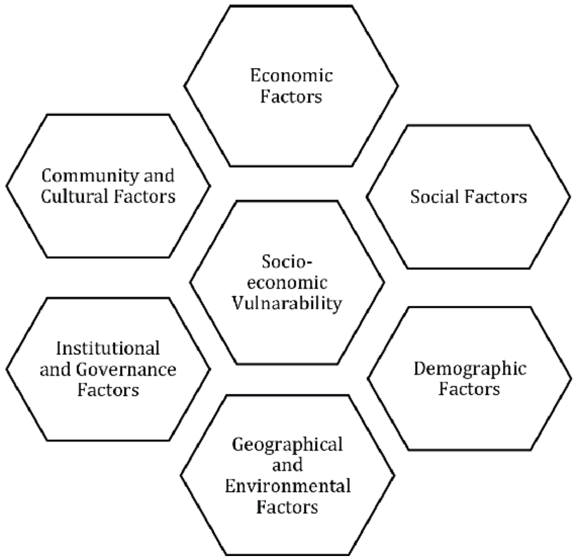

Figure 3.
Factors for socio-economic vulnerability. Source: Created by the authors.

Rumassala mountain, sea waves get more energized and forcefully enter the landside, where severe damages occurred during the Tsunami in 2004 [32]. Accordingly, the proximity of the city to the sea reflects that the impact of Tsunami disasters can be abrupt and devastating.

Besides, as stressed by [33], climate change impacts like rising sea levels and weather pattern changes increase Tsunami exposure by raising the vulnerability of the coastal community in Galle.

4. Short-term and long-term socio-economic impacts of the tsunami in Galle City

4.1 Short-term socio-economic impacts

Life losses and casualties—With the disaster that occurred in 2004, Galle City was victimized by vast damage along with other cities like Matara, Ampara, and Hambantota. Accordingly, over 4000 losses of human lives were reported in Galle City during the devastation [34].

Infrastructure damages—During the event, 3680 houses, three schools, including CWW Kannangara Collage, several roads, bridges, and maternity hospital in Mahamodara and Sambodhi homes for Children with special needs were damaged, causing extensive damage to the infrastructure in Galle City [35, 36]. Consequently, economic activities, supply chains, and essential services were disrupted, displacing thousands of communities and restricting access to healthcare services in Galle City.

Economic disruption—Over 70% of the fishing points were devasted [37], and nearly 80% of the tourism income dropped during the 2004 Tsunami event in Galle [36, 38]. This resulted in extensive unemployment and business failures due to the infrastructure losses in the affected area.

Further, this devastation of properties and infrastructure caused unexpected financial instability in 2005, necessitating a considerable investment in disaster recovery to regain the aftermath.

Displacement—During the disaster in 2004, over 100,000 people in Galle shifted to temporary shelters because of the displacement and socio-economic instability. This highlighted the necessity of humanitarian aid and rehabilitation exertions to speed up the recovery process and address the affected community requirements during the aftermath [39].

Healthcare services and sanitation—With over 70% sanitary facility damages and potable water contaminations, waterborne diseases increased by 30% over the Galle area, such as dysentery and cholera [38]. This led to the urgent need for sanitation interventions with medical and potable water supplies to prevent further medical snags.

Emotional distress or psychological trauma—Victimizing around 50% of the Galle City population in 2004, the Tsunami created extensive psychological trauma in the area. During the post-Tsunami research, survivors were identified with high Post-Traumatic Stress Disorder (PTSD) levels, depression, and anxiety due to the loss of properties and their loved ones [40, 41]. This clearly exposed the vulnerability of the socio-economic landscapes in Galle, causing the necessity of psychological interventions in the Tsunami aftermath to emerge [42].

4.2 Long-term socio-economic impacts

Reconstruction and recovery—In the recovery process of the Galle City after the Tsunami disaster in 2004, an extensive reconstruction and rehabilitation effort was there with the property loss, including houses, schools, and hospitals [43]. Consequently, allocating over $ 2 billion, the local government established rehabilitation programs to restore livelihood in the affected areas with the concept of build-back-better [36].

Economic recovery—Key sectors in Galle City, like tourism and fishing industries, revived with international funds and aid received after the Tsunami devastation in 2004 [44]. Consequently, by 2010, the tourism industry recovered along with a few other related sectors, decreasing the unemployment rate in the Galle municipal area. Funds and incentives for small business developments and infrastructure projects greatly supported the restoration of economic stability, highlighting the adaptability, resilience, and revitalization of the community in Galle [36].

Social transformation—Due to the calamity in 2004, Galle City underwent a substantial social transformation by reforming the social structure [16]. As discussed above, the displaced community in Galle created new communities by dispersing over the safe settlements [45]. Losing family breadwinners shifted household roles, and the devastation affected the family structures badly [46]. As a result, numerous social assistance networks emerged to improve resilience, disaster preparedness, unity, and cooperation in community groups.

Environmental impact—Coastal erosion and the obliteration of more than 50% of coral reefs and mangroves are the most crucial ecological impacts due to the 2004 Tsunami's long-term environmental impact [47–49]. As a result, the local fishing industry was interrupted, affecting thousands of coastal livelihoods in Galle City. Moreover, polluted water and contaminated soil disrupted the city's agricultural activities, hindering community income and food security [50]. This highlighted the necessity of adaptation and recovery measures to improve the city's resilience, restoring ecosystems and environmental damages.

Strategic preparedness—Most notably, after the Tsunami devastation in 2004, several strategies were implemented to address Galle's disaster preparedness. Consequently, regulations and guidelines declared by the National Housing Development Authority (NHDA), National Building Research Organization (NBRO), Society of Structural Engineers Sri Lanka (SSESL), and Urban Development Authority (UDA) were strongly implemented to strengthen the built environment in the coastal belt, Galle. Early warning systems, emergency response protocols, and comprehensive disaster management plans enhanced the strategic preparedness of the Galle City against Tsunami disasters. Accordingly, [51] has stressed that over 70% of the coastal population was trained in disaster preparedness and emergency response.

Migration and relocation—Due to displacement during the 2004 Tsunami event, thousands of coastal residents were relocated to urban areas and resettlement campsites [52]. Consequently, rapid urbanization and changes in demographic patterns occurred, creating a long-term impact on coastal community structures. Further, housing projects, infrastructure developments, and employment opportunities were introduced to settle the affected community in a new community area along with the relocation [53].

Education—With the damage to the schools in highly susceptible and low susceptible areas in Galle, over 10,000 students get distracted from their education [35]. Most of those devasted schools were restored by 2010, and a new educational system was introduced to enhance disaster resilience by addressing trauma in disaster situations [54]. Moreover, the education system was modified with several changes related to psychological well-being and livelihood upgrades in emergencies [55, 56].

Cultural heritage—One of the worst damages to Galle was the city's cultural heritage damage [8, 57]. This destruction affected the city's historical and cultural landmarks and significantly impacted its socio-economic factors and the overall economy [57].

5. Strategies implemented to eliminate the socio-economic vulnerability in Galle City

With the catastrophe in 2004, the necessity of implementing a strategic plan is highlighted, intending to eliminate socio-economic vulnerability while enhancing the city's resilience. Accordingly, the implemented strategies addressed numerous dimensions of resilience, including infrastructure resilience, coastal management, early warning systems, community preparedness, and regulatory frameworks.

5.1 Early warning systems

Implementing an Early warning system (EWS) is one of the most effective strategies to reduce socio-economic vulnerability to Tsunami disasters [20, 58]. Since EWS is integrated with real-time data analysis on seismic sensors and ocean buoys [59], it provides direct and accurate warnings of potential Tsunamis, permitting residents of Galle City to emergency evacuation, reducing the risk of fatalities and property damage. Early warnings can be dispersed *via* sirens, televisions, radios, and mobile alerts to evacuate vulnerable areas quickly before the devastation [60]. Moreover, Tsunami drills, educational programs, and public awareness campaigns increase community preparedness [61, 62]. Thus, EWS reduces fatalities and property damages during subsequent Tsunami events by enhancing economic stability [57, 63]. To ensure the effectiveness and sustainability of ESW, continuous maintenance and community involvement are of utmost importance in disaster resilience.

5.2 Infrastructure development

Infrastructure development reduces the socio-economic vulnerability [64, 65] to Tsunamis in Galle City with resilient structures and the built environment. Infrastructures, like coastal defenses, elevated buildings, and resilient material integrations, are some critical infrastructure developments related to Tsunami resilience [66, 67]. Accordingly, more than 3000 houses, three schools, and a few major hospitals were redeveloped with the integration of tsunami-resilient standards and ensured the future resilience of Tsunamis to reduce interruptions in critical infrastructure services [68, 69]. Besides, regulations and construction guidelines advancements prevent construction in highly vulnerable areas, providing lives and property security while strengthening recovery capabilities and economic stability [70].

5.3 Training and community preparedness

In order to make vulnerable communities aware of evacuation procedures and safety rules and regulations in case of emergencies, periodic emergency drills, educational programs, and community awareness campaigns are some of the significant strategic approaches [62, 71, 72]. These approaches effectively enhance the cultural and emotional preparedness of the vulnerable community, ensuring their safety and evacuation in case of Tsunamis [73].

5.4 Coastal management

Implementing sustainable disaster management practices and re-establishing natural coastal barriers like coastal vegetation intend to minimize the socio-economic vulnerability in Tsunamis [74, 75]. Moreover, natural defenses like the restoration of coral reefs and reforestation of mangroves reduce the Tsunami wave energy and force, eliminating coastal erosion. These holistic approaches protect the local fisheries from sea waves while protecting shorelines and properties [76, 77]. Besides, buffer zone requirements and land use development-related regulations protect vulnerable areas from construction and developments in Galle City [78–80]. Further, it enhances economic stability, ecological balance, and community resilience in Tsunami disasters.

5.5 Regulatory requirements

With the aftermath of the Tsunami in 2004, the local government has implemented a comprehensive zoning plan to prevent construction in high-risk or highly vulnerable areas in Galle City [53]. Disaster management plans focusing on risk reduction, preparedness, response, and recovery have been established and often updated following the timely advancements. To ensure the effectiveness and compliance of these management plans, local authorities, community organizations, and international agencies coordinate with each other with a thorough organization [81]. Consequently, these regulatory updates and implementations improve long-term disaster resilience, focusing on a proactive approach to Tsunami disaster management with community safety and sustainable development practices.

5.6 Economic restoration

Micro-loans and financial support are provided for the affected community to rebuild businesses and ensure economic stability. Moreover, to regain the workforce's capabilities and re-enter the industry, the relevant agencies provided new skills and vocational training while restoring the economic stability of Galle City. Besides, incentives were provided for the critical economic sectors in Galle City, such as fisheries and tourism, to revive the city's economy and livelihood [82].

5.7 Community support networks

Since psychological trauma is one of the significant issues shown by the survivors after the 2004 Tsunami disaster due to fatalities and property losses, the necessity of psychosocial counseling emerged [83, 84]. Community centers and other funding groups are incorporated with the community support networks to back this. Furthermore, social welfare programs provide financial help and fundamental requirements to improve community resilience and enhance social cohesion [85]. Accordingly, community support networks play a vital role in long-term disaster recovery and stability by attending to the practical and emotional requirements of the residents in Galle City.

5.8 Environmental preservation

As a critical socio-economic vulnerability reduction strategy, environmental conservation includes waste management, ecotourism, coral reef restoration, and mangrove reforestation, which can be identified as essential natural barriers in Tsunami events. These are mainly for shoreline protection and fishing industry support while promoting ecological balance with sustainable land use patterns and environmental regulation practices [86]. Accordingly, this holistic approach enhances the resilience of the Tsunami in Galle City from all ecological, social, and economic perspectives.

6. Recommendations for the potential improvements of socio-economic vulnerability in Galle City

While focusing on the socio-economic vulnerability in Tsunami devastations, this study highlighted numerous strategic approaches and measures undertaken to minimize future vulnerabilities in Galle City, Sri Lanka. In order to make it more advanced in the future, several potential improvements can be integrated into those mentioned above holistic approaches while enhancing the capabilities of socio-economic resilience. Consequently, advanced technologies with global trends can be incorporated into resilient strategies to improve the consistency and accuracy of early warning systems (EWS), such as machine learning and artificial intelligence developments [87]. Since it comprises, real-time seismic data analyzing capabilities, EWS's predictive capacities can be enhanced. Moreover, as per [88, 89], mobile warning systems can be developed and improved by integrating locally available telecommunication networks while accessing remote and underserved areas to make them more dispersed. To achieve this, network coverage is a significant factor to enhance and upgrade during and after the disaster event.

Green infrastructure developments and advancements like permeable surfaces, rain gardens, and green roofs are critical in stormwater management and urban flood mitigation practices [90, 91]. Under the Development Plan for Greater Galle Area 2019–2030, this objective has been covered by integrating coastal vegetation and urban park developments over the greater Galle area.

Promoting social housing or affordable housing projects with resilient features alongside the residential promotion zones in Hapugala, Uluwitike, and Attiligoda will be more beneficial for the communities in Galle City with low income and high vulnerability. Further, as suggested by [71], these vulnerability groups must be regularly updated and trained with evacuation procedures, safety protocols, and critical disaster preparedness practices hosted by local authorities and relevant international agencies to enhance socio-economic resilience.

Implementing coastal vegetation projects, including mangrove reforestation and coral reef restoration, fosters the natural defense along the coastal belt of Galle City, enhancing the industrial stability and the social cohesion of the vulnerable community groups and built environment. Moreover, introducing alternatives for fishing and tourism income sources is paramount to reducing dependency on high-risk economic industries and enhancing diversification and financial stability. Under this recommendation, a challenge can be raised related to the Tsunami-resilient guidelines in Sri Lanka declared by the local authorities and agencies, as these are a few separate guidelines available for the Tsunami-resilient constructions in the coastal belt. Accordingly, implementing a consolidated guideline with an effective disaster management plan is of utmost importance.

Most importantly, counseling projects and hotline healthcare systems can be initiated to address the psychosocial impact of the aftermath of the Tsunami, enhancing the community's well-being. Further, social cohesion and community networks can be fostered through social activities to strengthen unity during recovery.

Finally, enhancing the urban waste management system to reduce pollution in the Galle coastal belt through recycling programs and advanced waste disposal methods is essential for environmental health. Consequently, promoting ecotourism as a sustainable livelihood option will help preserve the environment and provide educational opportunities through guided nature tours and visits.

7. Conclusions

The study highlights the socio-economic vulnerabilities of the community and the built environment caused by the 2004 Tsunami in Galle City, Sri Lanka, with critical structural failures of socio-economic features. Consequently, to minimize these failures in future disaster events, holistic approaches and preparedness measures have been undertaken to a certain extent, enhancing the city's comprehensive disaster resilience plan. Furthermore, environmental conservation attempts like coral reef restoration and mangrove reforestation significantly support coastal protection in urban planning and social cohesion.

To further expand resilience, it is crucial to incorporate advanced technologies like machine learning and artificial intelligence into early warning systems, enhance urban waste management to reduce pollution, and encourage ecotourism as a sustainable livelihood. Moreover, developing community support networks and providing psychosocial counseling can mitigate such disasters' long-term psychological impact.

In summary, the holistic approaches highlighted in this study, encompassing socio-economic perspectives, specify a vigorous framework for advancing the Tsunami resilience of Galle City. Consequently, by investing in and refining these strategic approaches, Galle can better prepare for future Tssunami events, ensuring a more resilient and sustainable community.

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Section 3

Disaster Recovery and Survivor Agency

Chapter 7

Survivor Agency: Reflections on Post-Idai Recovery and Reconstruction Processes in Chimanimani District, Zimbabwe

Denboy Kudejira

Abstract

This chapter examines the dynamics of collaboration, conflict, and contestation that arise when external humanitarian agencies, including the state, international organizations, and NGOs, become involved in the daily lives of disaster survivors. It focuses on the aftermath of the March 2019 Tropical Cyclone Idai disaster in the Chimanimani district of Zimbabwe, drawing on concepts of survivor agency and moral economy to explore the sociocultural aspects of the recovery and reconstruction processes. The chapter highlights the limitations of viewing survivors merely as "disaster victims" or "beneficiaries" of aid, showing how this reductionist perspective undermines survivor agency. It also reveals how this perspective was contested in the post-Idai response. The diminished agency of survivors, exacerbated by unequal access to disaster relief, led to individualized grievances, resentment, noncompliance among some survivors, and opportunism among others. These individual responses hindered collective mobilization and the ability to challenge the actions of humanitarian agencies perceived as not aligning with local interpretations of the disaster. The chapter concludes that an effective long-term disaster response requires a holistic approach. This approach should address the underlying vulnerabilities that make communities susceptible to disasters and incorporate local meaning-making systems, rather than imposing interventions based on superficial assumptions and political interests.

Keywords: survivor agency, cyclone Idai, Chimanimani, disasters, moral economy

1. Introduction

This chapter employs the concept of survivor agency to explore the sociocultural aspects of post-Idai recovery and reconstruction processes in the Chimanimani district of Zimbabwe. Tropical Cyclone Idai, recorded as the deadliest weather-related in the modern history of Southern Africa, struck the region in March 2019, impacting at least 2.9 million people in Mozambique, Zimbabwe, and Malawi, and resulting in economic losses of more than $2 billion [1, 2]. In Zimbabwe, the storm severely affected the Eastern parts of the country, affecting more than 270,000 people, with 17,608 households left homeless. The storm resulted in over 340 fatalities, with at least 344 individuals reported missing, and caused an estimated economic loss in Zimbabwe ranging between $548 million and $622 million [3].

Following the devastating Tropical Cyclone, the president of Zimbabwe, His Excellency E. D. Mnangagwa, declared a state of disaster, which spurred immediate mobilization by external responders to aid the survivors. This declaration triggered an influx of United Nations (UN) agencies, international and national nongovernmental organizations (NGOs), churches, and the private sector, all working in collaboration with the state to provide emergency relief and implement postdisaster recovery and reconstruction initiatives. A survey by the UN Office for the Coordination of Humanitarian Affairs (UN OCHA) indicated that as of June 2019, at least 8 UN agencies, 53 NGOs, and 1 Red Cross Movement were operational in the affected districts. These agencies addressed various socioeconomic sectors impacted by the cyclone, including shelter, food security, health, education, child protection, nutrition, and water, sanitation, and hygiene (WASH). For instance, NGOs such as World Vision International, CARE International, and Plan International collaborated with the United Nations International Children's Emergency Fund (UNICEF) and the Ministry of Primary and Secondary Education in Zimbabwe to support education and child protection. Similarly, the Department of Social Development partnered with UN agencies and NGOs like the United Nations High Commissioner for Refugees (UNHCR), the International Organization for Migration (IOM), GOAL, Trocaire, Family AIDS Caring Trust (FACT), and Médecins Sans Frontières (MSF) to address shelter issues [4].

While media stories, institutional reports, and academic publications extensively document the relief, recovery, and reconstruction efforts following the Tropical Cyclone Idai disaster, a notable gap remains in understanding how the assumptions and theories guiding external agencies in designing and delivering disaster aid interventions in Chimanimani shaped the post-Idai landscape. Moreover, there is insufficient insight into the contestations and contradictions that emerged as these agencies interacted with survivors while delivering humanitarian assistance. This chapter aims to address these gaps by examining how the disaster response programs of external agencies influenced the survivors' capacity to exercise agency.

1.1 The concept of survivor agency

Human agency, defined as individuals' capacity to act independently and make autonomous decisions, plays a critical role in how individuals, households, and communities confront environmental challenges [5, 6]. Brown and Westaway [6] argue that individuals' capacity to act independently is shaped by the cognitive frameworks developed through their experiences, societal perceptions, and the environmental contexts they encounter. These societal perceptions and forms of action significantly influence the disaster responses and recovery strategies implemented by external agencies [5]. For Jerolleman [7], survivor agency entails individuals' ability to engage in public spheres and take effective actions to mitigate future risks. Jerolleman also emphasizes the significance of collective solidarity and mutual support among survivors as crucial expressions of agency during disasters. This perspective is echoed by the argument that fostering local agency enhances a resilient framework that is collective, enduring, and sustainable [6]. However, Jerolleman expresses concerns regarding disaster response policies and programs, which she believes can diminish survivor agency. She argues that inequitable access to resources and programs can erode solidarity and mutual support among survivors, fostering an environment where families compete rather than collaborate toward sustainable recovery.

Applying the concept of human agency in disaster response is therefore crucial as it challenges the perspective of portraying affected communities solely as passive victims of disasters. Instead, it acknowledges that survivors actively engage in emergency relief, recovery, and reconstruction efforts. Essentially, this approach challenges the perception of communities as merely disempowered and helpless, reliant solely on external humanitarian aid or state intervention for their survival. Instead, it recognizes them as political agents capable of influencing the course of postdisaster response [8].

To further explore the concept of survivor agency, particularly focusing on the interaction between survivors and service providers in the aftermath of Tropical Cyclone Idai, this chapter also draws on the notion of moral economy [9].

1.2 The concept of moral economy

Thompson defines moral economy as encompassing "the cultural values, attitudes, norms, and obligations agreed upon through popular consensus, which society legitimizes as the appropriate roles of individual parties within the community" [9]. He applied this concept to interpret the uprisings and food protests in eighteenth-century England, attributing these events to the deviation of millers, merchants, and financiers from society's moral expectations of fair practices. Despite the historical and geographical distance of Thompson's work, the concept of moral economy remains highly relevant, particularly in contemporary disaster studies. In her publication "A House of One's Own: The Moral Economy of Post-Disaster Aid in El Salvador," anthropologist Sliwinski utilizes the concept of moral economy to examine the power dynamics, humanitarian practices, and ethical issues that emerged from NGO interventions following the January 2001 earthquake in El Salvador [10]. Sliwinski investigates the lived experiences of 50 disaster-stricken families who interacted with humanitarian aid agencies in Lamaria after this catastrophic event. By exploring the gestures and actions of various stakeholders involved in recovery and reconstruction efforts, Sliwinski identifies the coexistence of diverse moral economies within disaster response contexts. Maldonado similarly observes that multiple moral economies operate within the cultural frameworks of disaster recovery, often reflecting unintended biases such as racism, classism, sexism, and ethnocentrism. She critiques the reconstruction planning post-Hurricane Katrina on the US Gulf Coast, noting that although it was lauded as participatory, residents lacked substantial decision-making power [11].

The concept of moral economy, thus, provides a framework for understanding the ethical dimensions, power dynamics, and cultural norms that influence interactions between survivors and humanitarian actors in post-Idai Chimanimani. It sheds light on how disaster survivors perceive and respond to aid interventions according to their cultural expectations and moral perspectives. Additionally, moral economy evaluates the legitimacy and appropriateness of actions taken by external agencies, examining how well these actions align with local norms and values. Ultimately, moral economy enhances the study of survivor agency within disaster contexts by facilitating analysis of the ethical aspects of aid delivery, the dynamics of power negotiation, and the resilience strategies employed by affected communities. It emphasizes the significance of honoring local cultures, values, and aspirations to foster genuine empowerment and sustainable recovery postdisaster.

The remainder of the chapter is structured as follows: Firstly, it provides a concise overview of the methods used to collect data for developing the overall argument. Secondly, it presents the findings of the research, teasing out the cooperations, conflicts, and contradictions that emerged as survivors became entangled in the disaster recovery and reconstruction projects of state and NGO agencies. This includes examining the construction and attribution of identities to survivors and how some individuals embraced these identities while others contested them. The chapter also explores how the simplistic portrayal of survivors solely as victims of disaster or passive beneficiaries of aid was challenged in post-Idai response processes in Chimanimani. Further, my interest in exploring survivor agency was sparked by the sentiments I frequently heard while interacting with survivors. Statements such as "*Anoshanda ku Idai* (they work at Idai)," referring to people working at a government and UN agency-established housing site for flood-displaced individuals; "*Akapfeka hembe dze Idai* (they are wearing Idai clothes)," referring to clothes donated by humanitarian agencies; and "*Tiri vanhu ve Idai* (we are the people of Idai)," often expressed by survivors in displacement camps who seemed to feel entitled to disaster aid, resonated with me. From these sentiments, I employed the concept of "survivor agency" to understand the various moral economies that emerged as different socioeconomic classes of survivors interacted in the aftermath of Tropical Cyclone Idai and as they engaged with providers of humanitarian assistance. The chapter concludes with a summary of key discoveries and their implications.

2. Data collection methods

This chapter is part of a larger PhD project titled "Disaster Authoritarianism: An Ethnography of State and NGO Responses in the Aftermath of Tropical Cyclone Idai in Chimanimani District, Zimbabwe." The project investigates the collaboration and contestation between the state, NGOs, and survivors following the Tropical Cyclone Idai disaster [12]. From November 2020 to December 2022, multiple ethnographic strategies were employed to gather data. I assumed the role of a volunteer program adviser for a local NGO implementing rural development initiatives in the Chimanimani district. I interacted daily with personnel at various organizational levels, including ground-level employees, middle managers, and senior executives. I conducted semistructured and informal interviews with the NGO's employees and actively participated in its recovery and reconstruction activities, as well as those implemented by other district-level stakeholders. Additionally, I carried out in-depth semistructured interviews with leaders of other NGOs and state agencies involved in disaster response initiatives, traditional authorities, and survivors of the tropical cyclone. Throughout the entire fieldwork period, I stayed with a host family that had survived the tropical cyclone. The fieldwork experience offered invaluable insights into the inner workings of NGOs and state agencies and the daily dynamics that shaped their interactions with survivors. These insights are discussed in greater detail in the following sections.

3. Local perspectives on the causes and impact of tropical cyclone Idai

Local understanding of the causes and destructive impact of Tropical Cyclone Idai in Chimanimani can be encapsulated by a statement from Jane, my fieldwork host, during my first visit to her house: "We don't know what actually happened." This sentiment was echoed by nearly everyone who witnessed and responded to the disaster, including local community members, traditional leaders, state officials, and employees of NGOs. It suggests that Tropical Cyclone Idai was not merely a hydro-meteorological event, but that its causes and destructive impacts are located within cultural, religious, and social systems of meaning-making as demonstrated below.

3.1 Tropical cyclone Idai disaster as a curse against inappropriate behaviors

Traditional leaders attributed the causes of the tropical disaster to the water spirits *(njuzu)* and the spirits of the land (*marombo enyika*). Drawing a parallel to the biblical destruction of Sodom and Gomorrah, a chief I interviewed during fieldwork believed that the *marombo enyika* were angered by the community's wrongdoings and thus caused the disaster. In African traditional cosmology, land is considered the property of the ancestors, with traditional leaders acting as custodians [13]. Consequently, certain areas are designated as sacred, prohibiting activities such as cutting down trees, burning, settlement, and cultivation. These areas include grave sites of dominant lineages and groves where the ancestors of these lineages are contacted [14]. Though physically deceased, the spirits of the ancestors are believed to be highly active and involved in the lives of their descendants. Through regular communication with these ancestors, traditional leaders ensure that their territories remain well-nourished and protected, as neglecting them is thought to invite curses or misfortunes [15, 16]. The traditional leaders firmly believed that as the tropical cyclone disaster was caused by angry spirits, post-Idai responses needed to consider this spiritual context. These beliefs significantly influenced how they interacted with survivors and humanitarian agencies, including the state and NGOs, in the aftermath of the cyclone.

For instance, on one occasion, I witnessed a chief invoking the tropical cyclone disaster as a basis for reprimanding bad behavior. This occurred at a beer hall when a brawl broke out between two young men, and the chief, disapproving of their behavior, shouted, "Hey, stop that! *Ndizvo zvinotideedzera ma cyclone izvi* (this is the kind of behaviour that invites cyclones)." For the chief, phenomena like the tropical cyclone disaster resulted from actions and attitudes that were unacceptable within the local culture, such as public fighting. Similarly, another chief expressed anger that the president authorized and sent search and rescue teams without first allowing traditional leaders to perform rituals. This oversight, according to the chief, further angered the ancestors who in turn hid the bodies of more than 300 people (those recorded as missing). As a result, traditional leaders fined the president for the state's failure to handle the emergency response in a way that appeased the spirits. For the traditional authorities, the disaster was not only about the deaths and destruction in Chimanimani but also carried deep cultural meanings. They viewed it as a manifestation of social and cultural disequilibrium, a punishment for deviating from the cultural and traditional norms and values of the local people.

Many survivors I interacted with shared a similar perspective. Across all social groups, a common narrative attributed the disaster to members of a local Christian religious sect, the Johanne Masowe, who were perceived as undermining the authority of the ancestors. The Johanne Masowe church is one of the early African-initiated churches that emerged during the African decolonization movement. Named after its founder, Shonhiwa Masedza, who adopted the name Johanne Masowe in 1931 and declared himself "John the Baptist of Africa," the church emphasizes prophecy over scripture reading [17]. Since its inception, this form of African Traditional Christianity has grown across Southern Africa. Followers of Johanne Masowe, locally known as "*mapositori*," are recognizable by their white robes and prefer open spaces for worship, often conducting rituals in mountains and other secluded areas to cleanse and ward off evil spirits. However, they were accused by locals of establishing shrines in sacred mountains traditionally used for cultural rituals [17], which allegedly angered the spirits, who are believed to have subsequently caused the cyclone to occur.

Other survivors attributed the disaster to the anger of the *njuzu* over the degradation of their "homes," the water bodies. In recent years, particularly in the communal areas heavily impacted by the tropical cyclone, Chimanimani has experienced a rise in alluvial gold panning along major water channels like the Rusitu and Nyahode rivers. Panners search for the valuable metal by digging into riverbanks, resulting in significant pollution and siltation of these water bodies. According to survivors, the *njuzu* were angered by the destruction of their habitats, leading them to summon Tropical Cyclone Idai as a destructive force. It is believed that the cyclone swept away those who were caught panning on the day the *njuzu* unleashed their wrath.

3.2 *"Kurarama inyasha"*—Tropical cyclone Idai was God's plan

However, other survivors interpreted Tropical Cyclone Idai differently, yet still within a spiritual context, seeing its devastation as inevitable and part of God's plan. They believed that only God knew the reasons for its occurrence and that through prayer, similar disasters could be prevented in the future. These beliefs underscore the profound influence of Christian values on African society and how they have shaped attitudes toward nature and disasters. While traditional leaders are expected to uphold and advance African culture and tradition, the growing influence of Christian values is gradually eroding these responsibilities. Many now perceive cultural rituals and traditional ceremonies as unnecessary. As Mabvurira et al. contend, African traditional religion endured alongside other faiths but experienced a significant decline in membership and relevance due to the spread of Christianity during the colonial period [17]. An interesting explanation that I gathered from at least three sources of how "God planned" the disaster is that he caused the tropical cyclone to make landfall in the middle of the night so that people could not see what was happening. This assertion was narrated by one participant as follows:

> *We thank God that He brought the cyclone during the night when our eyes could not see. We did not see how the destruction happened. We did not see how these huge boulders ended up here and how our neighbours drowned. If that had happened during the day, we were going to live with those visions for the rest of our lives.*

This narrative is further corroborated by a local musician who narrowly survived the disaster and subsequently released a track recounting his survival. In the song titled "*Kurarama Inyasha*" ("Survival is by Grace"), he describes how he narrowly escaped death on the night of the tropical cyclone by climbing a fig tree with four neighbors, where they spent over 12 hours before being rescued by others the next day. Some of the song's lyrics are as follows (**Table 1**):

Kurarama inyasha ndazviona	Survival is by grace I have seen it ...
Zvichida chaiva chinangwa chaMwari	Maybe it was God's plan ...
Ndivo vanopa, ndivo vanotora	He is the giver, and He is the taker ...
Zvichida mucherechedzo wenguva yaNoah	Maybe it was a reminder of Noah's time ...
Zvichida imviro-mviro yemagumo	Maybe these are signs of the end times ...
Kurarama inyasha ndazviona	Survival is by grace I have seen it ...
Ini pachangu ndorumbidza Mwari	I praise the Lord myself ...
Ndakapona nenyasha kwete kungwara	I survived by grace and not because I am clever...
Hama woye, tokutendai nerubatsiro rwenyu	Relatives, we thank you for the assistance

Table 1.
Kurarama inyasha*: Reminiscing tropical cyclone idai through song.*

Through his song, which now includes a video posted on YouTube, the singer praises God for his survival and acknowledges the crucial role played by the survivors in assisting each other, particularly during the emergency and early recovery stages. Thus, beyond interpreting the disaster through supernatural lenses—whether cultural or religious—the song highlights how local support systems were activated, mobilized, and utilized during the crisis. As elaborated further in the rest of this chapter, the agency expressed by the survivors as first responders influenced their interactions with state agencies and NGOs, who later came in with humanitarian support.

3.3 Impact of tropical cyclone Idai and the effectiveness of local support systems

Despite the subsequent support from external agencies, particularly state agencies, and NGOs, interviews with survivors highlighted the critical role of local support systems in responding to emergencies. Many families in Chimanimani were left homeless as their houses were swept away, while others lost essential supplies such as food and clothing. These families found refuge with neighbors and friends. I visited a family whose home had been swept away and who are now residing in a temporary shelter camp. This camp was one of four established through a partnership between the state, UN agencies such as the IOM, the United Nations Office for Project Services (UNOPS), the World Food Programme (WFP), and UNICEF, as well as international NGOs like CARE, CAFOD, and World Vision International. Collectively, the four camps housed a total of 224 displaced households (746 individuals) [18].

Tragically, the family that I visited also lost two children to the cyclone. Before relocating to the shelter camp, they had been hosted by a neighbor for five days, nursing injuries sustained during the flooding, while community members assisted in recovering the bodies of their drowned children. Another family that I visited mentioned sheltering and feeding about fifteen survivors in the aftermath of the tropical cyclone. One participant reflected on the solidarity shown in the community following the disaster:

> *One thing that stood out for me, despite being in the midst of a disaster, was the spirit of unity I witnessed. Everyone was pitching in to help each other. Normally, people often work individually, but during the cyclone, there was a strong sense of togetherness among everyone.*

A local chief also recounted how he housed and fed five villagers for over two weeks after their homes were destroyed by the floods. Indeed, the foundations of the moral economy ingrained in African culture, even from the precolonial era, dictate that traditional leaders bear the responsibility of providing such safety nets during disasters. As custodians of the land, chiefs are supposed to organize local subsistence systems and ensure their subjects have access to food during crises such as droughts [19]. Aligned with this role, chiefs deployed their Village Heads to assess and identify households most affected by the tropical cyclone in their respective areas. These identified households were prioritized for postdisaster aid interventions.

From a moral economy perspective, while the impact of the Tropical Cyclone Idai disaster varied among individuals and families, the responsibility for care and support became a collective effort within the community. The disaster revealed the unity and culture of solidarity inherent within Chimanimani society, motivating neighbors, individual first responders, and traditional leaders to take action and assist those in need of emergency help. Nevertheless, since the disaster necessitated a shared responsibility for care and support among community members, the postdisaster interventions implemented by external agencies were expected to align with and respect this preexisting unity and solidarity.

3.4 Survivors' attitudes toward the state and nonstate actors' response to tropical cyclone Idai

The response to Tropical Cyclone Idai by the state and NGO agencies had significant impacts on the social dynamics within the affected communities. These agencies introduced new language and processes antithetical to local norms, values, and expectations. By distinguishing "victims," "directly affected people," or "beneficiaries of disaster aid" from the rest of the community, the state and NGOs inadvertently created social tensions. This categorization, and the criteria used by humanitarian agencies to define a "directly affected person" or "beneficiary of disaster aid" generated jealousy and acrimony among the survivors.

An interview with a senior official in the government department of Agricultural Technical and Extension Services (Agritex), who also survived the cyclone, shed light on the contestations surrounding the definition of aid beneficiaries. According to the official:

> *Almost every household on the safe ground was accommodating other members of the community who had been displaced and providing them with shelter and food. For those who had been displaced, it means that they lost everything, including their sources of food. By accommodating the displaced, the hosting household was also depleting its food reserves, possibly for the next four months or even a year. So, everyone became directly affected and required disaster relief, but most of us did not receive it because others were more deserving.*

The Agritex official's point can be interpreted as an acknowledgment that, although he and others in similar situations did not receive disaster relief aid, he understood that there were households more severely affected and in greater need of support than he was. This understanding was based on his lived experiences of the disaster and local knowledge systems of defining who is most affected. For instance, when traditional leaders deployed their village heads to assess the situation in the aftermath of the disaster, they relied on relational experiences and day-to-day interactions to make judgments, rather than imposing predefined checklists to determine who should receive relief aid.

The disaster response approaches of external agencies in post-Idai Chimanimani reshaped agency and influenced the interactions between survivors and external service providers in numerous ways.

Firstly, the lack of policy consistency on the part of the government led to the emergence of various forms of moral economy. For example, the four displacement camps housed both former landlords and former tenants who did not have any properties registered in their names. Initially, the rural district council planned to allocate residential stands to all survivors, allowing them to build their structures with the understanding that they would pay for the stands later on an agreed payment plan. However, the survivors resisted this plan, arguing that they had lost their sources of income and lacked the means to begin constructing housing structures. After negotiations between the state, UN agencies, and international NGOs, an agreement was reached to initiate a housing scheme at a farm, later named Runyararo Village. This initiative aimed to construct permanent housing units for the survivors with the support of international organizations. However, it was unclear if the government-initiated housing scheme would benefit both former landlords and tenants. According to one government official, the primary beneficiaries were former landlords who previously had properties registered in their names. The official explained:

> *We have an individual who owned property before the disaster and another who was renting that property. The property remains under the ownership of the individual who constructed or bought it. The expectation is that the person who was renting can move into another property since they did not own any property. However, we are providing temporary shelter to everyone affected, allowing tenants time to find alternative accommodation.*

Contrary to the above statement, the coordinator of an international organization involved in camp management and the rollout of the Runyararo Village housing scheme shared a different perspective:

> *When we ask the authorities, they say they are assisting everyone, but those registered with the council will be allocated space first because their paperwork is already in order. It will take longer for those who did not own properties because they need to verify that people claiming housing are not imposters. The actual number of beneficiaries will depend on the outcome of the verification process. However, this information is not being directly communicated to people in the camps, leading to a lot of speculation.*

These policy inconsistencies created tension among survivors in the displacement camps. Some survivors, assigning themselves descriptors such as "*Isu tiri vanhu ve Idai* (we are the people of Idai)," believed that being taken into the camps signified an agreement with the government to provide them with permanent housing. In some cases, the former landlords claimed entitlement to the Runyararo Village housing scheme, while former tenants contested these claims. This landlord-tenant divide became increasingly evident in the camp administration system. Each of the four displacement camps had a management committee responsible for representing the residents in meetings with state officials and external humanitarian agencies. Ideally, the members of these committees were supposed to be elected by the residents, but the survivors I interviewed in one camp alleged that the committees were clandestinely formed by former landlords. A former tenant survivor commented, "We were nursing our wounds in the hospitals only to come back and see that the landlords had now formed a committee." On the surface, this statement suggests that only former tenants were injured and hospitalized, but some former landlords were also injured and hospitalized. However, the statement had a deeper meaning, exposing the power structures that emerged as former landlords and tenants interacted and revealing the opportunistic tendencies that arose as different "classes" of survivors occupied the same space following the tropical cyclone. The survivor alleged that some former landlords were not in their homes when the cyclone struck and only came to claim tents in the camp upon hearing that the state would compensate displaced people. These individuals reportedly formed the camp management committee, while other survivors were still nursing their wounds and held meetings with state agencies and NGOs, lobbying for decisions that favored only them. These allegations are rooted in the state's failure to communicate directly with camp residents about how it would handle the accommodation issue. The lack of transparency and consistency by the state created tensions, cynicism, and jealousy among the various classes of survivors housed in the displacement camps.

When I visited Chimanimani toward the end of my fieldwork in December 2021, the displacement camps had been decommissioned, and survivors had been relocated to their allocated housing units at Runyararo Village. At that time, twenty-eight housing units had been fully completed [20], with others at various stages of construction. All the camp dwellers—landlords and tenants—had been moved into the units, with some allocated fully completed four-roomed houses while others received temporary fabricated structures. The disparities in housing allocation, despite their shared experience of displacement, likely exacerbated tensions among the survivors, highlighting the government's inconsistent approach to postdisaster recovery and resettlement efforts.

Secondly, survivor agency was evident in the survivors' rejection of projects and decisions imposed upon them. The descriptor "*tiri vanhu ve Idai*" not only illustrates how survivors asserted entitlement to aid provided by external agencies but also clarifies how these claims enabled them to devise forms of agency, challenging decisions and programs imposed by aid providers. An example from projects funded by the Ministry of Women Affairs, Community, Small and Medium Enterprises Development (MWACSMED) is used to illustrate how survivors challenged the imposition of these projects.

MWACSMED administers a special grant for development projects aimed at benefiting women and girls. However, when Tropical Cyclone Idai struck Chimanimani, the ministry redirected the grant to fund two specific projects: poultry and garment sewing. These initiatives were intended to provide livelihood opportunities for households affected by the cyclone and relocated to displacement camps. Ministry officials visited the camps, urging residents to form groups of eight to ten people, each group choosing between the poultry and sewing projects. For example, groups opting for poultry received start-up materials such as chicks, feed, and equipment for poultry housing, while those choosing sewing were provided with sewing machines, fabric, and related accessories. Participation in these income-generating projects was voluntary, with the expectation that groups would reinvest proceeds from sales to achieve self-sustainability.

At one camp, ten households were given start-up materials for the poultry project, including a batch of one hundred chicks, along with cement and fencing materials for the fowl run. Another ten households received sewing materials, including six manual sewing machines and fabric. Approximately three months later, MWACSMED officials returned to the camp only to discover that no fowl run had been constructed, and none of the families participating in the poultry project could account for the cement and fencing materials provided by the ministry. Additionally, there were no clear explanations regarding the fate of the chicks; participants claimed they had sold them on credit to group members who promised to settle their debts later. Efforts by MWACSMED officials to follow up on the owed money proved futile as beneficiaries stopped cooperating and that was the demise of the poultry initiative.

Similarly, the group provided with equipment and materials for the sewing project saw no progress. Members began using the materials for personal purposes. Those entrusted with equipment on behalf of the group had all left the camp. They took the sewing machines and fabric intended for the project with them. Some relocated to urban areas to live with relatives, while others returned to their villages in the district.

The two cases described above illustrate how MWACSMED's approach to implementing disaster recovery projects contributed to shaping the attitudes of the camp residents. The poultry and garment-making projects were not initiated by the intended beneficiaries themselves. Rather, the state imposed these projects without consulting the camp dwellers, and in turn, the beneficiaries' only way of expressing displeasure was to accept being enrolled in the projects but not abide by the mode of operation as defined by the ministry.

When asked about his involvement in the state-funded projects, one of the camp dwellers responded:

> *How do you expect ten families to benefit from one hundred chickens? It was simply a waste of resources and time. It would have been better if they had distributed the chickens to individual families rather than groups.*

The dweller's concern suggests that MWACSMED, by not consulting the camp dwellers, perceived them as lacking agency. Consequently, they introduced initiatives that were not well-suited to the prevailing circumstances. The camp comprised 59 families totaling 309 residents, averaging 5 people per family [18]. As the dweller rightly pointed out, even if the poultry project were to operate for five years, it would not have significantly contributed to the economic well-being of ten households. Similarly, the provision of six sewing machines would not have generated substantial income for the ten families involved in the project. Furthermore, the state overlooked the social dynamics that formed as survivors relocated to the camps. Dwellers in this particular camp, for example, originated from various affected areas across the district, lacking prior relationships or collaborative histories. Many had only come into contact due to the disaster. Expecting these families from diverse backgrounds to effectively collaborate in groups was bound to fail. The ministry's failure to grasp this social context necessitated a challenge to its disaster response approach.

Thirdly, survivors contested external agencies, particularly NGOs, for failing to adhere to local cultural norms and establishing their own social structures that fuelled community conflict, exacerbated by a lack of transparency and accountability. An illustrative example highlighting concerns about NGOs' cultural insensitivity involved the use of NGO vehicles by local communities. During an interview, a research participant recounted her experience participating in post-Idai NGO-supported activities. She recounted an incident where she walked over 5 km to attend a training workshop organized by an NGO. On her way, she attempted to hitch a ride in the trainers' vehicle heading to the same venue, but they did not stop. Upon arriving at the workshop, she discovered the session was already in progress. The woman regarded the trainers' actions as culturally inappropriate, questioning why the NGO encouraged her to participate in workshops but declined to give her a ride, which contradicted local norms of social interaction. The trainers' decision not to stop stemmed from the NGO's policy prohibiting anyone other than its employees and authorized personnel from using their vehicles—a standard practice among international NGOs operating in Chimanimani. This policy aims to mitigate liability in case of accidents, which could involve compensation claims or medical expenses for injuries. NGO employees typically benefit from comprehensive medical insurance in such situations, unlike nonemployees. In practice, these policies often portrayed NGO employees as culturally insensitive underscoring the complexities and contradictions that arose when NGOs interacted with local cultures during the disaster response efforts.

Besides, NGOs were criticized for establishing new structures that sometimes duplicated existing state structures, leading to conflicts within communities. For instance, the NGO I volunteered for set up Community Health Committees (CHCs) whose members were trained to deliver primary health services, including addressing minor health issues and referring community members to nearby health centers. This role overlapped with that of Community Health Workers (CHWs) employed under the Ministry of Health and Child Care (MOHCC), who performed similar duties. However, CHC members received significantly higher allowances from the NGO compared to the CHWs' salaries from the MOHCC. The disparity demoralized the CHWs, who started to unfavorably compare their working conditions with those of the CHC members established by the NGO. This situation not only undermined community cohesion and solidarity, crucial tenets of agency, but also is likely to perpetuate divisions that could further weaken survivor agency.

Fourthly, concerns about transparency and accountability influenced survivors' perceptions and participation in postdisaster recovery and reconstruction activities initiated by external agencies. Some survivors believed they were short-changed by NGOs, while others speculated that NGO leaders misappropriated funds donated for personal gain. Following the declaration of a state of disaster, major national and international NGOs pledged substantial funds toward recovery and reconstruction projects that allegedly were never fully implemented. Suspicions of mismanagement arose due to the lack of transparency in many NGOs' disaster response approaches. A survivor who initially stayed in one of the camps before relocation to Runyararo Village described how NGOs abruptly withdrew support without informing residents, causing anxiety about accessing food and other essentials for her family. She expressed her concerns, stating:

> *It's not like before when we received monthly food hampers. The donors have stopped coming. The only people coming are from the IOM, but I am not so sure about their work. They are now only addressing members of the committee.*

The statement above underscores how external agencies inadvertently created a category of "passive beneficiaries of disaster aid" that proved difficult to sustain over time. This highlights a critical issue in disaster response where the initial influx of aid may not translate into sustainable support for affected communities in the long term.

Finally, the construction of survivor stereotypes and the homogenization of vulnerability influenced how survivors perceived state agencies, international organizations, and NGOs implementing recovery and reconstruction initiatives in post-Idai Chimanimani. The stereotyping can best be encapsulated in the following quote from a survivor:

> *I think they thought that everyone in Chimanimani was injured or dead. They brought their people even to count dead bodies, yet we have many youths here who are not employed… You would be visited by 5 to 10 NGO people in a day asking the same thing… I ended up asking them to pay me for information or just responded anyhow.*

The statement underscores a critique often directed at NGOs by scholars, highlighting how their actions can hinder intervention goals. It is argued that NGOs contribute to disadvantageous stereotypes by homogenizing diverse groups of people (see for instance [21]). As evidenced in the survivor's remarks, labeling everyone in Chimanimani as vulnerable survivors in need of rescue led some NGOs to overlook the agency demonstrated by local communities, who had already initiated rescue efforts and shared resources before NGO arrival. Due to this homogenization, NGOs sometimes brought in outsiders for basic enumeration tasks that local youth could have performed, thereby missing an opportunity to provide local employment postdisaster. Moreover, the other facet of the survivor's contribution relates to the fatigue ("NGO fatigue") that survivors experienced, especially from NGOs who were undertaking assessments and surveys soon after the disaster. Lacking coordination, these external agencies often duplicated efforts, making repeated visits and asking the same questions to traumatized survivors. In response, survivors began resisting these disjointed activities by demanding payment for information or responding indifferently, as the survivor described.

4. Conclusions

Disasters create humanitarian situations that bring together the state, NGOs, and other external agencies in to interact with survivors. These spaces of interaction become an arena within which new modes of relations are created and operationalized. In Chimanimani, Tropical Cyclone Idai produced a population of survivors who, besides mobilizing their local support systems, had to depend on these external agencies for emergency disaster relief, recovery, and reconstruction support.

While the externally driven initiatives offered essential emergency relief, employment opportunities, and long-term livelihood options to some survivors, some interventions failed to comply with the tenets of moral economy as interpreted locally by the survivors. The demise of state-funded initiatives like the poultry and sewing projects in one of the displacement camps exemplifies how survivors negotiated and resisted recovery and reconstruction interventions that diverged from local moral norms and expectations. These examples also demonstrate how the approaches employed by external service providers contributed to diminishing survivor agency. The lack of agency subsequently reduced the possibility of survivors mobilizing and challenging the actions of disaster responders perceived as not complying with locally constructed interpretations of the disaster. Unequal access to disaster aid among the survivors, for instance, prompted individualized actions including complaints, resentment, and opportunistic moves to derive individual benefits. Taken together, these individualized actions failed to build enough impetus to change the processes and practices of humanitarian agencies. Furthermore, this chapter reveals that

Tropical Cyclone Idai resulted in social restructuring, as the disaster impacted families differently. However, the analysis did not explore the specifics of these disaster-induced social restructuring elements. A more comprehensive understanding of the post-Idai landscape in Chimanimani can be achieved by focusing future research on the processes of class formation and examining how intersecting identity factors like gender, religion, and age shape and are shaped by postdisaster landscapes.

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Conflict of interest

The author declares no conflict of interest.

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Section 4

Advances in Seismic Potential and Predictive Analysis

Chapter 8

Application of Nowcasting Method to Assess Significant Earthquake Potential in North China

Shengfeng Zhang and Yongxian Zhang

Abstract

Earthquakes pose significant risks and challenges to human survival and societal development. Effectively assessing the imminent risk of strong earthquakes is crucial for societal and regional resilience. While the Sichuan and Yunnan regions of China are known for frequent earthquake activity, the North China region, despite historically fewer earthquakes, includes key areas such as Beijing, the capital of China, necessitating effective earthquake risk prevention. The Nowcasting method, successfully applied in the United States, Japan, and several big cities, offers a promising approach to earthquake risk assessment. This paper applies the Nowcasting method to the North China region, aiming to enhance the assessment of strong earthquake risks in this region, such as the Dezhou 5.5 earthquake and Dalian 4.6 earthquake, and investigate the effect on its performance from the aftershock events using the declustering method. In the end, we give a credible and scientific forward forecasting result after the last target earthquake in this region. Through comprehensive analysis, this study demonstrates the method's effectiveness and emphasizes its potential for improving earthquake preparedness in regions with significant urban infrastructure but relatively lower seismic activity.

Keywords: earthquake potential assessment, Nowcasting method, declustering approach, North China region, Dezhou 5.5 earthquake, Dalian 4.6 earthquake

1. Introduction

Earthquakes are one of the most destructive natural phenomena, with the potential to cause significant loss of life and property. It is of the utmost importance to assess earthquake risks in order to enhance disaster preparedness and mitigate potential impacts. The Sichuan and Yunnan regions in China are well-known for their seismic activity, whereas the North China region has experienced fewer earthquakes historically but includes critical areas such as the capital Beijing. The 1976 Tangshan M_W 7.6 earthquake serves as a stark reminder of the potential devastation in this region [1, 2]. North China is a region characterized by complex geological structures, which have significant implications for its seismic activity. The North China Craton, one of the oldest and most stable parts of the Earth's crust, forms the core of the region. This craton has experienced multiple phases of tectonic activity, including rifting, subsidence, and uplift, which have collectively shaped its current structural configuration [3, 4]. The region is bounded by several active tectonic zones, including the Yanshan Fold and Thrust Belt to the north, the Taihang Mountains to the west, and the Bohai Bay Basin to the east. The North China Plain, lying between the Yellow River and the Bohai Sea, is a major structural feature formed by the subsidence of the craton's eastern margin. Additionally, the TanLu fault, one of the most significant fault systems in East Asia, traverses the region and plays a crucial role in its seismicity [3, 5]. Historically, North China has experienced fewer earthquakes than regions like Sichuan and Yunnan. Nevertheless, the region is not immune to seismic hazards. The 1976 Tangshan earthquake was one of the deadliest earthquakes in the 20th century, causing extensive loss of life and property [2]. The aftershocks continue to occur up to the present time. Therefore, large earthquakes like the Tangshan earthquake highlighted the significant seismic risk in the region despite the relatively lower frequency of earthquakes.

The North China region seems seismically active in recent years due to the occurrence of many aftershock events after large earthquakes, with several fault lines capable of generating moderate to strong earthquakes. For example, the Dezhou M_S5.5 earthquake occurred on August 6, 2023, and the Dalian M_S4.6 earthquake occurred on August 23, 2023. The region's seismicity is influenced by the interaction between many main fault and sub-fault systems, which creates complex stress fields and fault movements [6]. The seismic activity in North China is typified by shallow earthquakes, which have the potential to cause severe ground shaking and extensive damage to infrastructure. However, there were few precursors in the fields of geochemistry, geomagnetism, geology, and others prior to the Dezhou M_S5.5 earthquake and Dalian M_S4.6 earthquake, which raises questions about the prospective evaluation of this capital region once again. **Figure 1** illustrates the spatial distribution of earthquakes that occurred between January 01, 1970, and January 06, 2024, with particular emphasis on the two earthquakes that occurred in the previous year.

The term 'Nowcasting' was originally coined in the field of meteorology and refers to the prediction of events in the near future, typically within a few hours to a few days. In seismology, the 'Nowcasting' was used to estimate the current state of seismic hazard by calculating the likelihood of future earthquakes based on the recent history of earthquake sequence [7]. In the past years, this method has been widely employed in the United States, Japan, New Zealand, Greece, and Indonesia for earthquake risk assessment, providing timely and actionable information on the assessment of strong earthquakes [8–14]. The integration of machine learning (ML) and stochastic simulated techniques with Nowcasting has also opened new avenues for enhancing prediction accuracy [15, 16]. Meanwhile, this method has been preliminary applied in regions like Sichuan and Yunnan of China [17, 18] and used to assess the potential before significant events [19]. However, its use in North China, an area with fewer but potentially more impactful earthquake events, remains constrained. Simultaneously, the awareness and concern about the area's new approach to forecasting significant events has increased in light of the Dezhou M_S5.5 earthquake and the Dalian M_S4.6 earthquake, especially in the capital region.

Therefore, the purpose of this study is to apply the Nowcasting approach to North China, emphasizing its usefulness in evaluating the potential prior to these two occurrences and improving its applicability to preparedness in this crucial region.

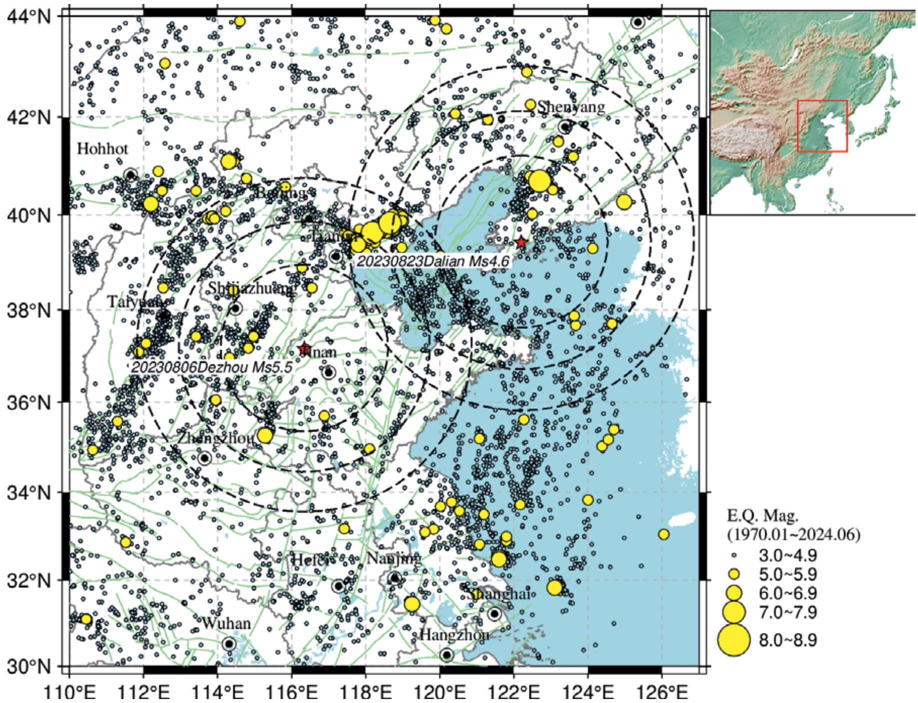

Figure 1.
Spatial distribution of earthquake epicenters occurred from January 01, 1970, to January 06, 2024. The red star indicates the two target earthquakes of the Dezhou M_S5.5 earthquake occurred on August 6, 2023, and the Dalian M_S4.6 earthquake occurred on August 23, 2023. The three circles surrounding two events present the region with a radius 200 km, 300 km, and 400 km, respectively. The green lines are the active faults in this region.

As continuing research in the study region of China Seismic Experimental Site (CSES), we also investigate the impact of the clustering feature of the seismicity on the outcome of the Nowcasting approach. This chapter highlights the significance of improved forecasting models in earthquake preparedness and mitigation strategies, in addition to adding to our understanding of the seismic risks in North China. Furthermore, it is anticipated that the global implementation of state-of-the-art forecasting techniques will be facilitated in regions with relatively low seismic activity but hold significant social importance.

2. Earthquake catalog used

In order to conduct this study, we collected an earthquake catalog of uniform fast reports from the China Earthquake Networks Center (CENC)[1]. The CENC is responsible for the real-time monitoring and reporting of activity, including earthquake and non-earthquake events across China, providing a comprehensive and reliable database of earthquake research. The earthquake catalog includes detailed information on the time, location, magnitude, and depth of earthquakes, which are basic and crucial for our analysis. The data collected covers a significant

1 CEA database: http://10.5.160.18/uniteDayCatalog/index.action.

period from January 01, 1970, to January 06, 2024, allowing for a thorough examination of seismic patterns and trends in this area. This extensive dataset enables us to apply advanced statistical methods, such as the Nowcasting method, to assess the potential for future large earthquakes. In this catalog, the magnitude of each earthquake was measured using various scales, which is crucial for understanding the energy release and potential damage. The appropriate magnitude measurements were selected, namely M_L for small to medium-sized earthquakes with a magnitude below 4.5 and M_S for larger earthquakes above 4.5. Furthermore, prior to the application of statistical forecasting models, the completeness magnitude level (Mc), which can be recognized as the lowest magnitude at which earthquakes in the catalog are reliably recorded, was considered. Understanding the Mc value is crucial for ensuring the dataset is complete and for accurately analyzing earthquake frequency and trends. **Figure 2** depicts the fundamental analysis of the catalog utilized in this study. From the magnitude-time and magnitude-number plots, it is evident that there is a lack of data following strong earthquakes. For instance, during a short time after the 1976 Tangshan 7.6 earthquake, the aftershocks below 4.0 are not fully recorded. But from the perspective of magnitude 2.0 ~ 4.0, choosing magnitude 3.0 as the threshold can ensure the completeness level of the whole catalog. However, in this particular location, an earthquake with a magnitude of 4.0 is critical and can cause widespread alarm. As a result, as compared to the CSES parameters setting, the target magnitude level is significantly lower. To guarantee that enough small events participated in the computation and were assigned the required magnitude, we chose 3.0 as the magnitude threshold in the following Nowcasting process.

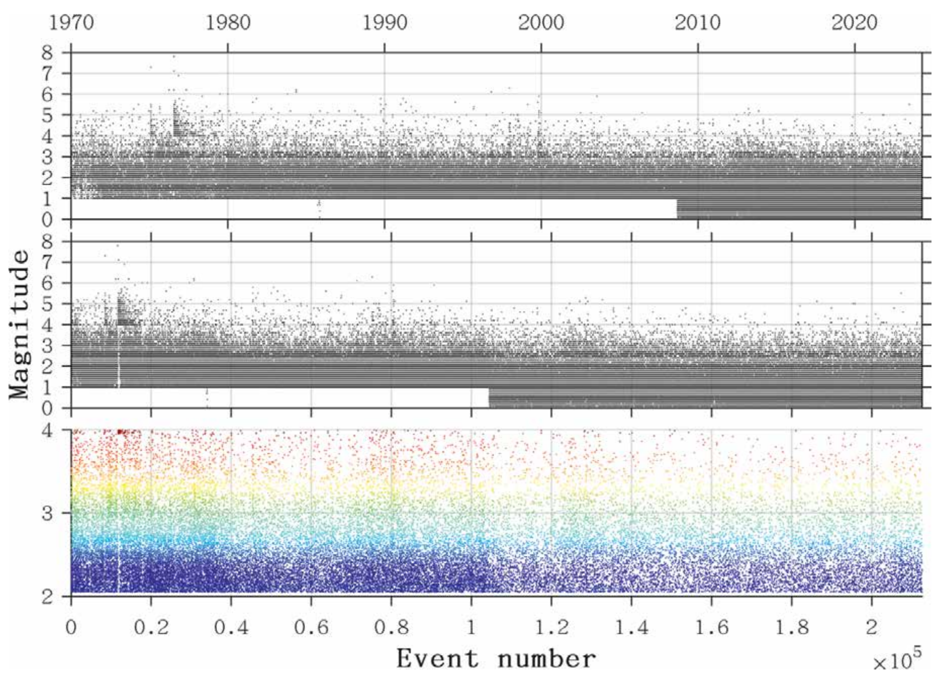

Figure 2.
Different plots of the catalog used in the following analysis. The plots from top to bottom are magnitude-time, magnitude-events number, and magnitude-event number with a magnitude range of 2.0–4.0. The color in the bottom plot indicates the events with the same magnitude level.

3. Declustering method used

Earthquakes often exhibit distinct spatiotemporal clustering characteristics, meaning that earthquakes tend to occur in groups both in space and time rather than as isolated events [20]. These clusters can be attributed to the underlying physical processes governing earthquake generation, such as stress accumulation and release along fault lines. The study of spatiotemporal clustering is crucial for understanding earthquake hazards [21, 22]. By analyzing the clustering patterns, seismologists were able to identify regions with heightened seismic risk and estimate the probability of future earthquakes. This information is of vital importance for developing effective mitigation measures, such as designing earthquake-resistant infrastructure and implementing Operational Earthquake Forecating (OEF) systems [23, 24]. In the field of statistical seismology, the process of earthquake declustering is a crucial process that aims to separate independent mainshocks from dependent aftershocks [25]. Declustering methods help in obtaining a clear pattern of the temporal and spatial distribution of seismic events, which is essential for the analysis of earthquake occurrences and for the development of forecasting models. The Gardner-Knopoff (G-K) method represents a widely used traditional approach to earthquake declustering [26]. Developed in the 1970s, this technique involves identifying aftershocks and foreshocks associated with a mainshock and removing them from the earthquake catalog. The G-K method employs a predefined temporal and spatial window around each earthquake event to determine whether subsequent earthquakes are aftershocks or independent events.

Although the North China region has historically experienced fewer seismic events compared to other parts of China such as Sichuan and Yunnan region, the occurrence of large earthquakes, such as the 1976 Tangshan M_W7.6 earthquake, has resulted in a notable clustering of earthquakes in this region. To investigate

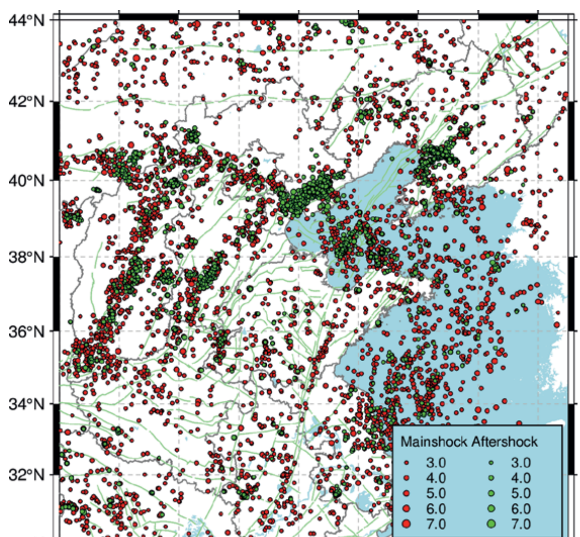

Figure 3.
Spatial distribution of the mainshocks and aftershocks distinguished using the G-K declustering method. The red and green dots indicate the mainshock events and aftershock events, respectively.

the influence of these aftershocks on the analysis of the Nowcasting method, we applied the declustering technique to the North China earthquake catalog. We utilized the traditional G-K declustering method to filter out aftershocks and mainshocks in the earthquake catalog. The spatial distribution of declustering earthquake events and the aftershock events can be seen in **Figure 3**. The results of the declustering method helped us recognize that the aftershock events in our study region are primarily located in specific zones. These zones include the aftershock region of the Tangshan earthquake, the western part of the Liaoning region, and the western part of North China, where many clusters have existed since earlier time. The Tangshan earthquake zone, known for its historical seismic activity, remains a focal point for aftershock events. Similarly, the western parts of the Liaoning region and North China exhibit notable clusters of seismic activity, suggesting a persistent aftershock sequence that aligns with earlier seismic patterns. This spatial clustering provides valuable insights into the ongoing seismic activity and potential areas of heightened earthquake risk within these regions. As a consequence of the aforementioned recognition, the declustering process resulted in a refined catalog of independent earthquake events, which is essential for accurate subsequent analysis and modeling.

4. Concept of Nowcasting analysis

Nowcasting is a statistical technique employed to estimate the current rate of earthquake occurrence based on historical earthquake events. This method leverages the concept that small earthquakes can be transferred into the 'natural time' sequence through the analysis on the intervals divided by large earthquakes. Through the statistical analysis of the 'natural time' sequence, then the likelihood of larger earthquakes in the near future can be obtained within a given region [7, 11]. The equation here mainly used is the Gutenberg-Richter relation, which describes the relation between the frequency and the magnitude [27]. Here we give a basic explanation of the Nowcasting process:

1. *Identify large and small events*: The 'natural time' sequence is constructed from the earthquake catalog by dividing the time into intervals based on the occurrence of significant earthquakes. The number of small earthquakes in each interval is counted to create the natural time series. We can identify large and small earthquakes by defining the target magnitude M_λ for large earthquakes and magnitude threshold M_δ for small events. Then the large events can be used to divide the catalog into intervals.

2. *'Natural time' sequence*: For each interval $[t_i, t_{i+1}]$, count the number of smaller earthquakes with $M_\lambda \geq M \geq M_\delta$ as N_i. For each interval, this count can be expressed as a sequence of $[N_i]$.

3. *Calculate the Cumulative Distribution Function (CDF)*: The Nowcasting method for earthquake potential assessment utilizes the CDF of 'natural time' sequence $[N_i]$. By employing the scientific mathematical approach described by Bevington and Robinson [28], the probability density function (PDF) and CDF for small events within each larger cycle are determined.

4. *Estimation of Earthquake Potential Score (EPS)*: The current CDF is computed based on the frequency of small events, $N(t)$, where t is the time elapsed since the recent large event. This current CDF is then used to define the earthquake potential score (EPS) at time t, providing a quantitative measure of the likelihood of a significant seismic event occurring.

The concept of 'natural time' has been used in many field, such as induced earthquake [29], geoelectric research [30], entropy change before a strong earthquake [31], and the order of parameters as a precursor change [32]. In comparison to the real-time sequence, the 'natural time' sequence offers a unique perspective by reordering events based on their occurrence intervals rather than their absolute times [33]. This approach may reveal hidden patterns and correlations that are not apparent in conventional time series analyses [34, 35]. By converting the sequence of events into a CDF based on their 'natural time' intervals, researchers can gain insights into the underlying dynamics of seismic activity. This approach is typically beneficial for identifying time period with elevated risk of earthquakes and for gathering important data on the temporal clustering of earthquakes.

5. Results of Nowcasting analysis

5.1 EPS before two target earthquakes

Figure 4 presents the EPS values derived from the Nowcasting method prior to the Dezhou 5.5 earthquake. **Figure 4(a)** demonstrates that before the Dezhou 5.5 earthquake, 846 small events with magnitudes between 3.0 and 5.5 occurred within a 400 km radius since the last 5.6 earthquake on November 1, 1999. The temporal distribution analysis of these historical earthquakes yielded an EPS value of 98% via the Nowcasting method. This high EPS value indicates a significant likelihood of a forthcoming major event based on the frequency and distribution of smaller earthquakes in the region. Conversely, when the entire North China region was considered in the Nowcasting analysis, the EPS value peaked, as shown in **Figure 4(b)**. This suggests a broader area of seismic activity that increases the number of sample in the computation and will give a more precise forecast to the study region.

The non-declustered results reveal numerous intervals demarcated by earthquakes exceeding the target magnitude. However, the application of a declustering catalog resulted in a reduction in the interval count, yet the EPS value remained high prior to the Dezhou 5.5 earthquake considering the 400 km circle region and the whole North China region, which is depicted in **Figure 4(c)** and **(d)**. Similar to the case of using a non-declustering catalog, the high EPS values before the target event indicate a strong likelihood of occurrence based on the preceding seismic activity. The elevated EPS values preceding these target events suggest that the Nowcasting method remains effective in forecasting the potential for significant earthquakes, provided that only mainshock events were considered. Although the declustering method reduces the number of intervals divided by large events, the evolution and fluctuation of the local stress level could still be expressed using the mainshock events. With regard to the target magnitude level of 5.5 and above in the North China region, the declustering method exerts only a slight influence on the Nowcasting analysis when the 'natural time' sequence was used as the input.

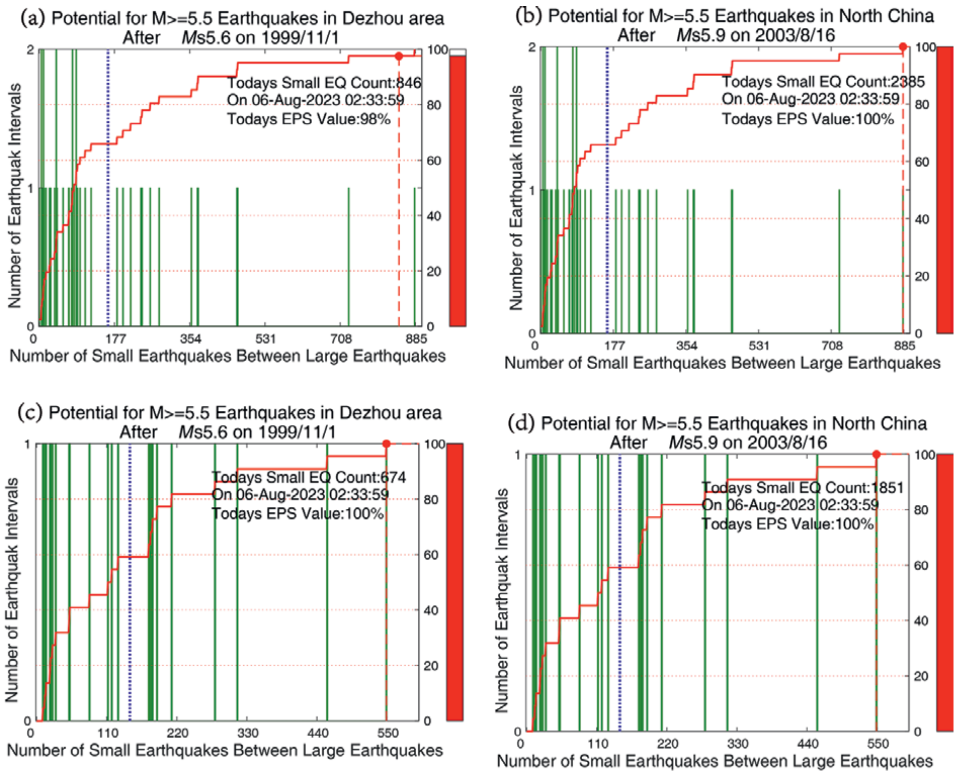

Figure 4.
Nowcasting plots before the occurrence of the Dezhou 5.5 earthquake based on the non-declustering and declustering catalogs. (a) EPS of Dezhou region using non-declustering catalog. (b) EPS of local region using non-declustering catalog. (c) EPS of Dezhou region using declustering catalog. (d) EPS of local region using declustering catalog. This the case of radius 400 km.

Figure 5 depicts the Nowcasting analysis results pertaining to the Dalian 4.6 earthquake. Both **Figure 5(a)** and **(c)** show outcomes similar to those observed for the Dezhou earthquake in **Figure 4(a)** and **(c)**, indicating the effectiveness of the Nowcasting methodology preceding the occurrence of the Dalian event. However, when expanding the analysis to encompass the entire North China region, whether using the non-declustering or declustering catalog, the EPS values remained notably low. This was primarily influenced by the scarcity of subsequent small earthquake events following the Dezhou 5.5 earthquake. Specifically, only 6 and 1 small events were recorded prior to the target events across the entire region, respectively. This paucity of precursor events contributed significantly to the lower EPS values derived from the historical natural time sequence analysis. **Table 1** lists all the EPS results before two target events with different circular regions, using both the non-declustering and declustering catalogs.

5.2 Forward Nowcasting to North China

Based on the above analysis, the Nowcasting method shows its special performance in the assessment of the target earthquakes. Once the local database of the North China region is constructed, then we can calculate the forward computation

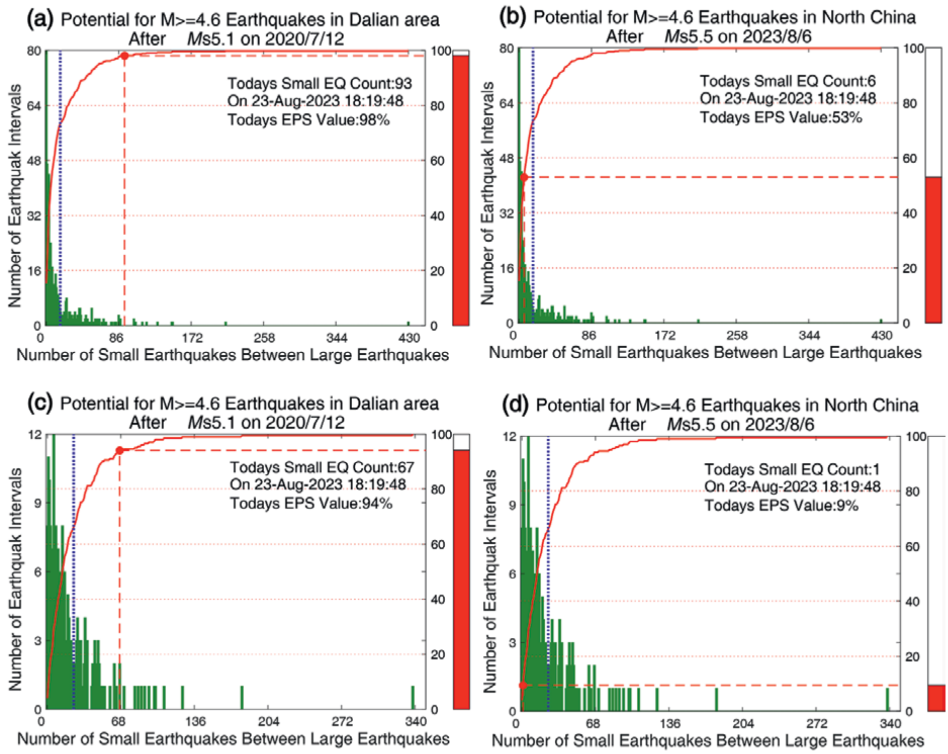

Figure 5.
Nowcasting plots before the occurrence of the Dalian 4.6 earthquake based on the non-declustering and declustering catalog. The other caption is the same as in ***Figure 4****.*

Target Events	M_λ	Radius	EPS result	
			non-declustering	**declustering**
2024-2108-06 Dezhou M_S5.5	5.5	200 km	90%	86%
		300 km	95%	100%
		400 km	98%	100%
2024-2108-23 Dalian M_S4.6	4.6	200 km	100%	99%
		300 km	100%	99%
		400 km	98%	94%

Table 1.
EPS before two target events with different circular regions radius R, using non-declustering and declustering catalogs.

to the next target events. **Figure 6** presents the forward Nowcasting results for the entire North China region since the occurrence of the last significant event using the non-declustered catalog. For instance, **Figure 6(a)** indicates that since the Dezhou 5.5 earthquake, it has occurred 89 small seismic events recorded up to the present time, yielding an EPS value of 55% based on the historical 'natural time' sequence. At the same time, for a target magnitude of 4.6, the EPS is markedly higher at 97%,

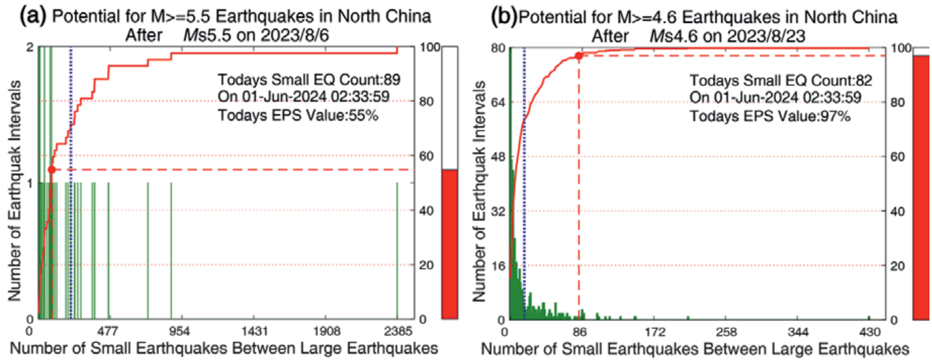

Figure 6.
Forward Nowcasting to the North China region since the time of the last target event using non-declustering catalogs. (a) Potential for earthquake above 5.5 since the occurrence of the last target event (Dezhou 5.5 earthquake). (b) Potential for earthquake above 4.6 since the occurrence of last target event (Dalian 4.6 earthquake).

offering valuable insight into the potential for the next target earthquake. From these results, it can be inferred that for target earthquakes exceeding 5.5, the accumulation of small events following the Dezhou 5.5 earthquake was insufficient, indicating that more time is required to gather a sufficient number of small events to reach a critical state. This suggests that the earthquake activity in the region has not yet reached the necessary conditions for another large earthquake of similar or greater magnitude in the immediate future. Conversely, for target events with magnitudes above 4.6, the EPS value is sufficiently high, indicating that the system is nearing a critical threshold state at this magnitude level. This high EPS value suggests that the accumulation of small seismic events has progressed enough to indicate a higher probability of an impending earthquake around this magnitude.

The implication of these findings is significant for earthquake preparedness and risk mitigation strategies in North China. It underscores the importance of continuous monitoring and the use of advanced forecasting models like Nowcasting to assess earthquake potential accurately. By understanding the accumulation patterns of small seismic events and their impact on the EPS value, people can better anticipate and prepare for potential seismic events, thereby enhancing the overall resilience of the region to earthquake hazards.

6. Conclusion and discussion

This study applies the Nowcasting approach to assess earthquake activity in North China, demonstrating its effectiveness in forecasting significant earthquakes such as the Dezhou 5.5 and Dalian 4.6 events. Prior to the Dezhou 5.5 earthquake, Nowcasting using non-declustering catalogs achieved a high EPS of 98%, indicating a strong likelihood of major seismic events following 846 small seismic events within a 400 km radius since the last 5.6 earthquake in 1999. The method maintained high EPS values even with declustering catalogs, emphasizing its reliability in forecasting earthquakes based on historical seismic patterns. Similarly, the analysis of the Dalian 4.6 earthquake confirmed the effectiveness of Nowcasting methodology in forecasting earthquake events leading up to significant occurrences. However, EPS values before the Dalian 4.6 earthquake computed for the entire North China region, whether using non-declustering or declustering catalogs, were lower due to the scarcity of small events following the Dezhou 5.5 earthquake. The forward potential assessment indicates that the current EPS value to the target earthquake above 5.5 and 4.6 is 55% and 97%, respectively, which provides a valuable and informative reference result for understanding the risk of the next significant events in this region.

In the traditional analysis of the China annual consultation meeting with regard to the prospective outlook for the subsequent one or three years, a multitude of techniques were typically used [36–38]. Compared with other approaches applied in the work, the Nowcasting method presents an indirect way to assess the stress state around the local region since the last target events and could provide us with the likelihood of the next target events in the near future. As is known, statistical forecasting models like probability models were helpful in contributing crucial insights for earthquake preparedness and mitigation strategies [39]. In addition to the current lack of significantly effective analytical methods, techniques such as the Nowcasting method, which can give probabilistic analyses and thus aid in decision-making, are particularly important. On the other hand, the reliability of forecasting models such as the Nowcasting method is intricately linked to the size and quality of the earthquake event sample. The availability of larger and more comprehensive datasets of small events is essential for improving accuracy and reducing uncertainties in forecasting future earthquakes. Moving forward, expanding earthquake sequence to include more extensive records of precursor events will provide a more robust foundation for predictive analytics. Furthermore, the refinement of models through the integration of advanced statistical techniques and machine learning algorithms can enhance the analysis of complex data, thereby improving forecasting capabilities across a range of magnitudes and geographical regions. For the benefit of the general public, the development of real-time monitoring systems with the capacity for continuous data integration and model validation is of the utmost importance to enhance early capabilities and optimize disaster preparedness strategies. These advancements are critical for strengthening societal resilience to earthquakes in North China and beyond, ultimately mitigating risks and minimizing the impact of significant earthquakes.

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