Triple HDP Nexus Approach
&
Climate Change Impacts in Yemen

Part 2

Dr. Tarek Al-Hibshi

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List of Acronyms

AI	– Artificial Intelligence
BBC	– British Broadcasting Corporation
BMZ	– Federal Ministry for Economic Cooperation and Development
CBOs	– Community-Based Organizations
CARE	– Cooperative for Assistance and Relief Everywhere
CSOs	– Civil Society Organizations
EPA	– Environmental Protection Authority
ESA	– European Space Agency (Europe)
EU	– European Union
EWS	– Early Warning Systems
FAO	– Food and Agriculture Organization of the United Nations
FEMA	– US Federal Emergency Management Agency
GCF	– Green Climate Fund
GHG	– Greenhouse Gas
GIS	– Geographic Information Systems
GPM	– Global Precipitation Measurement
HDP	– Humanitarian-Development-Peace
HEC-RAS	– Hydrologic Engineering Center - River Analysis System
HRP	– Humanitarian Response Plan
ICRC	– International Committee of the Red Cross
IDP	– Internally Displaced Person
IDPs	– Internally Displaced Persons
ILO	– International Labour Organization
IOM	– International Organization for Migration
IoT	– Internet of Things
KPIs	– Key Performance Indicators
MAI	– Ministry of Agriculture and Irrigation
M&E	– Monitoring and Evaluation
MEL	– Monitoring, Evaluation, and Learning Systems
MWE	– Ministry of Water and Environment
NAPA	– National Adaptation Program of Action
NASA	– National Aeronautics and Space Administration (United States)
NGOs	– Non-Governmental Organizations

(Cont.)

NWRA	– National Water Resources Authority
OCHA	– United Nations Office for the Coordination of Humanitarian Affairs
OECD-DAC	– Organization for Economic Co-operation and Development - Development Assistance Committee
PDA	– Peace and Development Association
PPPs	– Public-Private Partnerships
ROY	– Republic of Yemen
RS	– Remote Sensing
SDGs	– Sustainable Development Goals
ToT	– Training of Trainers
UN	– United Nations
UNDP	– United Nations Development Program
UNEP	– United Nations Environment Program
UNFCCC	– United Nations Framework Convention on Climate Change
UNICEF	– United Nations International Children's Emergency Fund
USAID	– United States Agency for International Development
US or USA	– United States of America
WB	– World Bank
WFP	– World Food Program
WHO	– World Health Organization
WMO	– World Meteorological Organization
WWF	– World Wide Fund for Nature
YCCI	– Yemen Climate Change Initiative
YHF	– Yemen Humanitarian Fund
YNI	– Yemen Nexus Initiative

Executive Summary

Yemen's landscape is dominated by arid and semi-arid conditions, with significant geographical variation across its five ecological zones: coastal plains, temperate highlands, high plateaus, desert interiors, and the islands' archipelago. The country experiences a monsoon-influenced climate, with distinct rainy and dry seasons that vary regionally.

Climate change is compounding these challenges, with increasing extreme weather events such as floods, droughts, and storms exacerbating displacement and environmental degradation. **IDP** camps, in particular, are highly vulnerable, with **45%** of sites at risk of flooding, leading to frequent secondary displacement.

The country has two main rainy seasons: Saif (April-May) and Kharif (July-September), with significant rainfall variations across regions. Recent extreme weather events, such as the July floods, have severely impacted western **governorates** like Al-Hodeidah, Hajjah, and Taiz, displacing thousands and damaging infrastructure.

Yemen lies at the crossroads of **climate change**, **humanitarian** crises, **development** challenges, and **peacebuilding** efforts. Consequently, Yemen is confronting one of the world's most acute **humanitarian** crises, with approximately **20.7 million** people in need of assistance and **4.3 million** internally **displaced people (IDPs)** as of **2021**.

With rising temperatures, more frequent droughts, water scarcity, and extreme weather events, the country is facing an accelerating crisis that threatens food security, displaces populations, and exacerbates resource-driven conflict. Addressing these difficulties requires a comprehensive and coordinated strategy that incorporates climate adaptation into **humanitarian**, **development**, and **peacebuilding (HDP) initiatives**, often known as the Nexus method.

While **humanitarian** aid remains the dominant focus for many organizations, followed closely by **development** and **peacebuilding** efforts, weak coordination across these

sectors limits the effectiveness of long-term resilience-building initiatives. **Climate change** is recognized as a major driver of displacement and conflict, yet only half of the organizations actively address it through adaptation strategies such as climate-smart agriculture, water management, and disaster risk reduction. Despite the urgent need for climate resilience, only a small fraction of organizations systematically measures the impact of their programs, highlighting a significant gap in monitoring and evaluation efforts. Additionally, financial constraints remain the most significant challenge, with the majority citing financing shortfalls as a barrier to long-term adaptation and resilience-building.

For the **Nexus approach** to deliver sustainable impact, organizations and policymakers must focus on stronger coordination, innovative funding mechanisms, and local capacity-building. Enhancing cross-sector collaboration through joint coordination platforms and improved data-sharing can increase efficiency and impact. Securing sustainable climate financing requires shifting from short-term emergency relief to multi-year resilience-building initiatives while promoting **public-private partnerships (PPPs)** for climate adaptation investments. Strengthening local adaptation strategies by supporting community-led climate initiatives and training programs will equip local institutions with the tools needed for climate-resilient policies. Furthermore, improving climate data collection and monitoring through **GIS**, **remote sensing**, and standardized impact assessment frameworks will help measure progress and ensure accountability.

To assess the **Nexus of climate change impacts on water, energy, and food security**, six key governorates have been identified based on their diverse geographical and socio-economic characteristics:

1. **Hadramout** – Faces severe water scarcity and agricultural sustainability challenges.
2. **Marib** – Historically significant for water management, with modern-day water resource vulnerabilities.
3. **Aden** – A coastal urban hub facing risks from sea-level rise, flooding, and freshwater salinization.

4. **Al-Hodeidah** – A major agricultural region affected by rising temperatures and water insecurity.
5. **Hajjah** – Experiences seasonal flooding and landslides, exacerbating humanitarian concerns.
6. **Taiz** – A densely populated conflict-affected area where **climate change** worsens water and food insecurity.

As **Yemen** continues to struggle with both environmental and **humanitarian** crises, **integrated climate adaptation and resilience strategies** are critical to mitigating the worsening impacts on communities and infrastructure.

Preface

This paper is divided into three sections, each addressing an important component of **climate change** and the **Nexus** strategy in **Yemen**. It intends to give a complete overview of the country's environmental concerns while also investigating potential responses that combine water, energy, and food security.

Part One: establishes the groundwork for the study by explaining the **Nexus** idea and its application to **Yemen's** distinct socio-environmental landscape. This section focuses on the theoretical framework and background required to understand how interconnected systems work in addressing resource management concerns.

Part two: examines the effects of **climate change** in six **governorates**: **Hadramout**, **Marib**, **Aden**, **Al-Hodeidah**, **Hajjah**, and **Taiz**. It investigates how **climate change** influences water availability, food production, and energy access in these areas. This section also looks at **Nexus**-based actions that can help to reduce climate risks and increase resilience.

Part three: offers' findings from an online questionnaire study of **Yemeni** local groups. This section examines major findings from stakeholders involved in climate adaptation and resource management, providing a localized perspective on the viability and efficacy of **Nexus**-based approaches. This section finishes with major suggestions that outline concrete solutions for improving **climate resilience** and sustainable resource management in **Yemen**.

The present study aims to add to **Yemen's** continuing discourse on **climate resilience** and sustainable development. By combining empirical findings with stakeholder viewpoints, we would like to advise policies and initiatives that solve the country's pressing environmental and **humanitarian** concerns.

We extend our gratitude to all contributors that participate the online questionnaire. Their valuable insights and cooperation have been instrumental in shaping this study.

PART III

Nexus Approach & Climate Change Impacts

Introduction: Yemen's Climate

Yemen's landscape comprises a predominantly desert climate, characterized by arid conditions. It is positioned at the southern tip of the **Arabian Peninsula** and has a surface area of approximately **527,970 square kilometers**[1] (**Fig. 1**)

Yemen's climate ranges from semiarid to arid-tropical, with significant geographical variation. The five main ecological zones are coastal plain, temperate highlands, high plateau, desert interior, and the islands' archipelago[2]. In general, winters in the high plateau can be frigid (below **0°C**), whereas summers are mild and dry. "**Monsoon** climate patterns determine the seasons, with winter (**December** to **March**) and

[1] **International Organization for Migration (IOM).** (2021). *Report on Migration, Environment, and Climate Change in Yemen.*

[2] *USAID, 2016*.

summer (**June to September**) representing various monsoon seasons. Spring (**April to May**) and fall/autumn (**October to November**) are transitional periods between seasons"[3].

Yemen is one of the world's greatest humanitarian crises, with an estimated **20.7 million** people in need of aid by the end of **2021**, including **4.3 million** internally displaced individuals (**IDPs**)[4]. More than **377,000** individuals were relocated in **2021** alone. Over **half** a **million** (**518,167**) disaster displacements were registered between **2008** and **2021**, with flooding and storms being the most common causes. **Yemen** also has **95,815 refugees** and **asylum seekers**, primarily from **Somalia** and **Ethiopia**[5].

The climate catastrophe is exacerbating **Yemen's humanitarian** and displacement crises, and it is expected to worsen further as extreme rainfall and flooding, as well as drought and other risks, become more regular and severe. The violence is also leading to environmental deterioration, such as deforestation as a result of fuel shortages caused by blockades and restrictions[6], which may have long-term negative consequences for the country's growth and may force further migration. Rapid urbanization has also caused environmental degradation in **Yemen's** cities[7].

IDP camps in **Yemen** are especially vulnerable to extreme weather events like flooding, because to poor infrastructure and weak disaster risk reduction procedures that do not account for the effects of **climate change**. Floods may swiftly destroy the little infrastructure in camps, while heatwaves leave people with few alternatives for cooling and shelter. A recent flood risk score for **IDP** sites in **Yemen** revealed that **307** sites were at high risk of flooding, **23** were at **medium/high** risk, and **338** were at medium risk, implying that over half (**45%**) of **IDP** sites are at danger[8]. Floods in **Marib** province in **2020**, for example, destroyed the tents and assets of **1,340** families in **Yemen's** displaced people camps, whereas flooding in **2013** affected over **8,000 IDPs** in camps and destroyed local infrastructure such as latrines, schools, and a health

[3] Republic of Yemen, 2013
[4] IDMC, 2022
[5] UNHCR, 2022
[6] Islamic Relief, 2022
[7] Republic of Yemen, 2018
[8] REACH/CCCM, 2022

clinic. Secondary displacement is a growing issue in Yemen, as previously displaced individuals are moved again due to conflict and/or climate disasters[9]. People who have been displaced are more likely to settle in hazard-prone areas of cities or regions, frequently in informal settlements, increasing the likelihood of being compelled to relocate again[10]. This is a particularly serious issue because displacement may have harmed or destroyed social networks and assets, leaving displaced persons with less means for coping or adapting. While climate conditions influence migration between Yemeni **districts**, the majority of migration is driven by socioeconomic concerns, with the poorest generally lacking the means to relocate.

Yemen typically has two primary rainy seasons, with rainfall patterns differing widely between locations. In the highlands, the rainy seasons are **Saif** (**April-May**) and **Kharif** (**July-September**). Rainfall along the shore is primarily concentrated during the winter months **(December-March)**[11]. The impact of this rainy season, which began in July, has killed at least **45** people and affected over **37,700** others, with the **western governorates** of **Al-Hodeidah**, **Hajjah**, and **Taiz** bearing the brunt of the affected **districts** and individuals. The highlands and traditionally flood-prone locations, such as **Al-Hodeidah**, **Amran**, and **Taiz**, are particularly vulnerable to flooding and its effects during the current **Kharif** season.

Significant Governorates for Climate Change and Nexus Study in Yemen.

The selection of the six **governorates** highlighted in blue— **Al-Hodeidah**, **Hajjah, Taiz**, **Aden**, **Marib**, and **Hadramout** —represents a strategic choice for studying the **Nexus** of **climate change** and its impacts on water, energy, and food security in Yemen (**Fig.2**). These **governorates** are chosen based on their diverse geographical, climatic, and socio-economic characteristics:

1. **Hadramout**: As the largest **governorate** in Yemen, **Hadramout** encompasses arid and semi-arid landscapes with critical challenges in water scarcity and

[9] IDMC, 2022
[10] IDMC, 2018
[11] WB, 2010

sustainable agriculture. Its vast desert areas and dependency on groundwater make it highly vulnerable to climate-induced changes.

Fig. 1: Geographic location map of **Republic Of Yemen (ROY)**. (Source: **the author**).

2. **Marib**: Known for its **historic role** in Yemen's water management through the ancient Marib **Dam**, this governorate is critical for studying the impact of **climate change** on water resources and agricultural productivity. The modern-day Marib **Dam** plays a key role in food production and livelihoods.

3. **Aden**: As a coastal **governorate** and the temporary capital of Yemen, Aden faces unique challenges from sea-level rise, coastal flooding, and salinization of freshwater resources. Its urban nature provides insight into how climate change impacts densely populated areas and infrastructure.

4. **Al-Hodeidah**: Situated on the Red Sea coast, Al-Hodeidah is significant for analyzing the effects of rising temperatures, declining rainfall, and the

vulnerability of coastal ecosystems. Its role as a major agricultural region highlights the **Nexus** between water security and food production.

5. **Hajjah**: With a diversified geography that encompasses highlands and coastal plains, this **governorate** is especially vulnerable to seasonal flooding and landslides. The interaction of extreme weather occurrences with persistent humanitarian difficulties in **Hajjah** emphasizes the crucial need for resilience-building programs and sustainable resource management.
6. **Taiz**: This **governorate** represents a densely populated and conflict-affected area, where climate change exacerbates existing vulnerabilities in water access and agricultural livelihoods. **Taiz** provides a unique context for studying the interplay between socio-economic stress and climate impacts.

These **governorates** cover a variety of environmental and socioeconomic situations, offering a comprehensive view of **climate change** and the **Nexus** in **Yemen**.

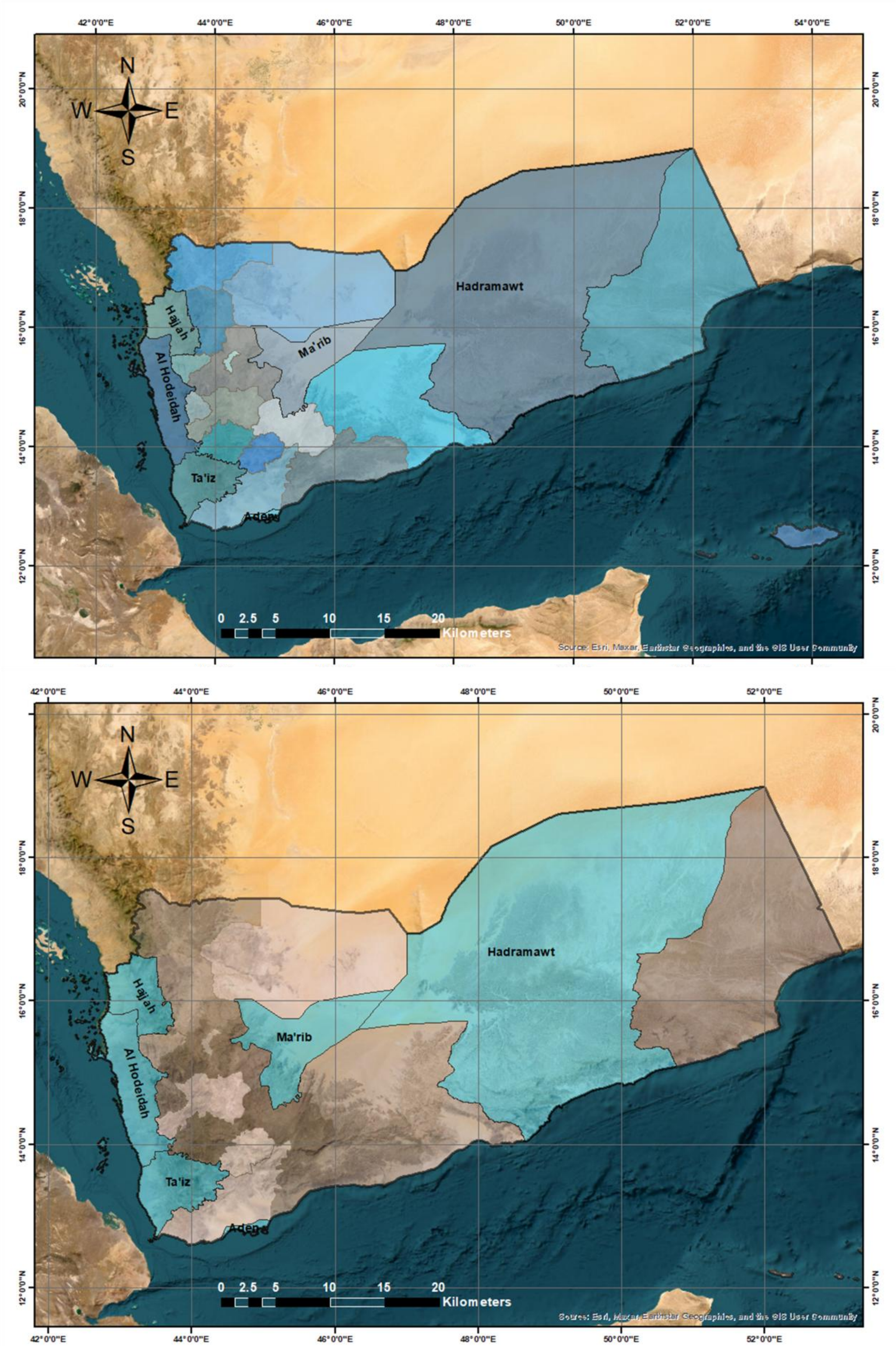

Fig. 2: ***Upper***: governorates of **Yemen**; ***Lower***: depicts the **6** selected **governorates** (cyan color). (Source**: the author**).

Hodeidah Governorate

I. Climate Change Impacts: Al-Hodeidah

I.1. Overview

Monitoring **climate change** successfully necessitates a combination of modern approaches for tracking environmental changes and forecasting future consequences. **Remote sensing** via satellites, such as those run by **NASA** and **ESA**, offers crucial information on temperature, sea-level rise, and vegetation changes[12]. Ground-based observation networks, which include meteorological stations, track local weather, atmospheric composition, and water resources[13]. **Climate modeling**, using modern computer tools, simulates long-term climate patterns to guide policy and mitigation efforts[14]. **Geographic Information Systems** (**GIS**) are essential for analyzing geographical data, mapping sensitive areas, and detecting trends[15]. Furthermore, citizen science programs and **Internet of Things** (**IoT**) devices improve data collecting, allowing for real-time monitoring and increased interaction[16]. Together, these techniques serve as the foundation for climate monitoring efforts, assisting with worldwide adaptation and mitigation actions. Earth observation can aid in critical **humanitarian** tasks like disaster management and risk assessment. Historical climate

12 WMO (2021). "Enhancing Early Warning Systems with Earth Observation Data." World Meteorological Organization.

13 IPCC (2021). "Climate Change 2021: The Physical Science Basis." Intergovernmental Panel on Climate Change.

14 NASA (2021). "Earth Observing System Data and Information System (EOSDIS)." National Aeronautics and Space Administration.

15 UNEP (2021). "Harnessing GIS for Climate Action." United Nations Environment Program.

16 Earthwatch Institute (2020). "The Role of Citizen Science in Climate Monitoring.

data, satellite image monitoring, and digital spatial maps are all useful resources for disaster management and risk reduction.

The utilization of **Earth observation data** enables the development of **early warning systems** that are crucial for saving lives during natural disasters. For instance, satellites provide real-time detection of storms, wildfires, and floods, offering essential information to emergency responders for timely action[17] [18].

According to the **World Meteorological Organization (WMO)**, satellite-based monitoring enhanced the accuracy of cyclone predictions by **20%** over the past decade[19]. Furthermore, historical climate data provides a better understanding of long-term environmental patterns, which aids in risk assessment. For example, drought-prone areas can be detected using decades of precipitation data, allowing **governments** to better manage water resources. Smith et al. (**2020**)[20] found that combining historical satellite data with ground observations reduced agricultural losses in **sub-Saharan Africa** by **15%** during droughts.

Digital spatial maps derived from **Earth observation data** also play a critical role in disaster planning and recovery. **High-resolution satellite images** enable the construction of precise risk maps, assisting urban planners and policymakers in identifying regions prone to landslides, floods, and other hazards. In **Nepal**, for example, satellite-generated damage assessments considerably accelerated post-earthquake rehabilitation operations[21]. These enhancements underline the necessity of leveraging **Earth observation technologies** to build resilience and reduce the effect of natural disasters. By incorporating these technologies into national disaster management frameworks, communities may better plan for and respond to **humanitarian** disasters.

[17] WMO (2021). "State of the Climate in 2021." World Meteorological Organization.

[18] NASA (2021). "Satellite Technology for Disaster Management." National Aeronautics and Space Administration.

[19] World Meteorological Organization (WMO). (2022). Enhancing Cyclone Prediction Accuracy with Satellite Monitoring. *WMO Bulletin*, 71(2), 12-18.

[20] Smith, J., Brown, K., & Taylor, R. (2020). Integrating Satellite and Ground Observations for Agricultural Risk Reduction in Sub-Saharan Africa. Journal of Climate Resilience, 15(3), 45-60.

[21] UNOSAT. (2015). Satellite Imagery for Post-Earthquake Damage Assessment in Nepal. Retrieved from https://www.unitar.org/unosat

In **2020**, **Al-Hodeidah governorate** in **Yemen** (**Fig. 3**) faced two major flood events that caused significant damage and displacement. In **April**, heavy rainfall led to severe flooding, displacing over **6,000** families and causing extensive infrastructure damage. However, the exact number of fatalities remains unclear, with some reports suggesting **30** deaths, though this figure may correspond to a different time frame[22]. In **July**, another bout of flooding caused widespread destruction, including over **16** reported fatalities and significant damage to homes, infrastructure, and agricultural land, further worsening the humanitarian crisis[23]. The floods impacted both residents and internally displaced persons (**IDPs**), with the **International Organization for Migration** (**IOM**) recording nearly **1,200** displaced households and the **United Nations Office for the Coordination of Humanitarian Affairs** (**OCHA**) reporting that **3,638** families were affected during this period (**USAID**, **FloodList**). These events highlight the devastating impact of recurring floods on **Al-Hodeidah's** population and infrastructure.

I.2. Historical Data Analysis

Climate Historical Data Analysis involves examining past climate records, such as temperature, precipitation, and extreme weather events, to identify trends, patterns, and anomalies over time. This analysis uses techniques like statistical modeling, **geostatistics**, and data visualization to assess long-term climate variability and its impacts.

Benefits:

1. **Trend Identification**
2. **Risk Assessment**
3. **Policy Planning**
4. **Resource Management**
5. **Disaster Preparedness**

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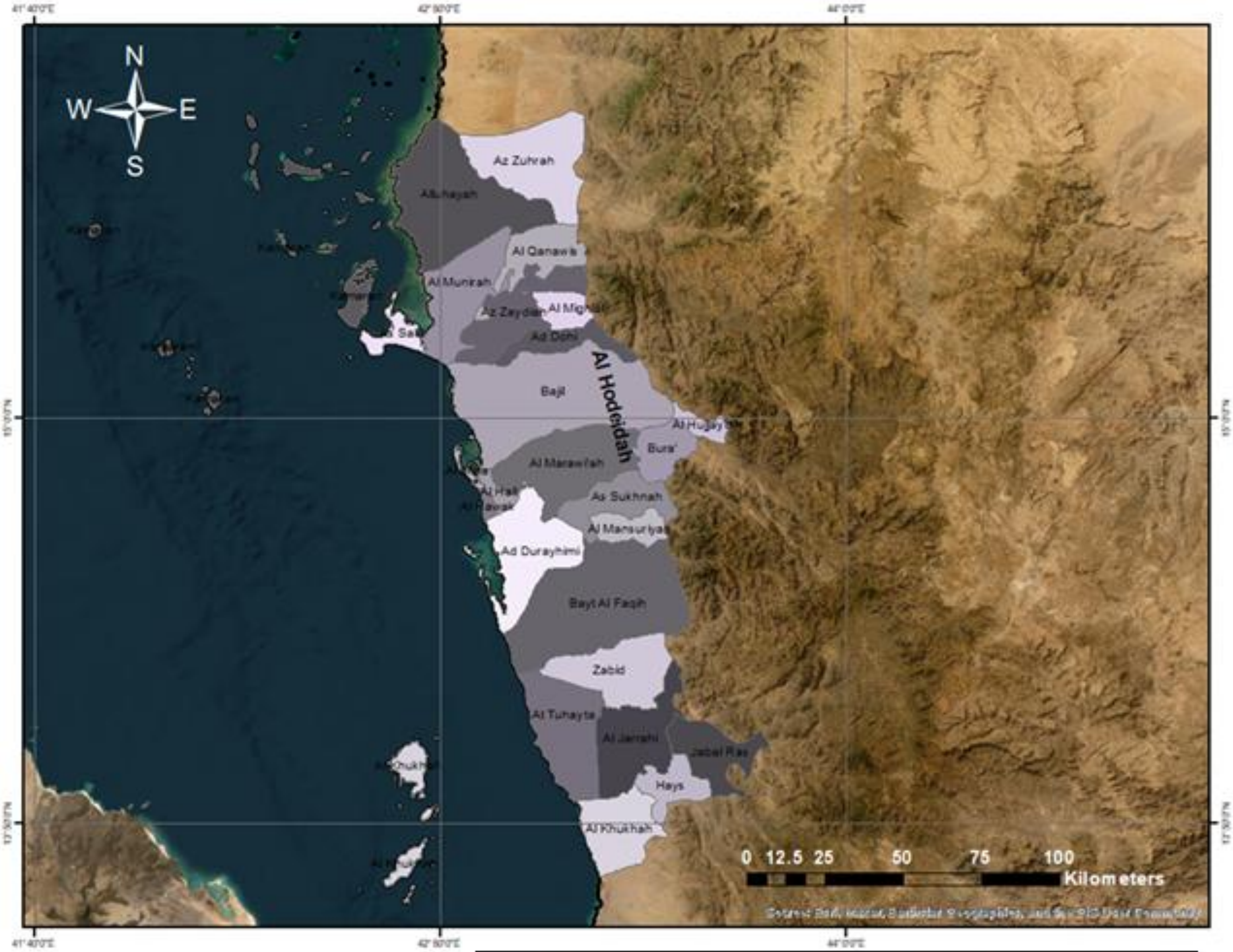
[22] International Organization for Migration (IOM). (2020). Yemen: Flooding Overview and Response. Retrieved from https://www.iom.int

[23] Humanitarian Outcomes Monitoring and Evaluation (HOME). (2020). Impact of 2020 Floods in Al Hudaydah, Yemen. Retrieved from https://www.humanitarianoutcomes.org

Climate historical data analysis is reviewing previous records, such as rainfall data, to find trends, patterns, and anomalies. It employs statistical modeling and **geostatistics** to examine long-term climate variability and its consequences. This analysis provides advantages such as recognizing patterns, analyzing risks, informing policy, managing resources, and improving catastrophe preparedness.

The graphic in **Figure 4** depicts total precipitation (in **millimeters**) from **2017** to **2023** using **TerraClimate** data, indicating significant fluctuation in yearly rainfall. Notably, **2018** and **2020** show higher total precipitation, with values exceeding **55 mm**, indicating wetter years. However, starting in **2021**, there is a noticeable decline in precipitation, with **2023** experiencing the lowest levels, suggesting a drying trend or reduced rainfall. The color coding, with blue bars for above-average precipitation and red bars for below-average years, illustrates the variability in rainfall over time. These shifts between wetter and drier years reflect broader climate variability, with potential impacts on agriculture, water resources, and ecosystems.

The precipitation chart (**Fig. 5**) illustrates rainfall trends from **January 2017** to **December 2023**, measured in millimeters (**mm**). The data reveals fluctuating patterns with periods of low precipitation interspersed with occasional spikes in rainfall. A significant peak is observed around early **2020**, exceeding **120 mm**, which indicates a major rainfall event during that period, while smaller peaks are noted toward **2022** and **2023**. For most of the timeframe, precipitation levels remain low, often below **20 mm**, reflecting arid or semi-arid conditions. Although the chart does not explicitly highlight seasonal cycles, periodic increases in rainfall suggest possible seasonal patterns. These observations provide valuable insights into rainfall variability and can be useful for assessing the impact of extreme weather events on agriculture, water resources, and infrastructure.



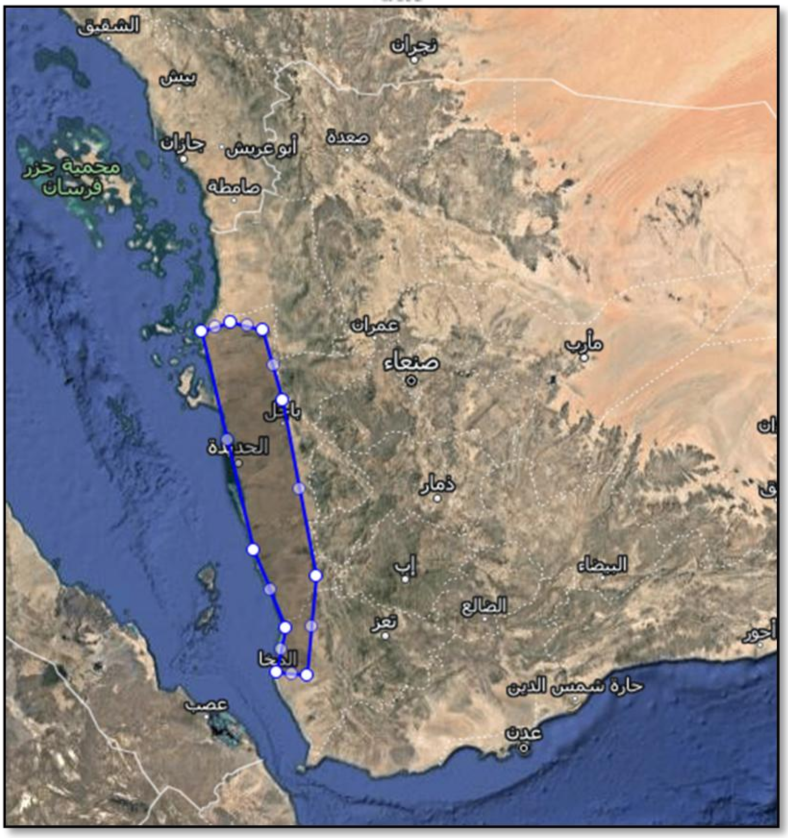


Fig. 3: ***Upper***: depicts the districts off **Al-Hodeidah governorates**. ***Lower***: the image depicts the bounded area (blue color) for climate analysis. (Source: **the author**).

Key Insights from Precipitation Analysis:

1. **Rainfall Variability**: Both figures indicate significant fluctuations in precipitation over time, with periods of high rainfall interspersed with extended periods of low precipitation. This highlights a variable climate pattern in the region.

2. **Extreme Rainfall Events**: Figure 4 (line chart) reveals extreme rainfall events, particularly around early **2020**, where precipitation exceeded **120 mm**. These events point to the occurrence of intense, short-duration storms or heavy rainfall periods.

3. **Declining Rainfall Trends**: Figure 5 (bar chart) suggests a declining trend in total annual precipitation, particularly from **2021** to **2023**, with **2023** showing the lowest levels. This could indicate a drying trend or increasing water scarcity in recent years.

4. **Seasonal and Annual Variability**: Both figures demonstrate seasonal and annual variability, with significant peaks and troughs in precipitation levels. Such variability underscores the challenges of managing water resources and planning agricultural activities in the region.

5. **Potential Climate Impacts**: The data suggests increasing rainfall extremes—both in intensity and decline—possibly due to climate change. This variability can exacerbate challenges such as droughts, floods, and their associated impacts on agriculture, water security, and ecosystems.

These findings emphasize the need for adaptive water management strategies and climate resilience planning to mitigate the adverse effects of such precipitation variability.

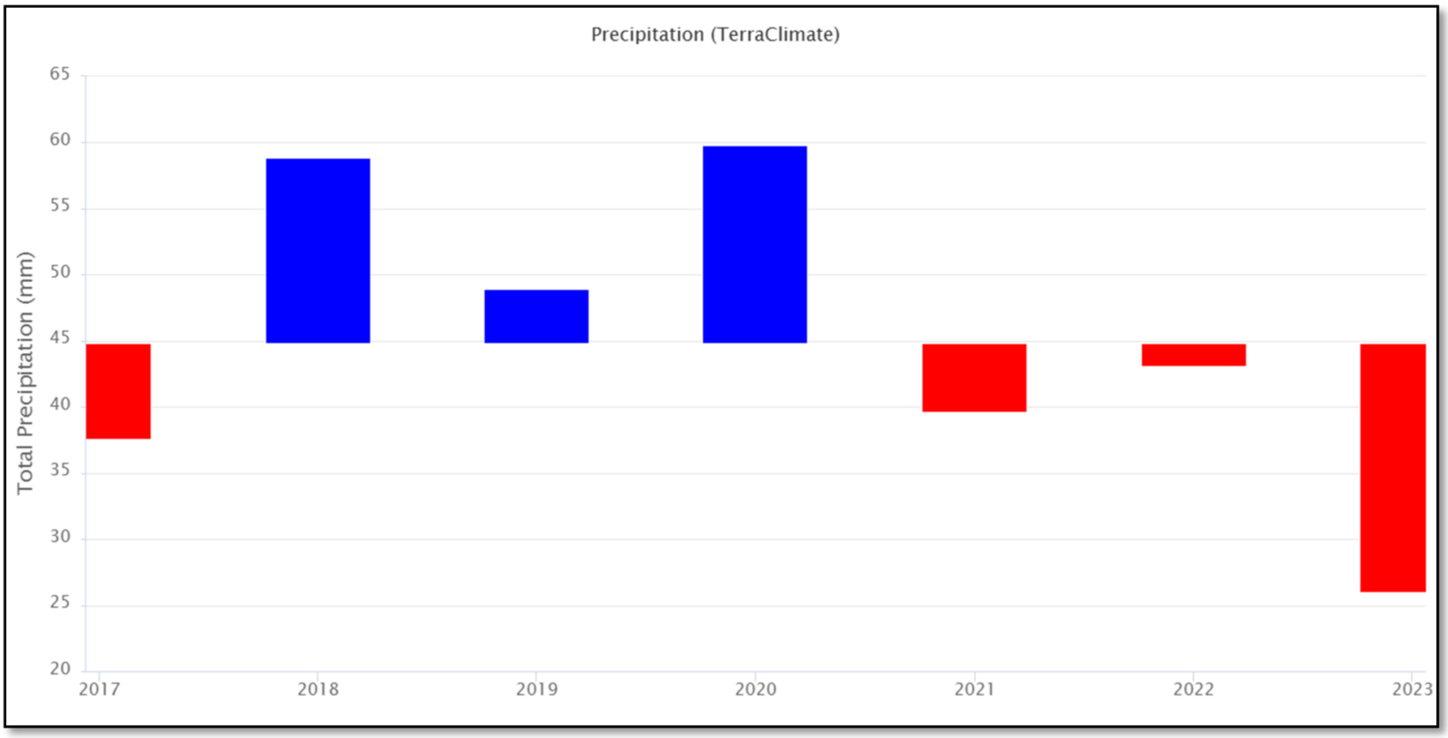


Fig. 4: Total precipitation (in **millimeters**) from **2017** to **2023** based on **TerraClimate** data. (Source: **TerraClimate**).

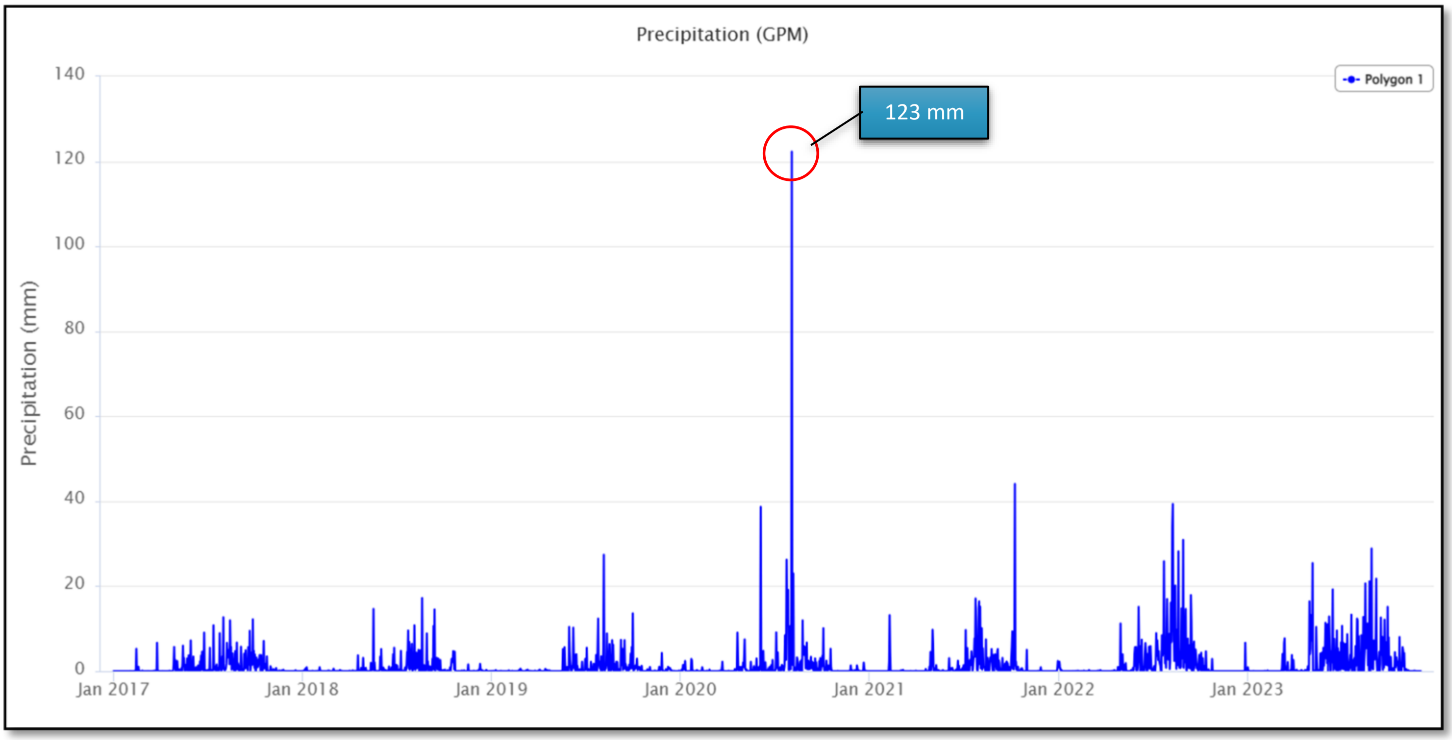


Fig. 5: Shows the rainfall trends from January **2017** to December **2023**, measured in millimeters (**mm**). (Source: **GPM**).

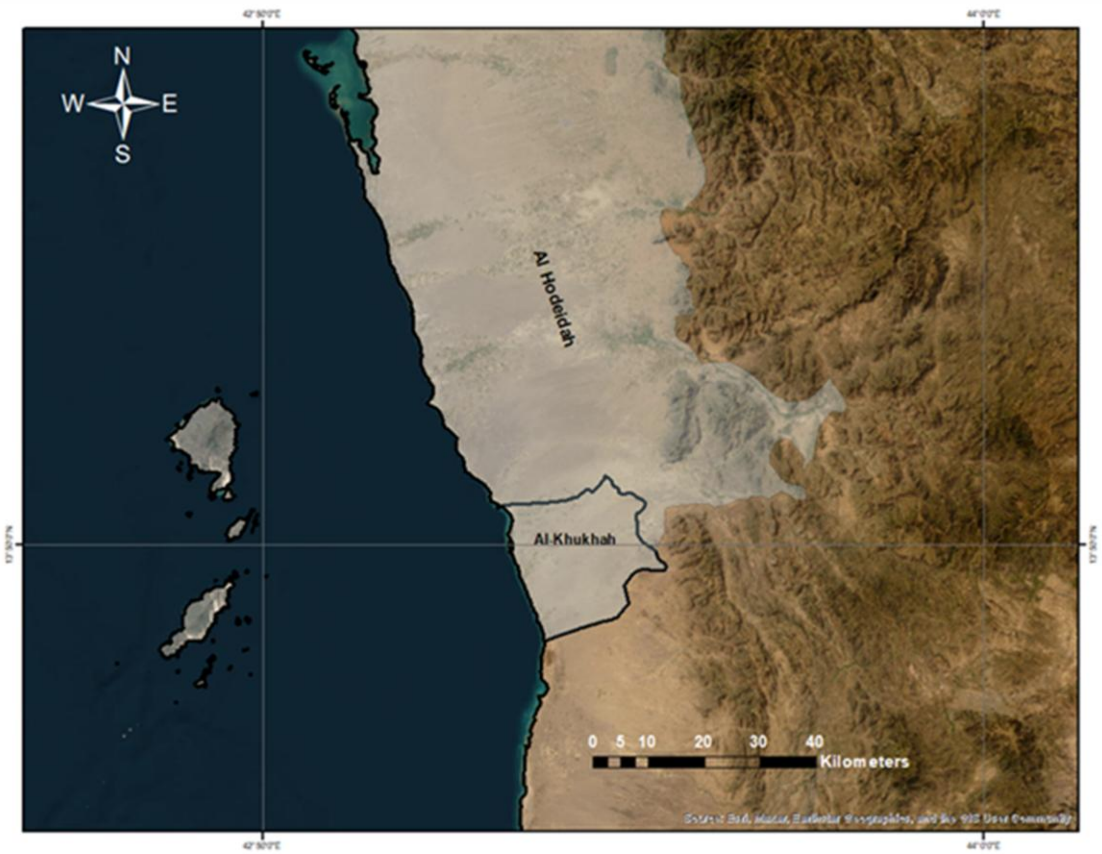


Fig. 6: Depicts the location of **Al-Khukhah** district. (Source: **the author**).

The raster precipitation map (**Figs. 6** and **7**-***Upper***) illustrates precipitation levels (in **millimeters**) across **Al-Hodeidah** and **Al-Khukha** regions. The color gradient ranges from high precipitation (represented by blue, reaching values up to **860 mm**) to low precipitation (yellow/orange, with values as low as **229 mm**). **Figure 7**, ***Lower***, depicts a zoomed view of **Al-Khukhah district**, which has a higher rainfall concentration than the northern portions of **Al-Hodiedah governorate**. This location has a significant potential for flooding.

Map Analysis: Insights and Implications

- **High Precipitation Zones**: The coastal areas, particularly near **Al-Hodeidah**, show significant precipitation levels, represented by shades of blue. These regions are likely more prone to flooding due to their proximity to the coast and higher rainfall.

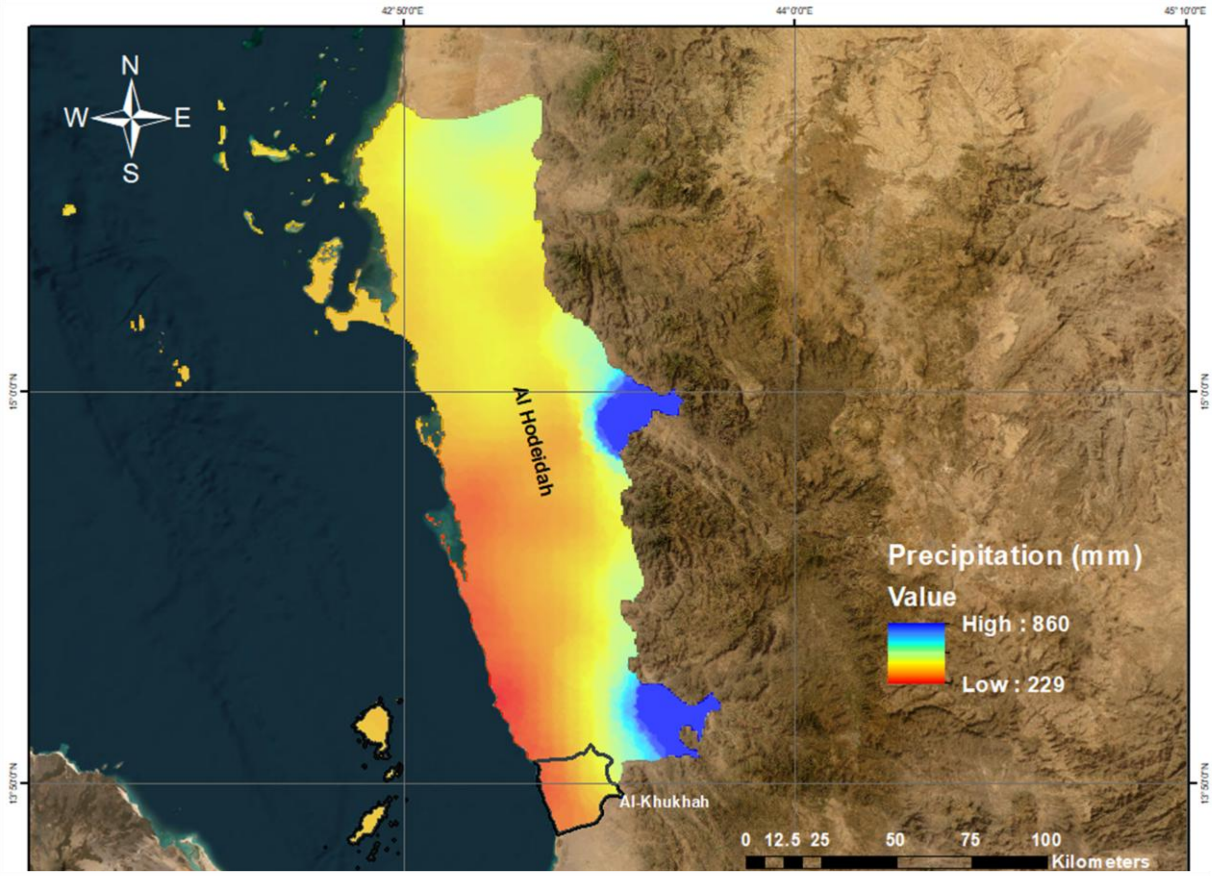
- **Low Precipitation Zones**: The inland areas, represented in orange and yellow, experience much lower precipitation. These zones might face issues like drought or water scarcity but are less likely to experience frequent flooding.
- **Implications**: The variation in precipitation suggests that the coastal zones demand more attention regarding flood mitigation strategies and infrastructure development. Conversely, inland areas require sustainable water management practices to address potential water deficits.

The map can serve as a vital tool for regional planning, aiding in the identification of priority areas for climate adaptation measures, disaster risk reduction, and sustainable resource management.

Figure 8, depicts a map of flood risk scores and internally displaced persons (**IDP**) sites in **Yemen's Al-Hodeidah's governorate**, using two-dimensional hydraulic flood hazard modeling. Based on the above-mentioned digital raster maps, flood risk scores and the locations of **internally displaced persons** (**IDP**) map (**Fig. 8**) revealed the following main findings and impacts:

Key Observations

1. **Flood Risk Areas**:
    - Regions highlighted in **yellow shades** represent areas with varying flood risk levels, ranging from **low** to **extreme**. The darker shades indicate **higher flood risks**.
    - **Flood-prone regions** are concentrated near low-lying and coastal areas, particularly along river basins and drainage systems.
2. **Internally Displaced Persons (IDP) Sites**:
    - The blue dots mark the locations of **IDP** sites. Many of these sites are situated in areas classified as medium or high flood-risk zones.
    - This placement highlights the vulnerability of displaced populations to flooding, exacerbating their existing humanitarian challenges.



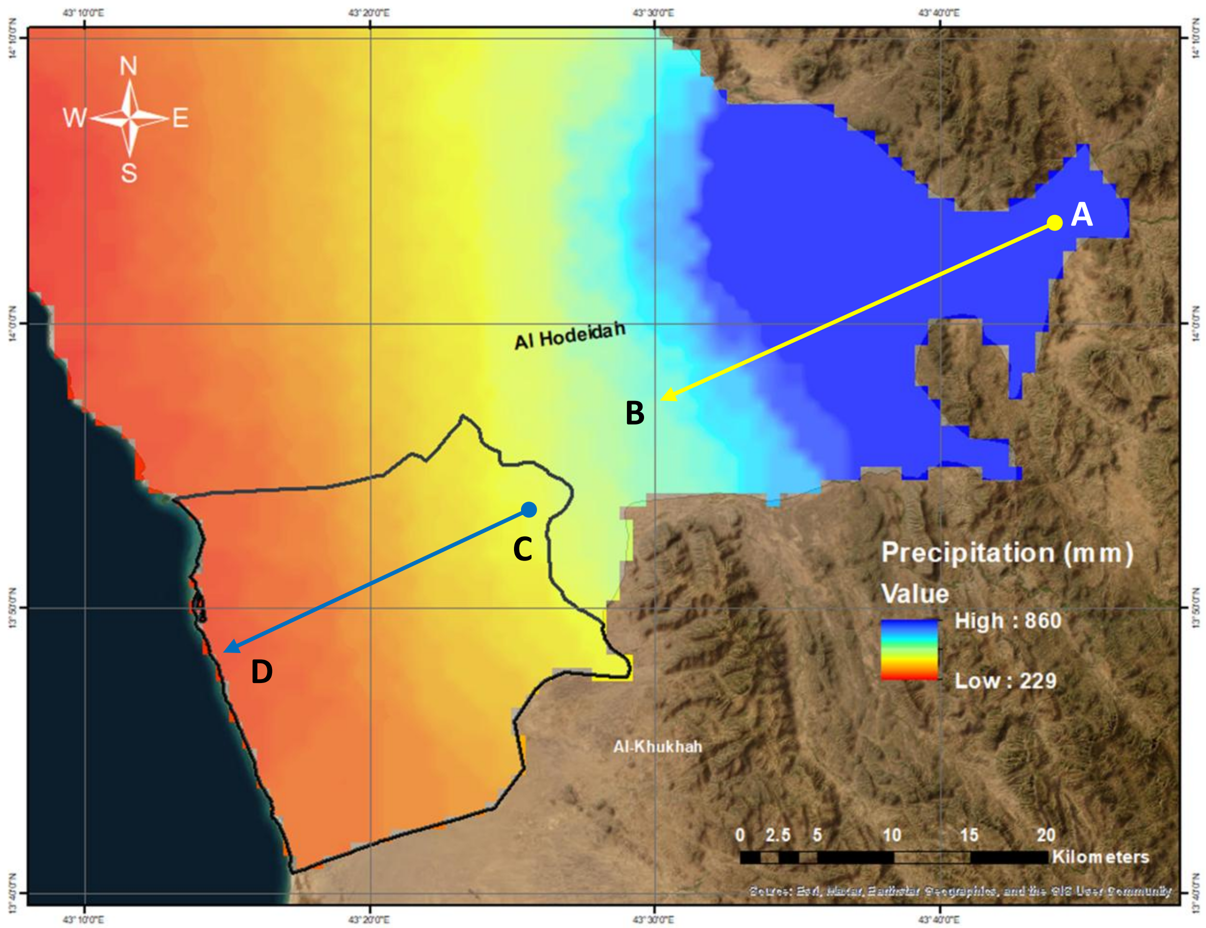


Fig. 7: ***Upper***: Rainfall concentration; ***Lower***: Direction of increasing rainfall. (Source: **the author**).

3. **Geographical Factors**:

    - The topography depicted in the map indicates that elevated areas, represented by dark-gray shading, have less flood risk due to natural drainage.

    - Coastal zones and flat regions are at higher risk due to their proximity to water sources and lack of elevation.

4. **Prioritization for Interventions**:

    - Areas with a combination of high flood risk and **IDP** concentration need urgent attention. These areas require targeted interventions such as flood mitigation measures and relocation strategies.

Flood Impacts

The map in Figure 7 depicts flood risk scores and the locations of internally displaced persons (**IDP**) sites in Yemen's Al-Hodeidah **governorate**, using two-dimensional hydraulic flood hazard modeling. Flood-prone regions, represented by yellow shades, vary in risk levels from low to extreme, with darker shades indicating higher risks. These areas are primarily concentrated in low-lying coastal zones and along river basins, while elevated regions, shown in dark-gray shading, are less prone to flooding due to natural drainage. Notably, many **IDP** sites, marked as blue dots, are situated within medium to high flood-risk zones, highlighting the vulnerability of displaced populations to flooding and exacerbating their existing challenges. Flooding in these areas poses significant risks, including displacement, damage to infrastructure such as roads and agricultural lands, and threats to water and sanitation systems, compounding **humanitarian** needs. Additionally, the overlap of high flood-risk zones and **IDP** concentrations underscores the urgency for targeted interventions, such as flood mitigation measures, disaster preparedness, and relocation strategies. Recurring floods also contribute to environmental degradation, including soil erosion and contamination of water sources, further stressing the region's fragile ecosystem. This map emphasizes the need for prioritizing disaster response and resource allocation to protect vulnerable communities.

Box 1: Flood Map Analysis

The flood map (Fig. 7), created using **satellite image analysis**, is an important tool for prioritizing flood mitigation actions and allocating resources to safeguard vulnerable populations in **Al-Hodeidah governorate**. It provides valuable insights into high-risk zones, enabling targeted interventions to minimize the adverse impacts of flooding on displaced populations and infrastructure. Furthermore, the map can guide policymakers in implementing long-term strategies such as improving drainage systems, reinforcing embankments, and adopting sustainable land-use practices. By integrating this data into disaster risk management plans, stakeholders can enhance resilience and reduce vulnerability, ensuring a safer environment for affected communities while addressing the broader implications of climate change.

Additionally, the flood map serves as a crucial reference for emergency response teams, allowing for more efficient evacuation planning and resource distribution during flood events. It also aids urban planners in designing flood-resistant infrastructure and housing developments, ultimately contributing to sustainable urban expansion. Moreover, continued monitoring and updates to the map can help track changes in flood patterns over time, enabling adaptive strategies that align with evolving environmental conditions.

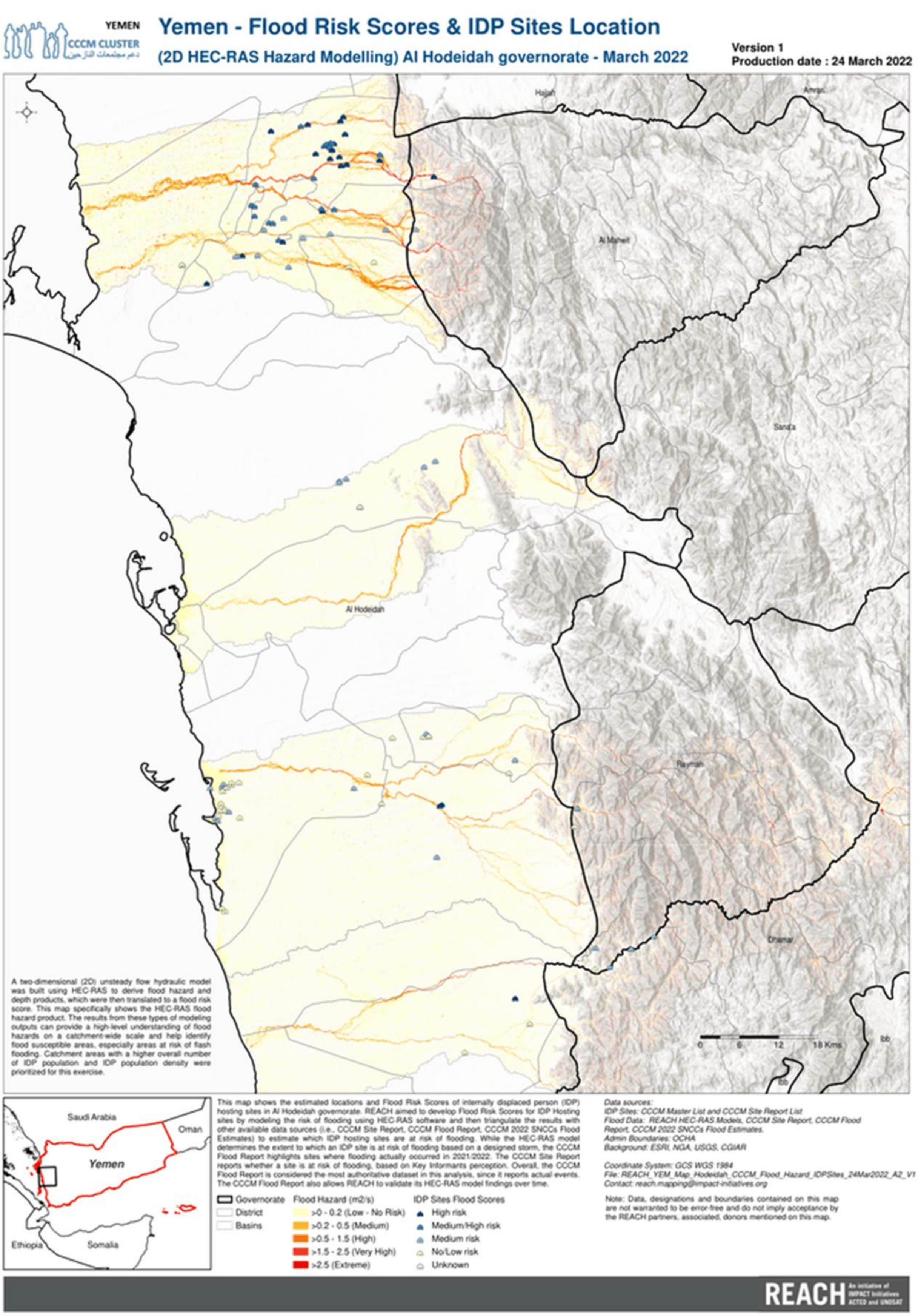
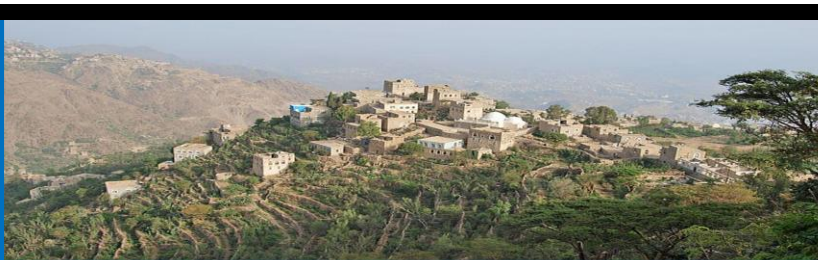


Fig. 8: Illustrates the flood zones within **Al-Hodiedah governorate** (Yellow areas). (Source: **REACH**.)

Taiz Governorate



II. Climate Change Impacts: Taiz

II.1. Overview

Climate Change and Its Impact on Taiz Governorate

Taiz **governorate**, situated in the **southern** highlands of Yemen, is one of the most populous regions in the country. It is characterized by a varied topography that includes mountainous terrain, valleys, and coastal areas (Figs. 9 and 10). This diversity makes the region particularly vulnerable to the multifaceted impacts of climate change.

Key Impacts of Climate Change on Taiz

1. **Rising Temperatures**:

   Taiz is experiencing increasing temperatures, which exacerbate water scarcity in an already arid environment. The rising heat intensifies evaporation rates, leading to reduced availability of surface and groundwater resources. This is particularly concerning for agricultural activities, which are the backbone of the region's economy.

2. **Erratic Rainfall Patterns**:

   The **governorate** has witnessed significant shifts in rainfall patterns, including irregular precipitation and shorter rainy seasons. These changes contribute to flash floods during intense rain events and prolonged drought periods, both of which severely impact agriculture, infrastructure, and local livelihoods.

3. **Flood Risks**:

   Climate-induced intense rainfall events have led to an increase in flash floods, particularly in urban areas with inadequate drainage systems. These floods damage critical infrastructure, displace communities, and spread waterborne diseases, posing a major public health risk.

4. **Drought Conditions**:

   Prolonged periods of drought, attributed to **climate change**, are becoming more frequent in **Taiz**. This has resulted in crop failures, reduced food security, and a decline in livestock productivity. The water crisis is further worsened as groundwater sources become increasingly depleted.

5. **Ecosystem Degradation**:

   Climate change is altering natural ecosystems in **Taiz**, leading to the loss of biodiversity. Forested areas in the governorate are shrinking due to deforestation and climate stress, which reduces their role in regulating the local climate and supporting agriculture.

6. **Humanitarian Challenges**:

   The combined effects of **climate change** and conflict in **Yemen** exacerbate vulnerabilities in **Taiz**. Displacement due to both conflict and climate-induced disasters has increased, placing additional pressure on limited resources. Internally displaced persons (**IDPs**) often face heightened exposure to climate risks, including floods and heatwaves.

Adaptation and Mitigation Measures

To address the growing impacts of **climate change**, **Taiz** requires targeted interventions:

- **Water Resource Management**: Investments in water harvesting, storage, and efficient irrigation systems can help mitigate water scarcity.
- **Climate-Resilient Agriculture**: Promoting drought-resistant crops and sustainable farming practices can enhance food security.
- **Disaster Preparedness**: Strengthening **early warning systems** and infrastructure to cope with floods and droughts is critical.
- **Reforestation and Ecosystem Restoration**: Protecting and restoring forests and ecosystems can help reduce the adverse effects of **climate change**.

Finally, Taiz **governorate** has considerable climate-related issues, particularly in the areas of water security, agriculture, and catastrophe risk. Addressing these concerns demands a comprehensive and inclusive approach that integrates local, national, and international efforts to strengthen resilience and secure the region's long-term prosperity.

Taiz **governorate** in Yemen has experienced several significant floods in recent years, notably in **2024**. Here are some of the major incidents:

- **August 2, 2024**: Severe flooding in the **Maqbanah district** of Taiz city resulted in **15** deaths and displaced approximately **10,000** people. The floods buried at least **80** wells, destroyed crops, and caused significant damage to houses and infrastructure.
- **April 2024**: Heavy seasonal rainfall from mid-March to late **April** led to flooding in many of **Yemen's governorates**, including Taiz. This event affected more than **18,000** families.
- **August 2024**: Torrential rains and widespread flooding damaged homes and shelters of host communities and internally displaced persons (**IDPs**) in Taiz. Approximately **5,321** families were affected during this period.

These incidents highlight the vulnerability of Taiz to flooding, particularly during the rainy seasons. In addition, Taiz has experienced multiple floods in the past due to seasonal rains, poor infrastructure, and the region's mountainous terrain. Here are a few historical instances:

2010: ***Event***: **Yemen**, including **Taiz**, was struck by severe flooding caused by unusually heavy rains. Many areas experienced flash floods that led to fatalities, infrastructure damage, and the displacement of people[24].

2009: ***Event***: Torrential rains caused rivers to overflow, leading to extensive flooding in **Taiz** and surrounding areas. Roads were damaged, and numerous families were displaced[25].

2008: ***Event***: Heavy rainfall in the region caused significant flooding in **Taiz**, damaging homes, infrastructure, and agricultural lands. Many rural communities were affected, and displacement was widespread[26].

1997-1998: ***Event***: The **El Niño** phenomenon brought torrential rains to **Yemen**, leading to severe flooding. This event was among the most damaging, with infrastructure, homes, and agricultural land destroyed[27].

II.2. Historical Data Analysis

The map in **Fig. 11** depicts spatial precipitation distribution across a specific area, with precipitation values presented in millimeters and classified into distinct ranges using a color gradient. The analysis and relevant remarks are as follows:

Data Analysis

1. **Precipitation Gradient**:

   The precipitation gradient across the area shows a clear west-to-east pattern, with the western part (red zone) receiving the lowest precipitation values, ranging from **211** to **599** **mm**. Moving eastward, precipitation increases

[24] Yemen Floods (2010) - Yemen Humanitarian Response Plan." United Nations Office for the Coordination of Humanitarian Affairs (OCHA).

[25] Yemen 2009: Flash Floods Impact Report." United Nations Development Program (UNDP).

[26] Floods and Rainy Season Impact in Yemen." International Federation of Red Cross and Red Crescent Societies (IFRC).

[27] El Niño and its Impact on Yemen's Weather and Flooding." The National Center of Meteorology, Yemen.

progressively, transitioning through orange, yellow, green, and blue zones, indicating a gradual rise in rainfall. The easternmost region (deep blue zone) experiences the highest precipitation levels highlighting a significant spatial variation in rainfall distribution.

2. **Geographical Influence:**

   The sharp precipitation gradient implies that topographical or climatic conditions play an important influence in determining rainfall distribution. Coastal areas in the west may receive less precipitation due to rain-shadow effects or proximity to arid regions, whereas eastern areas with higher precipitation are more likely to coincide with elevated terrains or regions affected by orographic rainfall, in which moist air is forced to rise and cool, resulting in increased rainfall.

3. **Area of Concern**:

   The core orange-to-yellow zones show moderate precipitation (**986-2,149 mm**). These areas could serve as a transitional buffer between desert and rainy zones.

4. **Variability in Precipitation**:

   The map (**Fig. 11**) shows significant regional heterogeneity, indicating different microclimates or weather patterns in the targeted area.

Comments and Implications

Effective management and planning techniques must account for the regional diversity in precipitation across the region. High-precipitation areas (blue zones) have a greater potential for groundwater recharge and surface water harvesting, whereas arid western zones have water scarcity concerns, needing effective water resource management. In terms of agriculture, locations with moderate-to-high precipitation (green to blue zones) are good for rain-fed farming, whereas arid areas may require irrigation. **Climate resilience** is crucial, as the arid **western zones** (red and orange) are more susceptible to drought, necessitating sustainable development techniques.

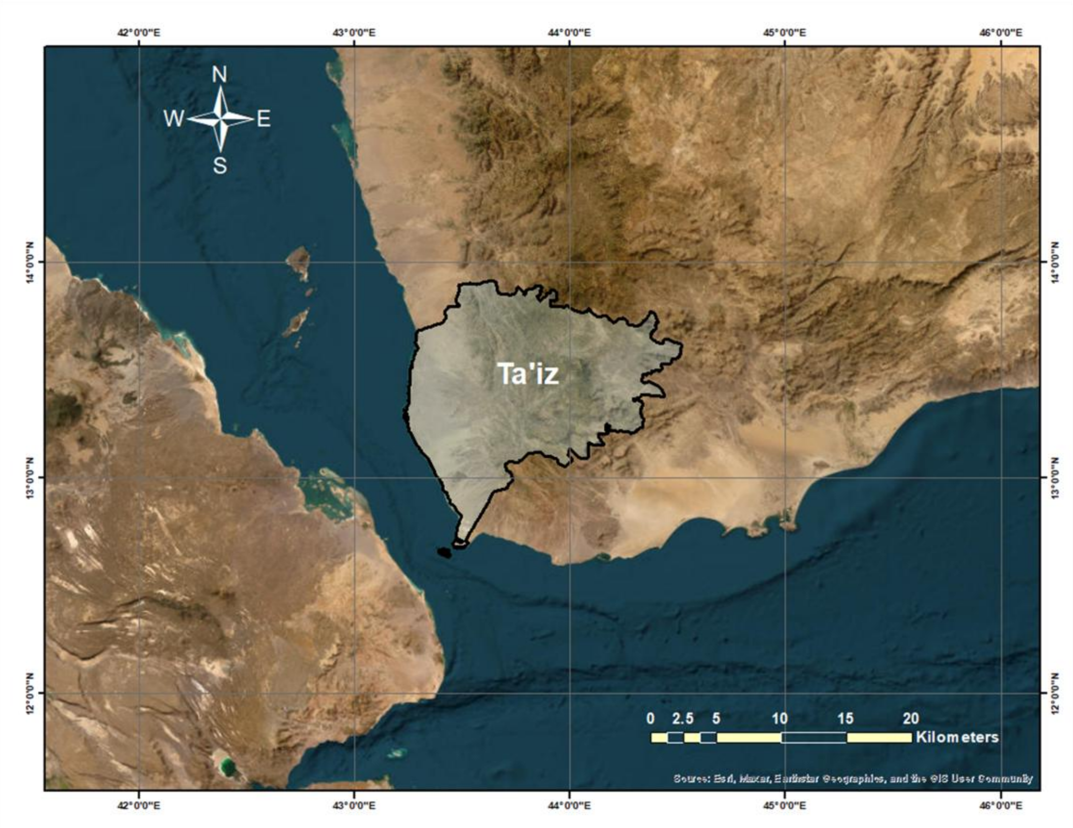


Fig. 9: Shows the geographic location of **Taiz governorate**. (Source**: the author**).

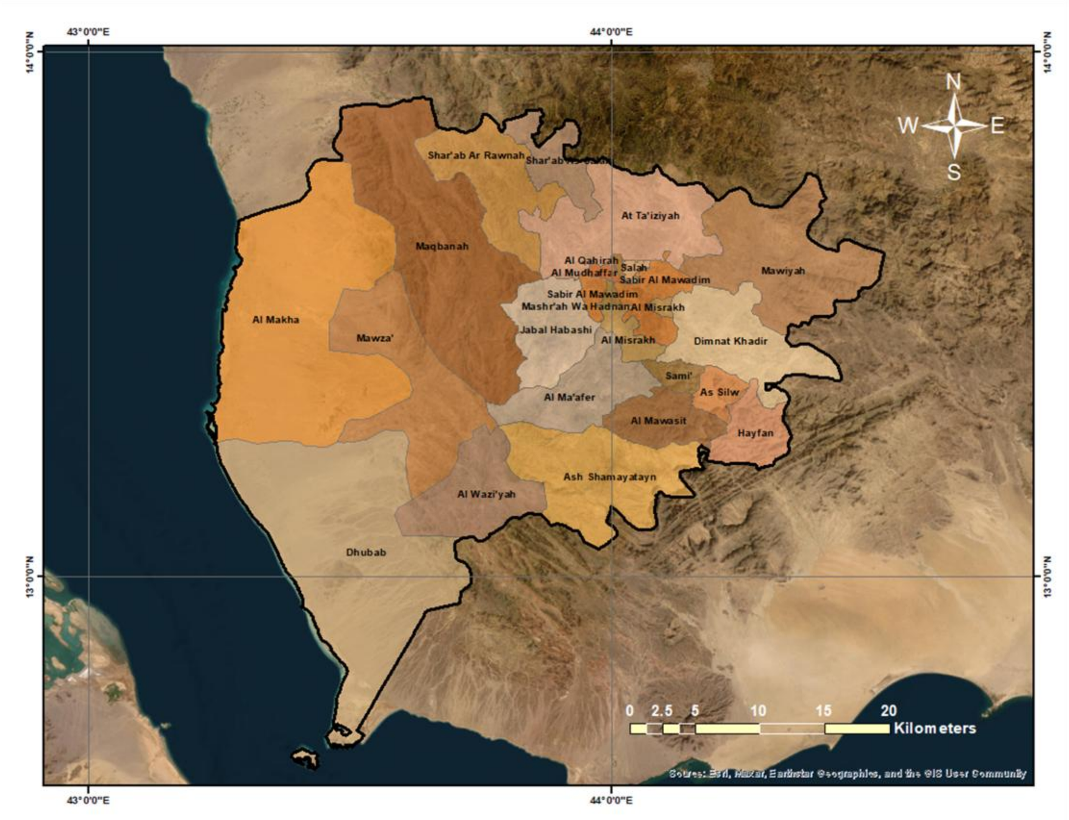


Fig. 10: Depicts the Districts of **Taiz governorate** (Source**: the author**).

Furthermore, while the eastern high-precipitation areas might support rich biodiversity, they may also be vulnerable to landslides and soil erosion caused by heavy rains. Urban and infrastructure planning should account for these differences, incorporating efficient water delivery systems in low-precipitation areas and focusing on flood control in high-precipitation areas.

To present a comprehensive study linking precipitation patterns on the map with land use, vegetation patterns, and disaster risk zones, the following is an enlarged analysis with implications:

Comprehensive Analysis

1. Precipitation and Land Use

Land-use planning in the region must account for the distinct precipitation zones and their respective characteristics. Arid zones (red to orange), with low precipitation levels of **211–986 mm**, are primarily suited for sparse settlements or urban areas reliant on imported water or advanced water management systems, limited agriculture with drought-resistant crops or livestock grazing, and solar energy projects due to clear skies. Water scarcity remains a key constraint for development in these areas. Moderate precipitation zones (yellow to green), receiving higher than **986 mm** of rainfall[28], are ideal for mixed agriculture, including rain-fed crops and horticulture, settlements with moderate water resource availability, and managed forest plantations or agroforestry projects. These regions serve as an ecological transition buffer between arid and wetter areas. High precipitation zones (blue), support dense forests, biodiversity-rich ecosystems, intensive agriculture with water-demanding crops like rice or tea, and hydropower generation or water-intensive industries. However, these areas require careful land-use planning to integrate soil conservation measures and mitigate erosion risks.

2. Precipitation and Disaster Risk Zones

28 **PERSIANN-CCS** grid rainfall data shows high values when compared to **TerraClimate** data. The **RESIANN-CCS** grid data was used to display rainfall concentrations in the **Taiz** region.

Precipitation zones in the region face distinct challenges and risks associated with their rainfall patterns. Low precipitation zones (red to orange) are at high risk of drought and desertification due to prolonged dry spells, along with dust storms and soil degradation, making effective water management strategies, such as desalination plants or reservoirs, critical. Moderate precipitation zones (yellow to green) are vulnerable to moderate droughts during below-average rainfall years and flash floods during intense rainfall due to limited water infiltration capacity, necessitating a balanced approach to water harvesting and soil conservation. High precipitation zones (blue) face significant susceptibility to disasters, including floods caused by excessive surface runoff, landslides in sloped terrains, and soil erosion from intense rainfall. Implementing disaster risk reduction strategies such as afforestation, terracing, and floodplain management is essential to mitigate these risks.

Implications for Study Area

1. **Integrated Water Management**:
   - Establish region-specific water management systems, including rainwater harvesting in arid zones and flood control measures in high-rainfall areas.
2. **Disaster Preparedness**:
   - Implement **early warning systems** for droughts and floods.
   - Develop community-based disaster resilience programs, particularly in blue zones prone to landslides and floods.
3. **Climate Adaptation Strategies**:
   - Link precipitation patterns to long-term **climate change** projections.
   - Develop adaptive plans for communities relying on natural resources.

The graph in Fig. 13 depicts precipitation trends (in **mm**) for a given polygon from January **2017** to January **2024**, as calculated using **TerraClimate** data. The analysis and its potential influence on the research region are presented below:

Analysis of Precipitation Patterns

1. **Seasonal Variations**

The data reveals recurring peaks and troughs, showcasing distinct seasonal precipitation patterns. High rainfall is concentrated during specific months, likely corresponding to monsoon or wet seasons, while dry periods dominate the remaining months.

2. **Inter-annual Variability**

The amplitude of precipitation varies significantly across years. For example:

- **2018** and **2021** experienced extreme peaks, with precipitation exceeding **60 mm**.
- In contrast, **2020** and **2022** displayed relatively lower and more consistent precipitation levels.

3. **Dry Periods**

Several prolonged dry spells are evident in the data, such as during late **2019**, **2022**, and early **2023**. These periods of notably low precipitation highlight potential drought risks.

4. **Trends and Fluctuations**

There are no clear linear trends indicating a long-term increase or decrease in precipitation. However, the observed high inter-annual variability suggests the possibility of shifting climatic conditions.

Insights and Implications of Precipitation Patterns

Extreme precipitation peaks could lead to localized flooding events, posing risks to infrastructure, agriculture, and human settlements. Conversely, prolonged dry periods, such as those observed in **2019** and **2022**, highlight vulnerabilities to drought, potentially stressing water resources, reducing agricultural productivity, and impacting local biodiversity. The significant variability in precipitation underscores the importance of adaptive water resource management strategies, enabling effective storage and distribution to mitigate risks during dry spells and capitalize on surplus water during wetter periods. Additionally, the observed fluctuations may serve as indicators of climate change's impact on the hydrological cycle, warranting further studies to understand long-term changes and their implications.

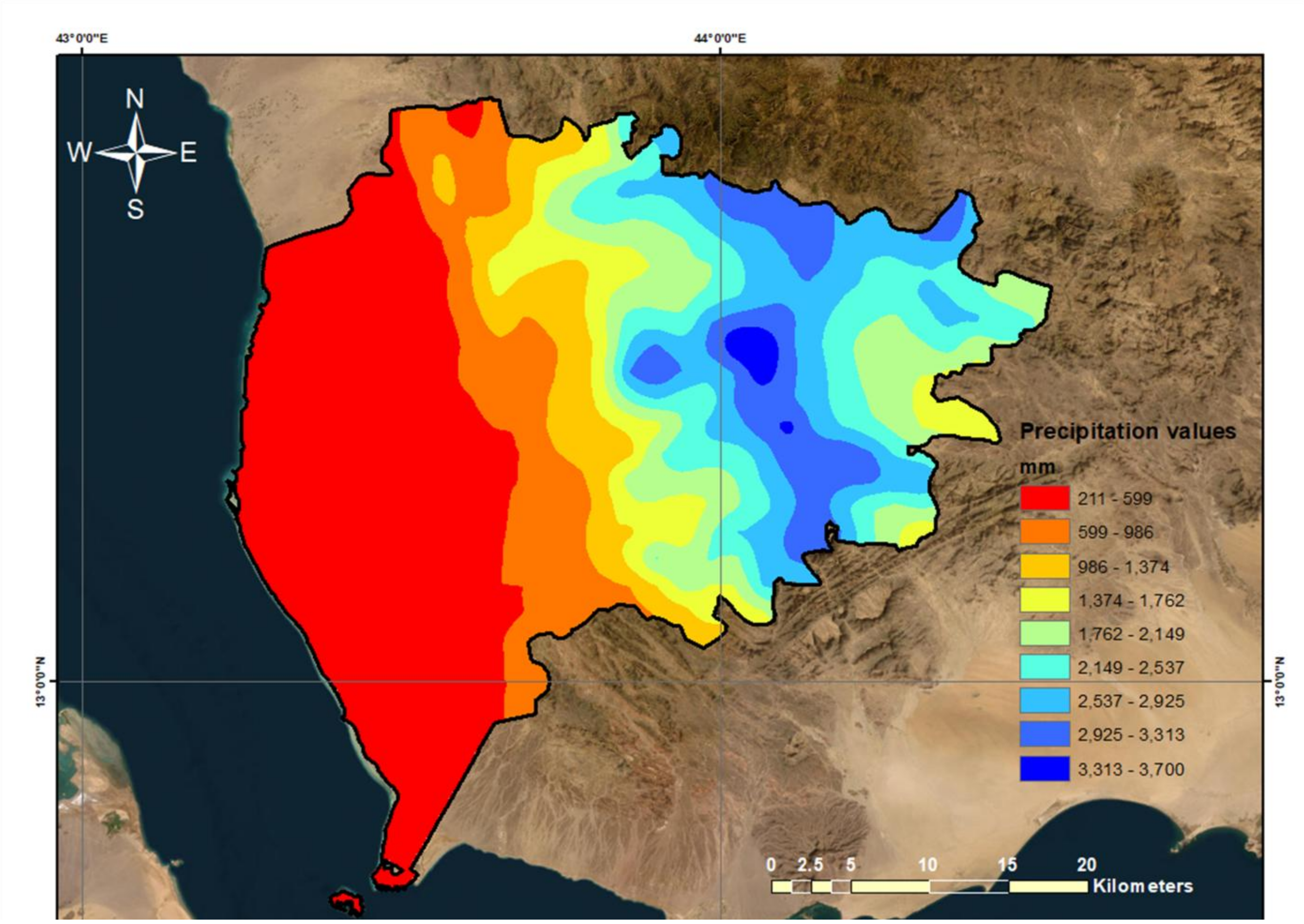


Fig. 11: Depicts the spatial rainfall distribution within Taiz **governorate** (Source**: the author**).

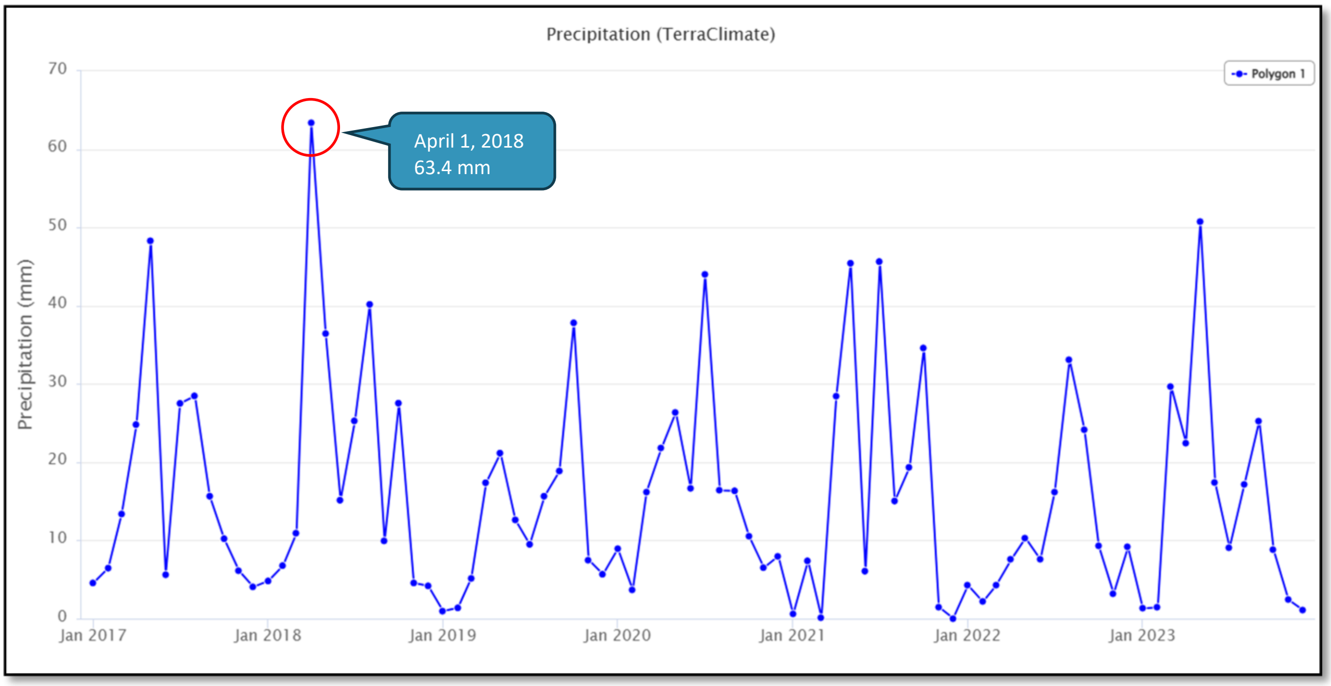


Fig. 12: Depicts the historical rainfall data of Taiz **Governorate** between **2017-2023** (**Data Source**: **TerraClimate**).

Flood Impacts on the Area

"Flood Impacts on the Area" investigates the consequences of flooding on local populations, infrastructure, and the environment, emphasizing the problems brought by frequent and severe floods. This evaluation sheds light on the damage caused by floods and the implications for livelihoods, public health, and economic stability as depicted in **Figure 13**.

1. Humanitarian Impacts

The **humanitarian** consequences of flooding are especially severe for internally displaced people (**IDPs**), as many **IDP** settlements are located in medium to high flood hazard zones, putting vulnerable populations at risk of displacement, injury, or death. **IDPs'** temporary shelters are often vulnerable to floods, increasing their risk of contracting waterborne infections, losing their housing, and experiencing livelihood disruptions. Flooding can also ruin roads and infrastructure, separating **IDP** settlements from critical services like healthcare, food supply, and education. This disturbance impedes the delivery of **humanitarian** aid, worsening already terrible living circumstances (**Fig. 13**).

2. Infrastructure and Settlement Impacts

Flooding endangers both urban and rural areas, with urban centers like **Taiz City** sustaining damage to homes, businesses, and public infrastructure such as highways and water delivery systems. Flooding in rural regions can destroy basic facilities and livelihoods based on agriculture, exacerbating vulnerability. Major transportation networks that run through high-hazard zones may become impassable, interrupting movement and trade, while bridges and culverts in flood-prone areas face increased danger of collapse or catastrophic damage.

3. Agricultural Impacts

Flooding in rural areas can cause crop destruction, loss of cultivated land, and soil erosion, all of which have a substantial influence on food security and agricultural output. Prolonged waterlogging in medium and high flood risk zones worsens the situation by lowering soil fertility and impeding re-cultivation attempts, making recovery difficult for impacted people.

4. Environmental Impacts

Flooding can cause severe environmental impacts, including erosion and land degradation, as high-intensity floods strip away topsoil, particularly in areas with steep slopes or inadequate vegetation cover, resulting in long-term damage to the land. Additionally, flooding often contaminates water sources with sewage, chemicals, and debris, posing significant health risks to humans and wildlife. The destruction of habitats in flood-prone areas further contributes to biodiversity loss, displacing both terrestrial and aquatic species and disrupting ecosystems.

5. Disaster Risk Amplification

Flooding in medium and high flood hazard zones perpetuates a cycle of displacement and poverty for impacted communities, compounding their vulnerabilities over time. **Climate change** exacerbates this risk, as flood frequency and severity are predicted to rise, emphasizing the critical need for long-term risk reduction initiatives to reduce these consequences.

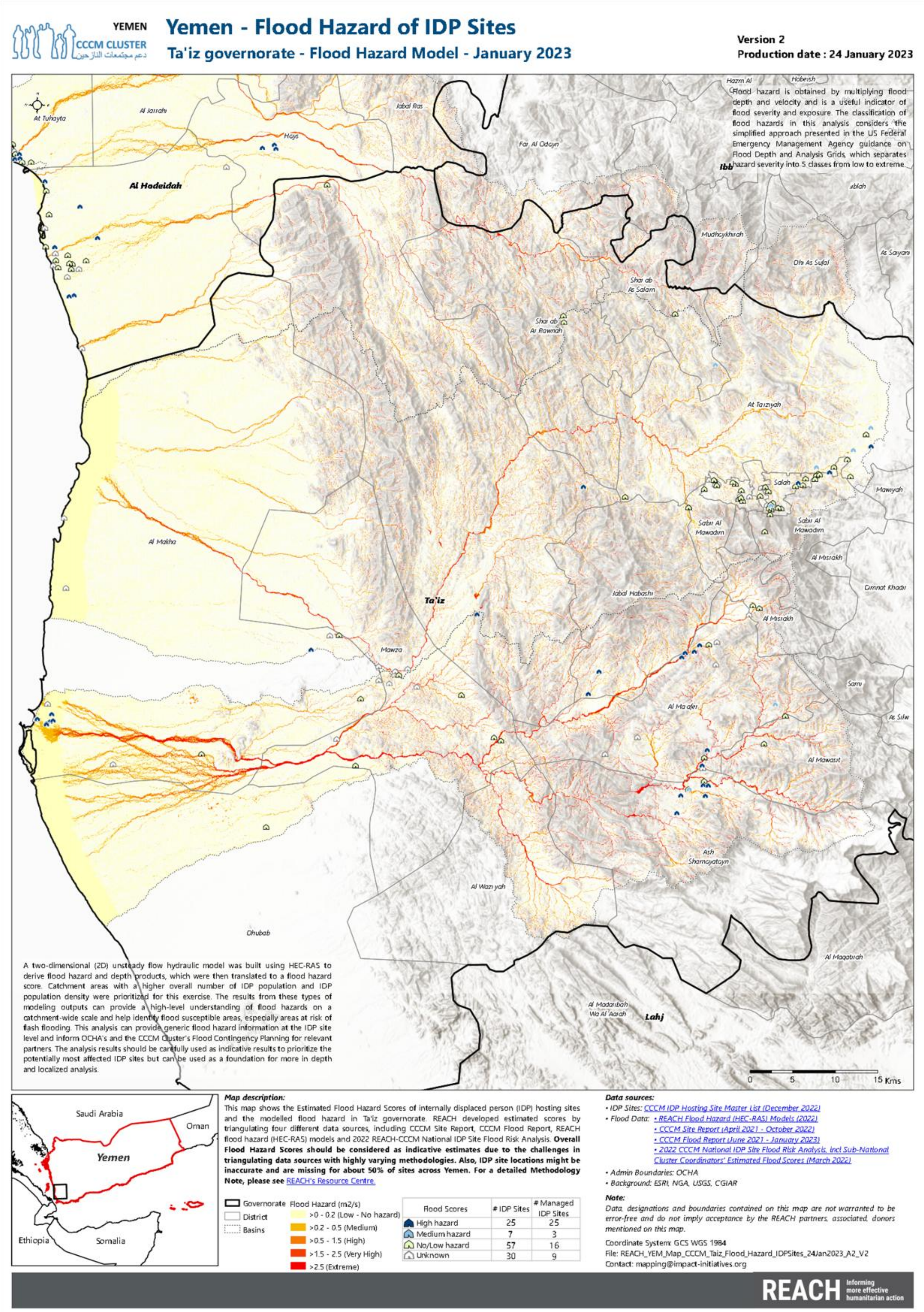


Fig. 13: Depicts the flooded areas of some parts of **Taiz Governorate** (**Source: REACH**).

Aden Governorate

III. Climate Change Impacts: Aden

III.1. Overview

Aden, a port city in **Yemen**, is strategically located along the north coast of the **Gulf of Aden**, situated on a peninsula that encloses the eastern side of **Al-Tawāhī Harbour**. This geographical positioning has historically made **Aden** a vital maritime hub[29] (**Fig. 14**). Despite its arid climate, **Aden** is not immune to the impacts of seasonal heavy rains. In recent years, torrential downpours have led to significant flooding, causing widespread damage to infrastructure and homes. For instance, in **mid-April 2020**, exceptionally heavy rains resulted in deadly floods across **Yemen**, including **Aden**, exacerbating the challenges faced by the war-stricken country[30] (**Figs. 15** - **18**).

The city's coastal location and topography contribute to its vulnerability to such natural disasters. Floodwaters can quickly inundate low-lying areas, leading to displacement and increasing the spread of waterborne diseases. The combination of conflict, inadequate infrastructure, and extreme weather events underscores the need for comprehensive disaster preparedness and resilient infrastructure development in **Aden**.

In **2020**, **Aden** experienced severe flooding that caused significant damage and loss of life. These floods swept through all regions, washing away countless cars and trucks and causing extensive damage to homes. The source reported that at least five people lost their lives as the flooding devastated numerous neighborhoods, destroying

[29] https://www.britannica.com/place/Aden?utm_source=chatgpt.com

[30] https://www.icrc.org/en/document/yemen-torrential-floods-wreak-havoc-war-stricken-country?utm_source=chatgpt.com

hundreds of homes and shops and leading to significant material losses. The following images depict the severe rain and the impact of these floods wreaking havoc across the city (**Figs. 15** - **18**).

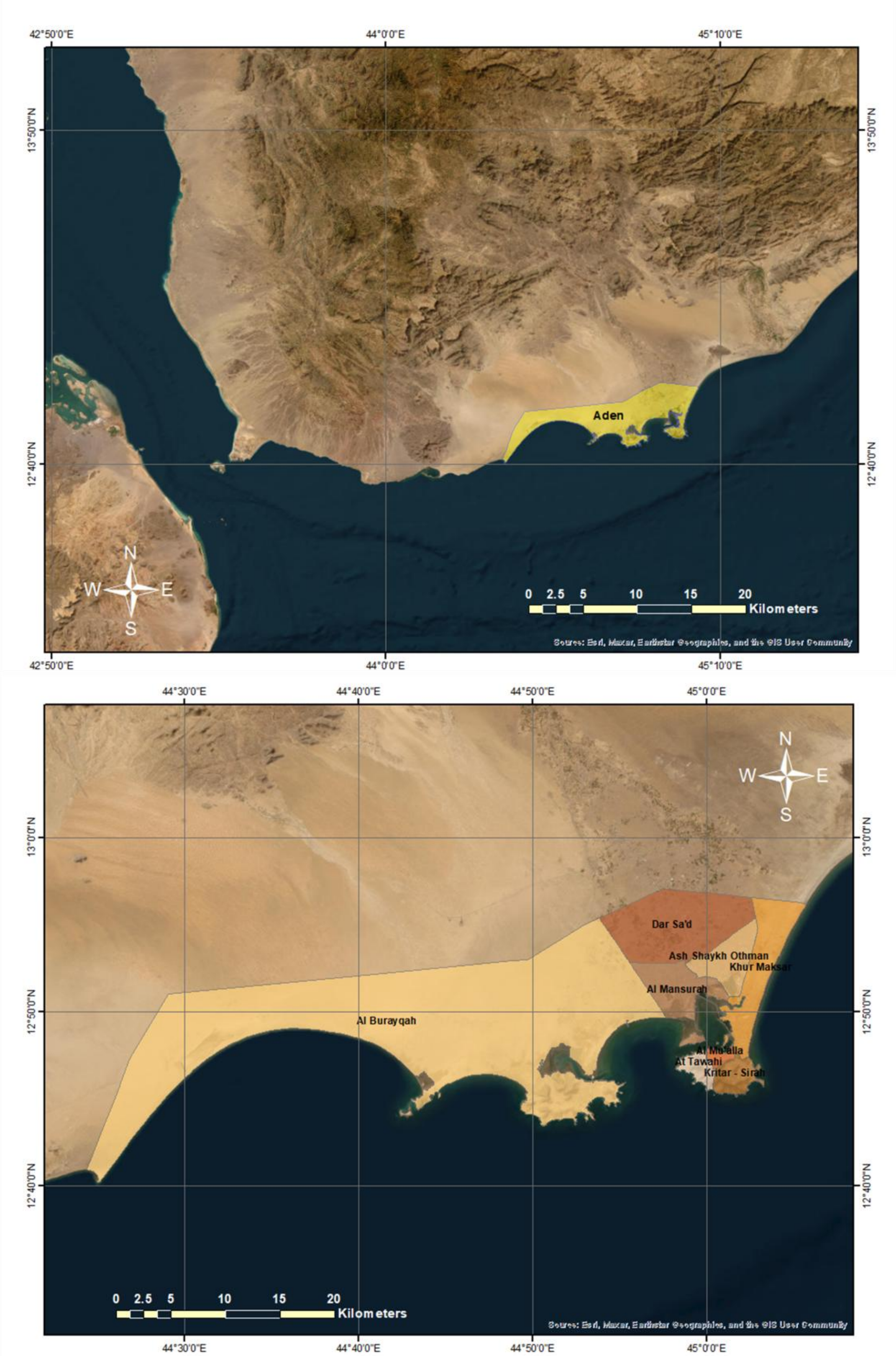


Fig. 14: Both maps depict the geographic location and the districts in **Aden** (Source**: the author**).

Fig. 15: Heavy rains which have caused massive torrential floods in **Aden** (**2020**). (Source: **ypagency**). https://en.ypagency.net/167427

Fig. 16: People stand on automobiles that were destroyed by the floods – **Aden** (**2020**). (Source: **ICRC**). https://www.icrc.org/en/document/yemen-torrential-floods-wreak-havoc-war-stricken-country?utm_source=chatgpt.com

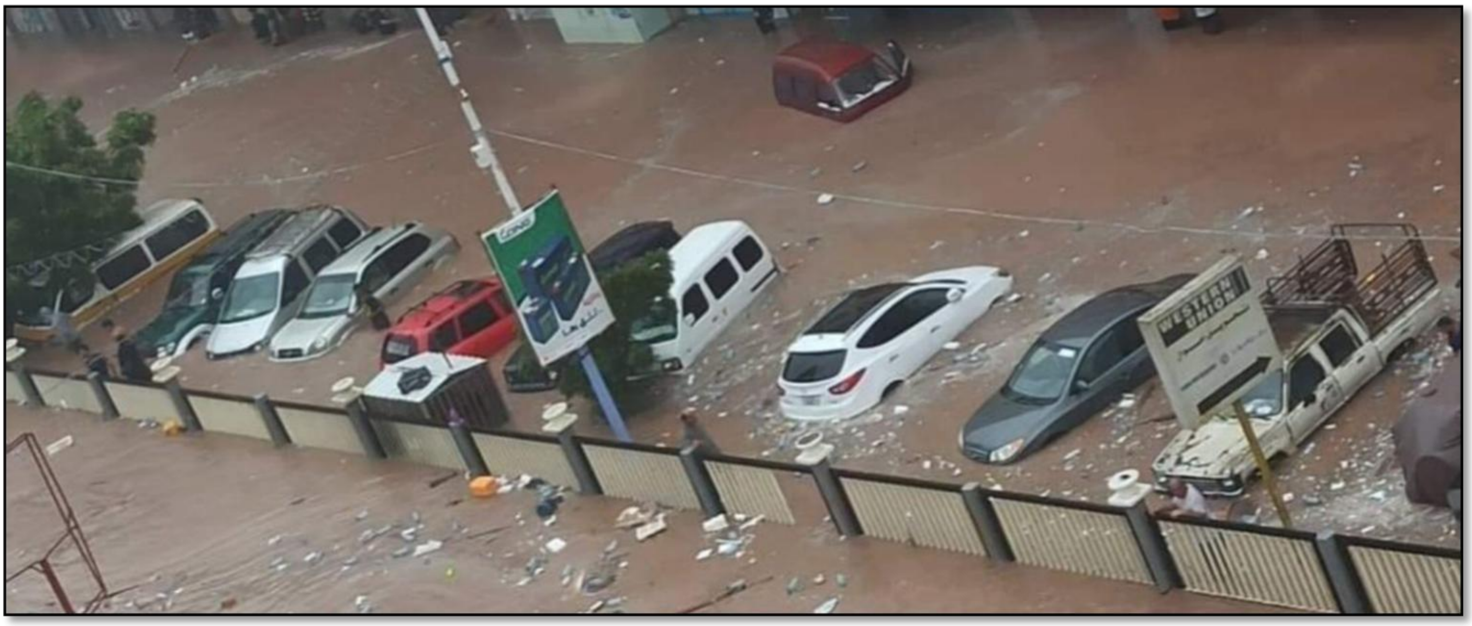


Fig. 17: Flood disaster destroyed the properties in **2020** – **Aden**. (Source: **middleeasteye, 2020**)
https://www.middleeasteye.net/news/yemen-aden-disaster-area-flash-floods.

Fig. 18: A devastating flash floods caused by up to **125 mm** (**5 inches**) of rain in just **24 hours** in **Aden**. (Source: **watchers**, **2020**).
https://watchers.news/2020/04/22/aden-declared-a-disaster-area-after-catastrophic-flooding-kills-10-yemen/, 2020

III.2. Climate Data Analysis

Numeric Precipitation Data Analysis

The chart of Figure 19 depicts daily precipitation data for the Aden region from **June 2017** to **December 2023**, measured in millimeters (**mm**) using **GPM** (**Global Precipitation Measurement**) data. The primary findings are shown below.

1. **Highly Variable Rainfall**:

   The precipitation data reveals substantial variability, characterized by numerous days with little to no rainfall, punctuated by sharp spikes indicating extreme rainfall events. This pattern is typical of arid and semi-arid regions like Aden, where rainfall is sporadic and often linked to specific weather systems.

2. **Extreme Rainfall Events:**

   Significant spikes in rainfall, particularly in **2019**, **2020**, and **2023**, with daily precipitation exceeding **100-175 mm**, likely correspond to severe storms or extreme weather events. These extreme events are often associated with flash floods, a persistent issue in Aden due to its low-lying geography and inadequate drainage infrastructure.

3. **Seasonality:**

   Rainfall in Aden shows no consistent seasonal pattern but is concentrated in brief, intense events rather than being evenly distributed throughout the year. This aligns with Aden's climate, which is influenced by tropical and subtropical weather systems that occasionally bring intense rain.

4. **Trends Over Time:**

   There are no clear signs of a gradual increase or decrease in annual rainfall totals, but the occurrence of extreme events suggests potential implications of climate change, which can amplify the intensity and frequency of such events.

Potential Impacts:

- **Flood Risk**: The sharp peaks, particularly in **2019** and **2020**, suggest a high likelihood of floods during these extreme rainfall events.
- **Urban Planning Challenges**: **Aden's** infrastructure must account for these extreme events to reduce damage and improve resilience.

Note: This preliminary historical climate data shows the prevailing rainfall conditions from **2017** to **2023**. This aids in the creation of an image of the predominant rainfall circumstances during these years, as well as understanding their impact on flood development and forecasting.

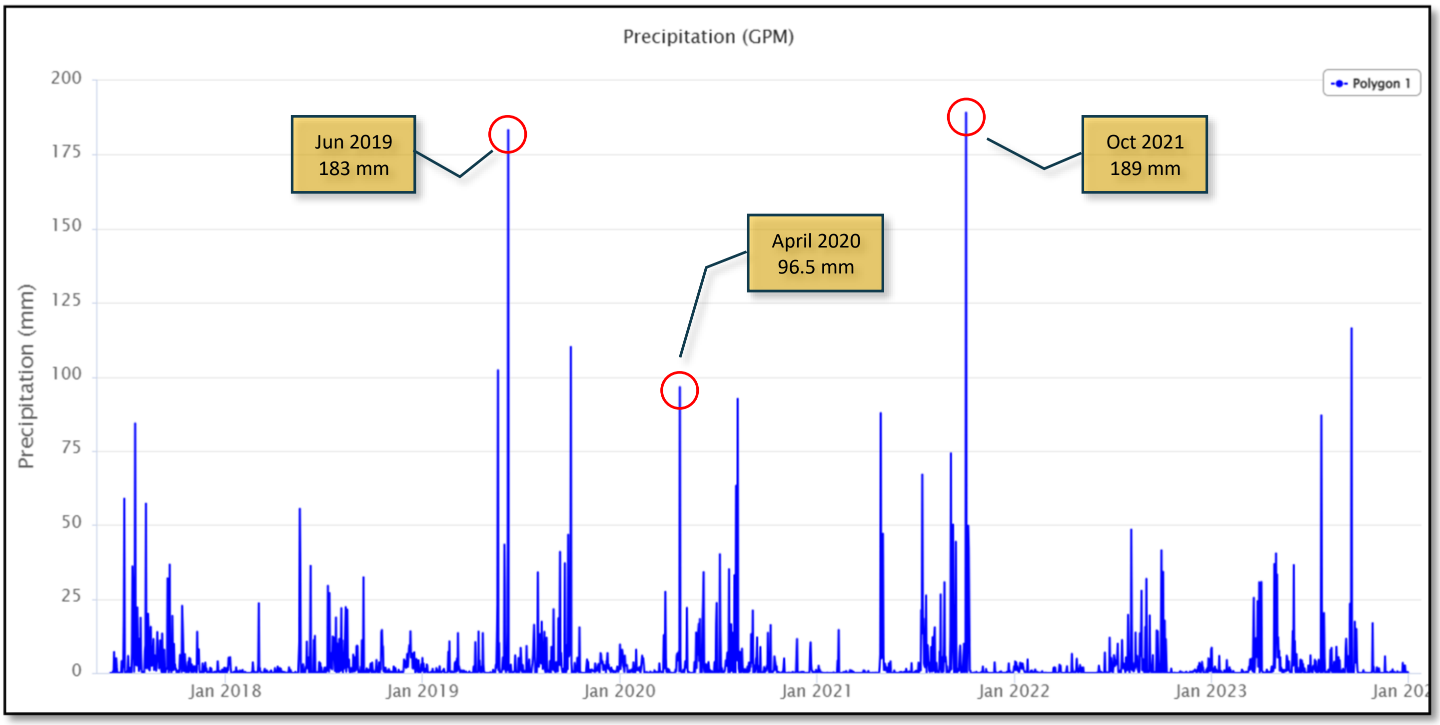


Fig. 19: The rainfall chart highlights the extreme variability of precipitation in **Aden** from **2017** to **2023**.

Benefits of Using Raster Images for Rainfall Analysis

Raster images provide a powerful tool for visualizing and analyzing spatial patterns of rainfall distribution over large areas. By representing data in a grid format, they allow for precise quantification of rainfall values at specific locations and the identification of gradients or hotspots. This format is particularly useful for:

1. **Spatial Analysis**: Enables detailed examination of rainfall variability across different regions, helping to identify areas of high and low precipitation.

2. **Data Integration**: Easily integrates with **Geographic Information Systems (GIS)** for combining rainfall data with other spatial datasets, such as population density or infrastructure locations.

3. **Decision Support**: Supports evidence-based planning and decision-making for flood risk management, water resource allocation, and climate adaptation strategies.

4. **Trend Analysis**: Facilitates tracking changes in rainfall patterns over time, essential for understanding the impacts of climate change and planning for future scenarios.

This type of visualization is extremely useful for making informed, location-specific decisions to reduce risks and better manage resources.

Raster Image Precipitation Data Analysis

Findings:

1. **Spatial Distribution of Rainfall**:

   The image of **Figure 20** depicts yearly rainfall levels in **Aden** from **2017** to **2023**, demonstrating a distinct spatial distribution. Rainfall is concentrated along the coast, with values ranging from **192-245 mm per year** (blue and cyan), whereas inland areas receive substantially less rainfall, **124-164 mm per year** (red and orange). As one proceeds further inland, a clear gradient of decreasing rainfall emerges.

2. **High-Risk Zones**:

   Coastal areas with higher rainfall are more prone to flash flooding, especially where urban centers and infrastructure intersect with these high-precipitation zones, while inland areas with lower rainfall face challenges related to water scarcity, including drought and limited water resources for agriculture and livelihoods.

3. **Vulnerability to Extreme Events**:

   The difference in rainfall across the region implies a vulnerability to extreme rainfall events in high-rainfall zones, which can enhance flooding hazards in urban and low-lying coastal areas.

Suggestions:

1. **Flood Mitigation**:

   To effectively prevent flash floods in high-rainfall coastal areas, it is critical to improve drainage infrastructure and develop **Early Warning Systems** (**EWS**) customized to specific high-risk zones. Upgrading drainage systems to handle extreme rainfall improves water management and reduces the likelihood of flooding, whereas **EWS** based on **real-time rainfall** patterns can provide timely alerts to authorities and communities, allowing for proactive responses to potential flood risks. This comprehensive method helps to limit flood damage and protect sensitive locations.

2. **Integrated Water Resource Management**:

   To address water scarcity and balance regional water availability, areas with higher rainfall can be utilized for rainwater harvesting, collecting and storing excess water. This harvested water can then be distributed to areas with lower rainfall through well-designed storage and distribution systems, ensuring a more equitable and sustainable water supply across regions.

3. **Urban Planning**:

   To mitigate flood risks along the coast, it is essential to restrict construction in high-risk flood-prone areas while simultaneously introducing green infrastructure, such as permeable pavements and urban green spaces. These measures will not only reduce surface runoff but also protect vulnerable areas from flooding, promoting a more sustainable and resilient urban environment.

4. **Drought Resilience**:

To address limited water availability in inland regions, water conservation measures such as drip irrigation should be supported, while exploring sustainable solutions like desalination or groundwater recharge to ensure reliable water access in arid zones. This combined approach helps optimize water use and ensures long-term water security in areas facing water scarcity.

5. **Data-Driven Decisions**:

To effectively manage flood and drought risks, sophisticated hydrological modeling is required to predict flood hazards and inform zoning rules, as well as constant monitoring of precipitation trends to adjust strategies for management in real time. This combination approach enables informed decision-making and proactive steps to mitigate the impacts of both flooding and drought.

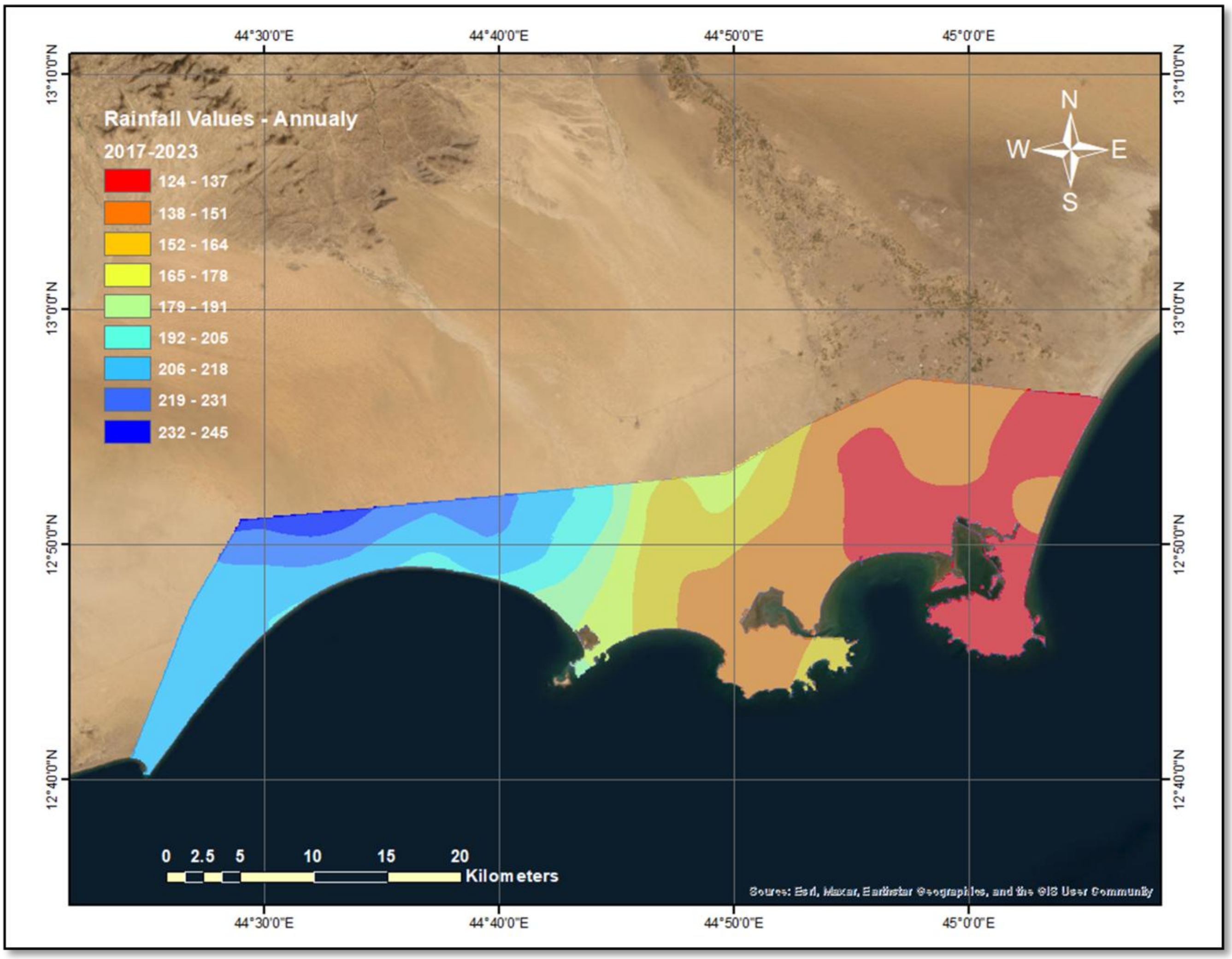


Fig. 20: The map depicts the rainfall distribution within **Aden Governorate (**Source**: the author**).

Hadramout Governorate

IV. Climate Change Impacts: Hadramout

IV.1. Overview

Geography of Hadramout Governorate

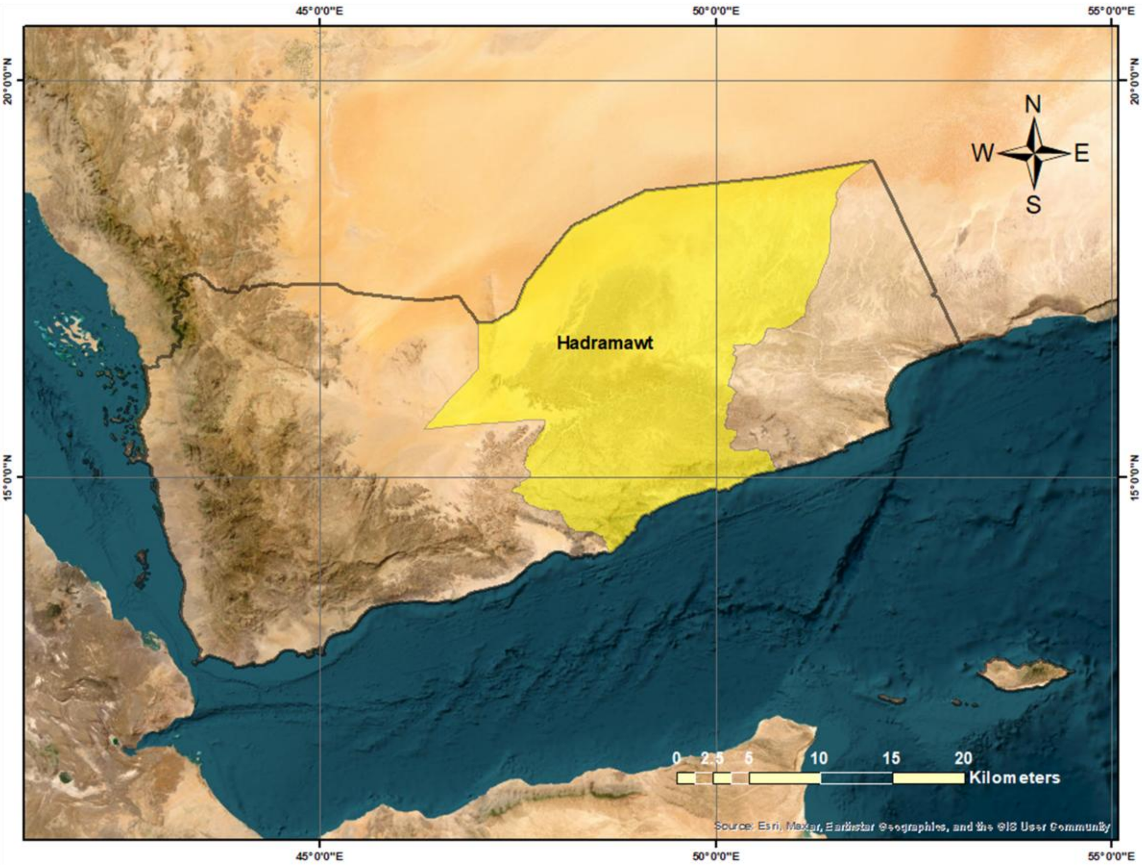
Hadramout is the largest governorate in Yemen, located in the eastern part of the country. It stretches from the coast of the Arabian Sea to the vast deserts in the north, including parts of the Rub' al Khali (Empty Quarter), (Figure 21). The governorate is characterized by a diverse landscape, including mountains, valleys, and coastal plains. The Wadi Hadramout, a large valley, runs through the region, making it an important agricultural and cultural area. The climate is arid, with hot temperatures and minimal rainfall[31].

Al-Mukalla City

Al-Mukalla is the **capital city** of Hadramout **governorate** and a major port on the Arabian Sea. Located on the coast, it serves as an important economic hub due to its strategic location for trade and fishing. Al-Mukalla has a rich history, with historical sites and traditional architecture, reflecting its cultural heritage. The city has a mix of modern and traditional infrastructure and is a key center for commerce, with a focus on maritime activities, oil exports, and agriculture[32] (Figs. 22 & 23).

[31] https://www.preventionweb.net/publication/damage-losses-and-needs-assessment-october-2008-tropical-storm-and-floods-hadramout-and?utm_source=chatgpt.com

[32] https://www.britannica.com/place/Al-Mukalla?utm_source=chatgpt.com



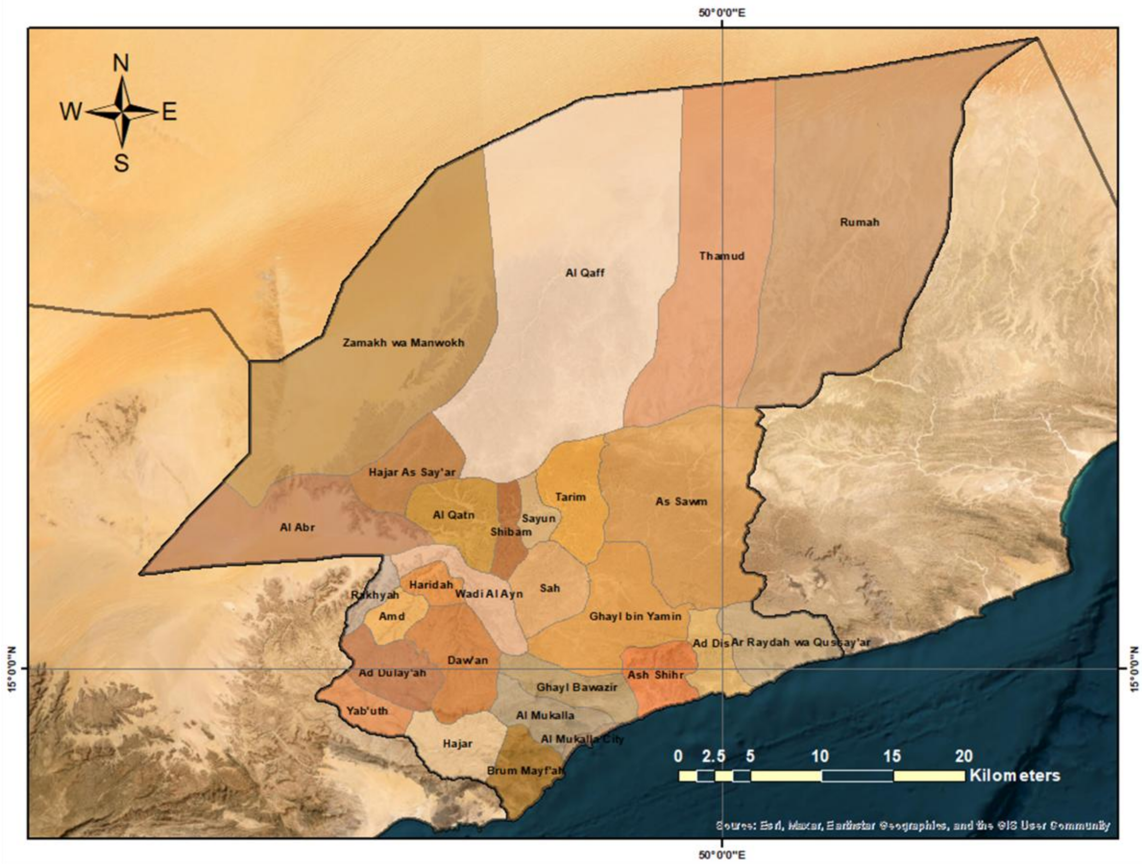


Fig. 21: ***Upper***: depicts the geographic location of **Hadramout** at the **Arabian Peninsula**; ***Lower***: shows the districts of **Hadramout governorate**. (Source: **the author**).

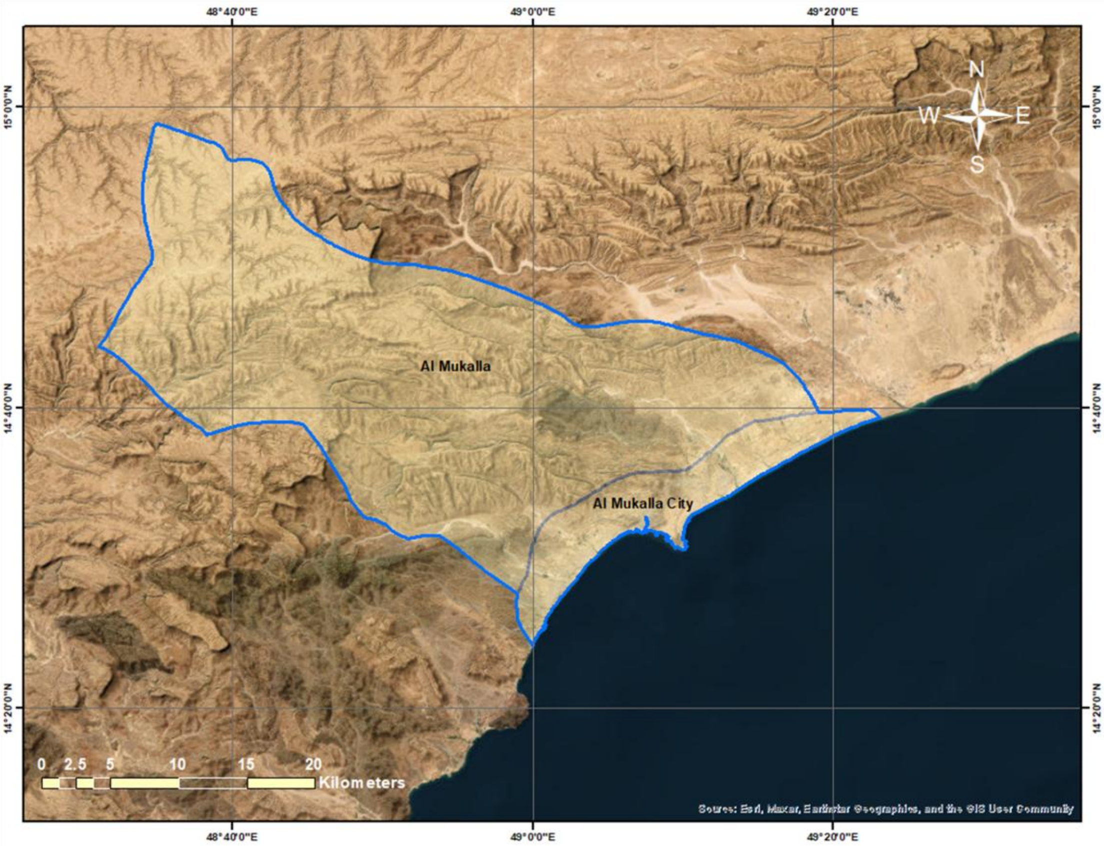


Fig. 22: Depicts the **Al-Mukalla Governorate** and **Al-Mukalla City** location. (Source: **the author**).

Fig. 23: Shows part of **Al-Mukalla City** (Source: **www.flickr.com**).

IV.2. Flood History in Hadramout Governorate and Al-Mukalla City

Hadramout governorate and its **capital**, **Al-Mukalla**, have seen many major flooding occurrences in recent years, owing mostly to strong seasonal rains. These floods have caused extensive damage to infrastructure, residences, and agricultural grounds, resulting in loss of life and displacement (**Figs. 24** & **25**).

- **2008 floods:**

Tropical Storm **03B** hit **Hadramout** and **Al-Mahra governorates** in **October 2008**, causing heavy rain and flooding. The storm dumped over **91 mm** of rain over **30 hours**, substantially more than the average **5-6 mm**. This event claimed **73** lives, left **17** persons missing, and caused major damage to infrastructure and residences[33].

- **2021 Floods:**

In **May 2021**, heavy rainfall caused flooding in the city of **Tarim**, located in **Hadramout**. The torrential rains resulted in the deaths of **13** individuals and displaced many families[34].

- **2024 Floods:**

In **April 2024**, **Al-Mukalla**, the capital city of **Hadramout Governorate**, faced considerable flooding as a result of heavy rainfall. The severe rains caused widespread flooding in the city, resulting in significant damage to infrastructure and residences. The floods severely impacted **internally displaced persons** (**IDP**) camps in the governorate, inflicting widespread destruction and displacement. These repeated floods show **Hadramout** and **Al-Mukalla's** vulnerability to extreme weather events, emphasizing the importance of better flood control and infrastructure resilience.

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33 https://www.preventionweb.net/publication/damage-losses-and-needs-assessment-october-2008-tropical-storm-and-floods-hadramout-and?utm_source=chatgpt.com

34 https://ensany.com/campaign/3699?utm_source=chatgpt.com

Fig. 24: The floods caused significant damage to the service and agricultural sectors – **Al-Mukalla**. (Source: **hodhodyemennews**).
https://hodhodyemennews.net/en_US/2024/04/18/floods-in-hadhramaut-cause-significant-damage-kill-one-person/

Fig. 25: The floods caused significant damage to the service and agricultural sectors – **Al-Mukalla**. (Source: **Daily Sabah**).
https://www.dailysabah.com/world/mid-east/flooding-from-heavy-seasonal-rains-kills-16-in-yemen

IV.3. Climate Data Analysis

Numeric Precipitation Data Analysis

The scene (**Fig. 26**) depicts a time series graphic of precipitation data from the **GPM** (**Global Precipitation Measurement**) mission. It plots precipitation in millimeters (**mm**) with time, from early **2018** to early **2024**. Below is a detailed description of time-series precipitation data:

Key Observations

The plot highlights distinct peaks indicating extreme precipitation events, with the highest occurring in early **2019** and early **2023**, exceeding **80-100 mm**. Precipitation is sporadic, with long dry periods interrupted by short, intense rainfall events, possibly showing seasonal patterns. Extended low-intensity periods are evident between these peaks. The irregular and extreme spikes may reflect the impact of **climate change**, contributing to more intense and unpredictable rainfall patterns.

Implications

High precipitation maxima may cause floods in sensitive regions such as **Hadramout** and **Al-Mukalla**, resulting in substantial infrastructure damage. Rainfall is sporadic, emphasizing the importance of rainwater harvesting and storage for resource management during dry years. Furthermore, this information is critical for building **early warning systems** to predict and mitigate the effects of extreme precipitation events.

Recommendations

Long-term monitoring using **GPM** data is essential to assess the effects of climate variability in the region. Correlating precipitation peaks with flood or drought events can help understand their direct impacts, while analyzing seasonal and inter-annual variability can reveal patterns and trends. This data should guide the design of resilient drainage and storage infrastructure to handle heavy rainfall and water shortages.

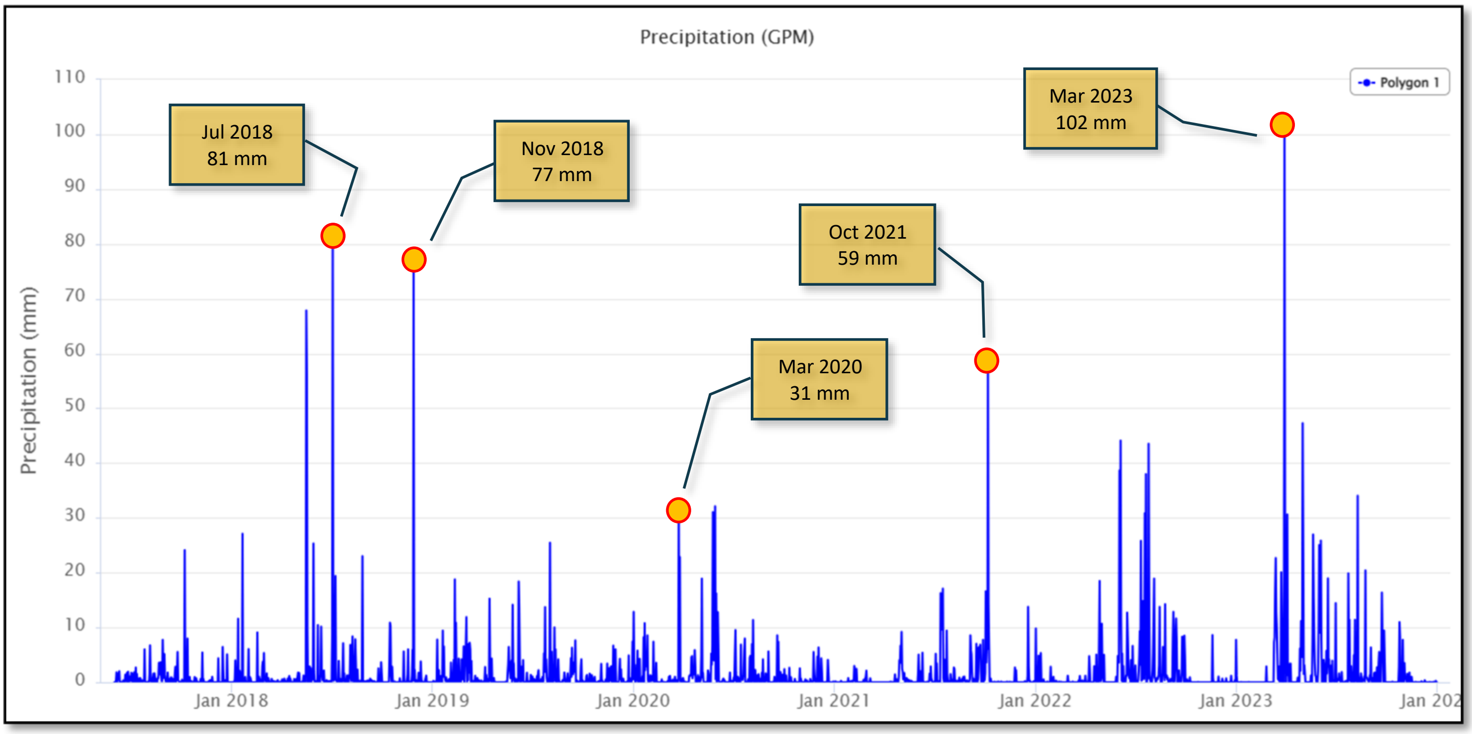


Fig. 26: The rainfall chart highlights the extreme variability of max. precipitation values in **Al-Mukalla** area from **2017** to **2023**. (Source: **Giovanni**). https://giovanni.gsfc.nasa.gov/giovanni/#service=VtPf&starttime=&endtime=&dataKeyword=Precipitation

Raster image Precipitation Data Analysis

Analysis

Precipitation Distribution and Geographical Context

Rainfall across the region shows significant spatial variation, increasing progressively from the southeastern coastal areas, such as **Al-Mukalla City**, toward the northern and western inland regions. Coastal areas, marked in **red (115–142 mm)**, experience relatively low rainfall, aligning with their arid to semi-arid climate. Inland areas show moderate rainfall levels, represented by **orange to yellow (143–202 mm)**, while the northern and western regions exhibit significantly higher rainfall, marked by **blue and green shades (292–396 mm)** (**Fig. 27**).

This stark contrast in precipitation levels is influenced by geographical factors, with inland highlands benefiting from orographic lifting due to topographic features, while coastal zones remain drier. The map highlights these variations, emphasizing the need for tailored water resource management and infrastructure planning across the region.

Implications

Low-lying coastal locations with minimal precipitation may still face flash flooding dangers from infrequent heavy rainfall events, particularly during extreme weather conditions. To address this, heavier rainfall locations in the inland regions might be targeted for rainwater collection and storage systems, which would help to feed the drier coastal zones. **Al-Mukalla City** should also implement climate-resilient urban development techniques to deal with the problems provided by low rainfall and probable extreme events. Furthermore, interior locations with higher rainfall are better adapted to agricultural activities, but arid coastal areas will require effective water management measures to maintain agriculture.

Integrated Climate-Resilient Nexus Solutions for Hadramout

1. **Water-Climate Nexus**

   Challenges:

   Coastal areas like **Al-Mukalla** face water scarcity due to low rainfall, while inland regions with higher rainfall often lack adequate infrastructure for water harvesting. **Climate change** worsens the frequency and intensity of extreme events, such as flash floods and prolonged droughts.

   Nexus Solutions:

   To address this, rainwater harvesting systems should be implemented in high-rainfall inland areas, with the collected water used to replenish groundwater or supply arid coastal zones. Additionally, integrated desalination and groundwater recharge systems powered by renewable energy can ensure sustainable water availability. Monitoring precipitation patterns through satellite data, such as **GPM**, will help adapt water management strategies in real-time.

2. **Food-Climate Nexus**

Challenges:

Agriculture in inland areas with higher rainfall is increasingly vulnerable to erratic precipitation patterns and flooding. Coastal regions, grappling with water shortages, struggle to maintain agricultural productivity.

Nexus Solutions:

Promoting climate-resilient crops and advanced irrigation techniques, such as drip irrigation, can conserve water and enhance yields. Establishing efficient food storage and distribution systems that prioritize water-energy management will help mitigate climate-related disruptions to food security.

3. **Integrated Nexus-Based Solutions**

Flood Management:

Using rainfall data from maps and models will allow for better flood prediction and guide the strategic placement of infrastructure, such as dams and drainage systems. Green infrastructure, such as permeable pavements and urban green spaces, should be introduced to reduce runoff and mitigate flooding, especially in urban areas like **Al-Mukalla**.

Policy and Governance:

Policies must integrate water, energy, and food systems into climate adaptation strategies to foster sustainable development. Raising community awareness about climate-resilient practices and the **Nexus approach** will ensure effective stakeholder participation.

4. **Climate Change Resilience Through the Nexus Approach**

The **Nexus approach**, which recognizes the interconnections between water, energy, and food systems, offers a holistic solution to climate challenges in Hadramout. By addressing multiple dimensions simultaneously, it enhances resource use efficiency, mitigates environmental impacts, and boosts the region's capacity to adapt to climate variability, fostering long-term sustainability.

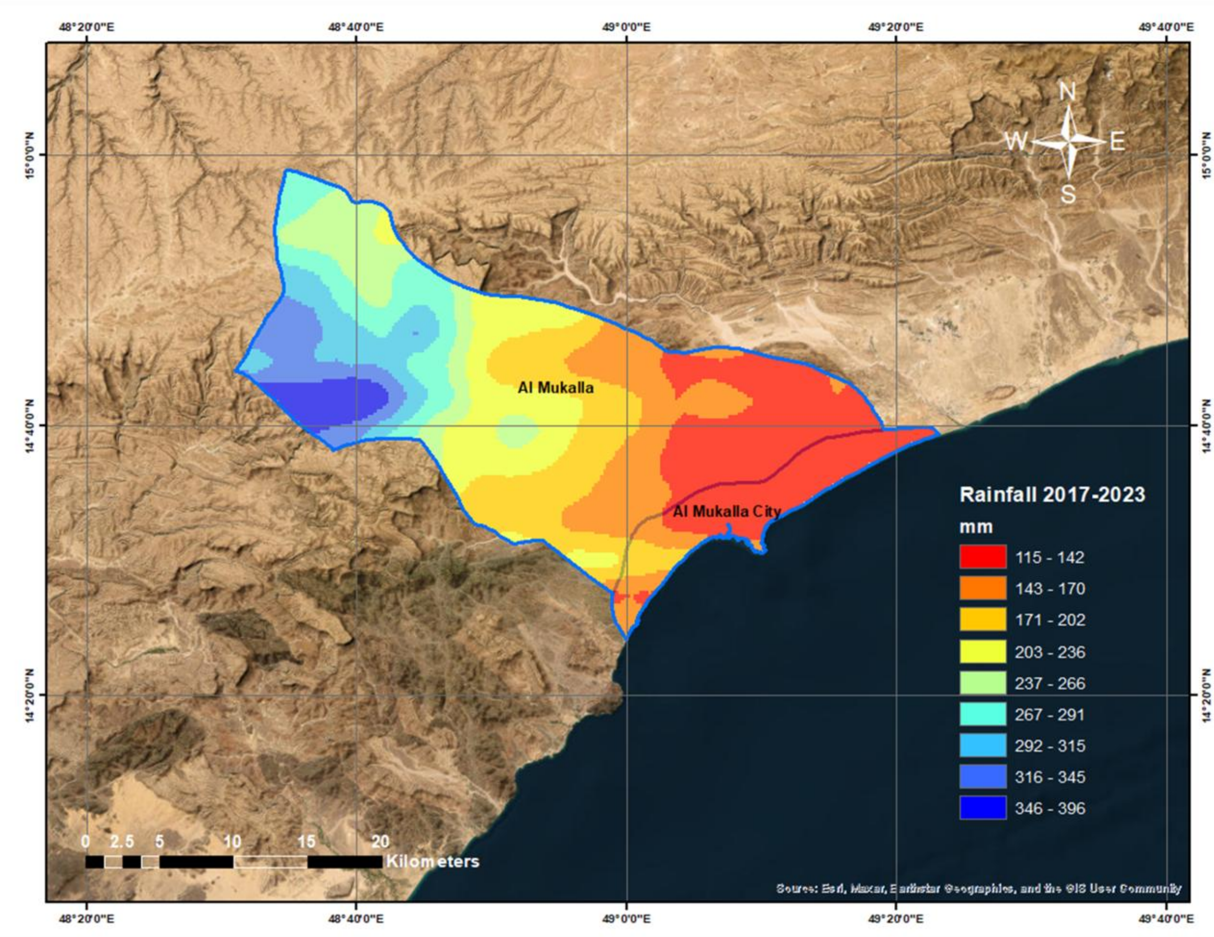


Fig. 27: Shows the rainfall distribution within **Al-Mukalla district and Al-Mukalla city** (Source: **the author**).

Marib Governorate

V. Climate Change Impacts: Marib

V.1. Overview

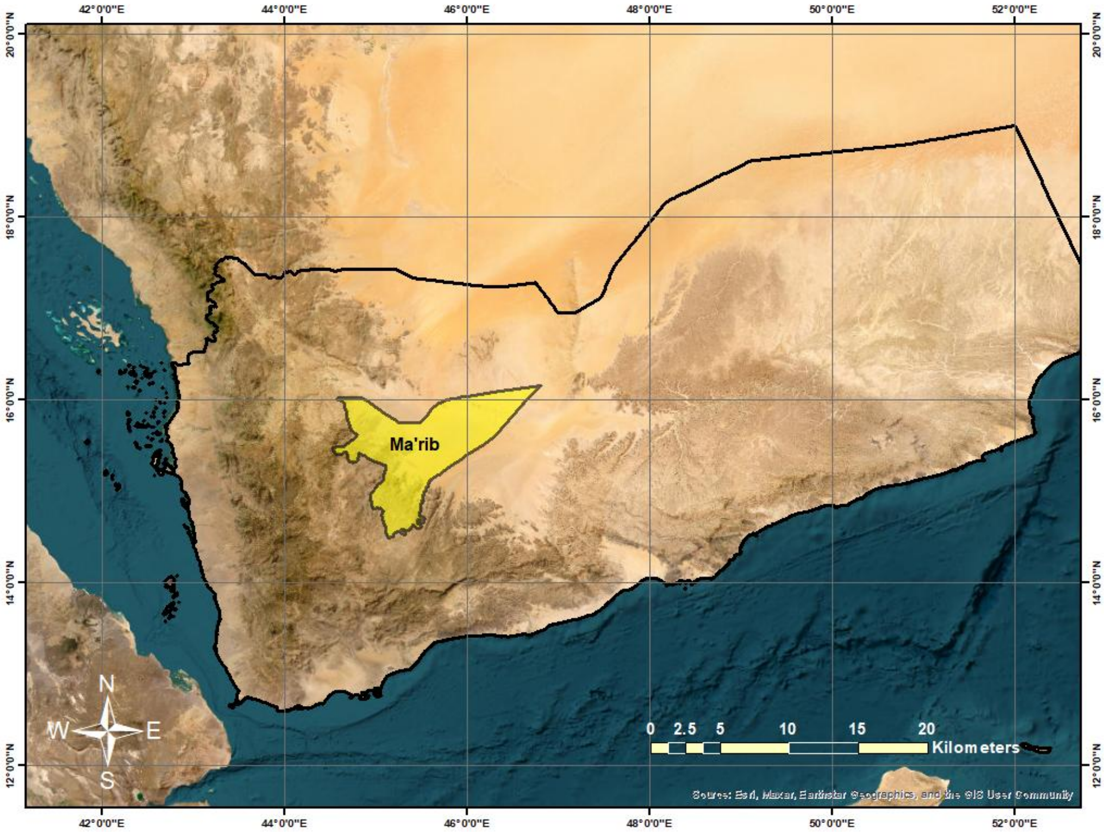
Geography of Marib Governorate

Marib is located in the northeastern part of Yemen on the Arabian Peninsula, approximately **173** kilometers east of the capital, Sana'a. Geographically, it lies at the edge of the Rub' al Khali (**Empty Quarter**), the largest continuous sand desert in the world, and is bordered by mountainous terrain to the west and expansive desert plains to the east (Fig. 28). Historically, Marib served as a critical hub connecting the southern Arabian trade routes to the northern regions, playing a significant role in the incense trade. Its strategic position between fertile valleys and desert landscapes made it a vital area for ancient civilizations, such as the **Sabaean Kingdom**.

Historically, it was the center of the old **Sabaean** monarchy, with Marib acting as the capital. The area is notable for the ruins of the **Great Dam** of Marib, an ancient engineering marvel. The **Great Dam** of Marib, constructed in the **8th** century **BC**, was a monumental feat that transformed the region into a fertile oasis, supporting agriculture and sustaining the **Sabaean** civilization. However, its collapse in the **6th** century **AD** led to significant environmental and societal changes, contributing to the decline of the **Sabaean kingdom**[35] [36] (Figs. 29 & 30).

[35] https://www.amusingplanet.com/2018/11/the-collapse-of-marib-dam-and-fall-of.html?utm_source=chatgpt.com

[36] Britannica. *Marib*. Retrieved from https://www.britannica.com/place/Marib



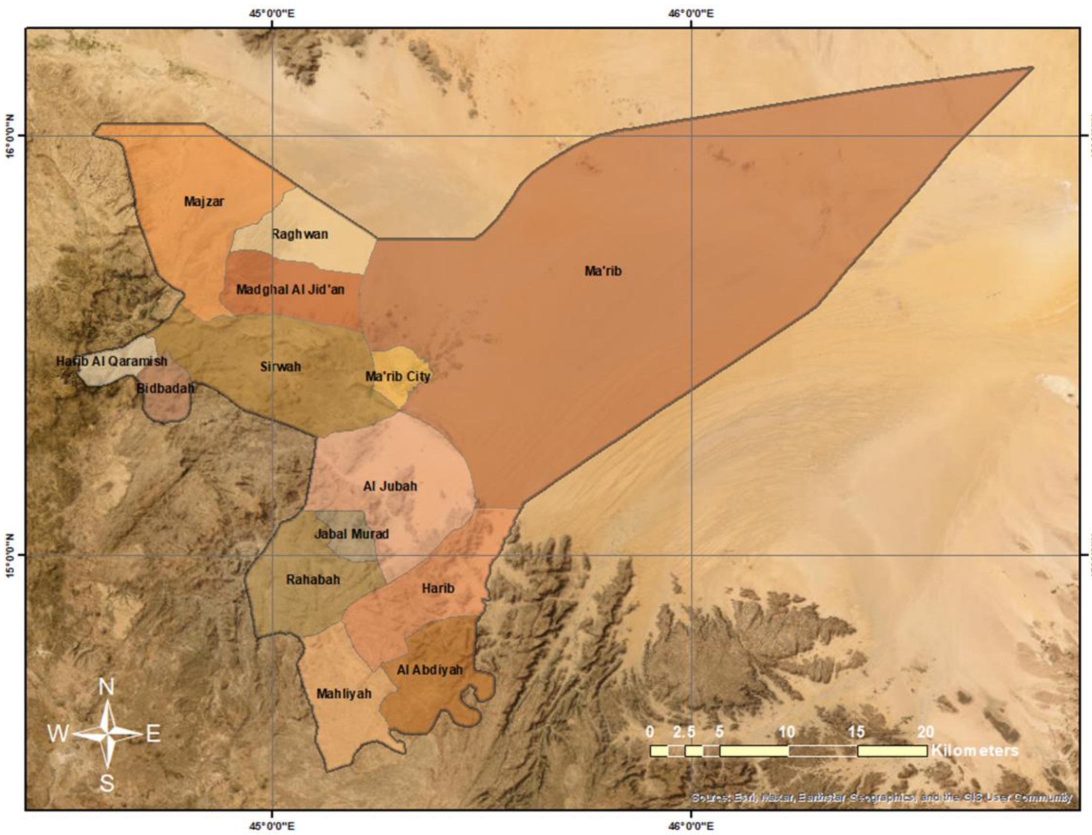


Fig. 28: ***Upper***: depicts the geographic location of Marib at the **Arabian Peninsula**;
Lower: shows the districts of **Marib Governorate**. (Source: **the author**).

Fig. 29: Shows the Ruins of the ancient Barran Temple, **Marib** (Source: **https://www.britannica.com**). https://www.britannica.com/place/Marib?utm_source=chatgpt.com

Fig. 30: The photograph depicts the ruins of the Great Dam of **Marib**. (Source: **amusingplanet**). https://www.amusingplanet.com/2018/11/the-collapse-of-marib-dam-and-fall-of.html?utm_source=chatgpt.com

Marib has seen recurring floods in recent years, which have been exacerbated by **climate change** and ongoing conflicts. Heavy rains caused catastrophic flooding in **August 2020**, affecting over **35,000** homes across Yemen, with Marib among the hardest afflicted. The floods caused severe damage to infrastructure, residences, and displacement camps, exacerbating the difficulties encountered by internally displaced people (**IDPs**) in the region (Figs. 31 & 32).

Rains and flooding at **21** Marib displacement sites have destroyed **600** shelters and damaged **2,800** more, affecting over **20,000** people. Floods have accelerated the spread of waterborne diseases such as cholera, malaria, and dengue fever, putting severe strain on health systems. The situation exacerbated in **2022**, when windstorms and accompanying floods affected almost **150,000** Marib inhabitants and **IDPs**. The storms wrecked shelters, destroyed personal items, and caused severe animal and property losses. These frequent natural disasters have stretched Marib's already limited resources, stressing the urgent need for comprehensive disaster management techniques and robust infrastructure to protect vulnerable populations[37 38 39].

Fig. 31: Shows the floods in Marib province, **2020** (Source: **almashareq**). https://almashareq.com/en_GB/articles/cnmi_am/features/2020/10/07/feature-02

37 IOM, 2024
38 WHO, 2024
39 https://www.bbc.com/news/articles/cql3d1p6yq6o?utm_source=chatgpt.com

Fig. 32: **Marib governorate** in **Yemen** had extraordinary severe rainfall followed by storms, high gusts with dust, and a massive flow of floods. (Source: **Executive Unit IDPs**). ttps://www.exuye.org/en/791

V.2. Climate Data Analysis

Numeric Precipitation Data Analysis

Figure 33 illustrates a time series graph of precipitation data from the **GPM** (**Global Precipitation Measurement**) mission. It shows precipitation in millimeters (**mm**) over time, from **Jan. 2017** to **Dec. 2023**. The following is a detailed discussion of time-series precipitation data:

1. **Peak Precipitation Events**:

The chart reveals several distinct spikes in precipitation, indicating extreme rainfall events. Notable peaks occurred in early **2019**, late **2022**, and early **2023**, with precipitation levels surpassing **100 mm** during some instances.

2. **General Precipitation Trends:**

Rainfall appears sporadic, characterized by extended periods of low or no rainfall interrupted by short but intense precipitation events. This pattern suggests that rainfall distribution is uneven throughout the year, potentially linked to seasonal or specific weather systems.

3. Low-Intensity Periods:

Prolonged intervals of minimal rainfall are evident, particularly between the peak events. These dry spells highlight the region's vulnerability to water shortages and drought conditions.

4. Potential Implications:

The extreme rainfall spikes suggest a heightened risk of flooding, especially in areas with insufficient drainage infrastructure. Additionally, the sporadic and unpredictable rainfall patterns emphasize the importance of water management strategies, such as rainwater harvesting during heavy rainfall periods and preparedness for droughts during extended dry spells.

5. Climate Change Connection:

The irregularity and intensity of precipitation events may reflect the influence of climate change, potentially driving more extreme and less predictable weather patterns in the region. This reinforces the urgency for climate adaptation strategies.

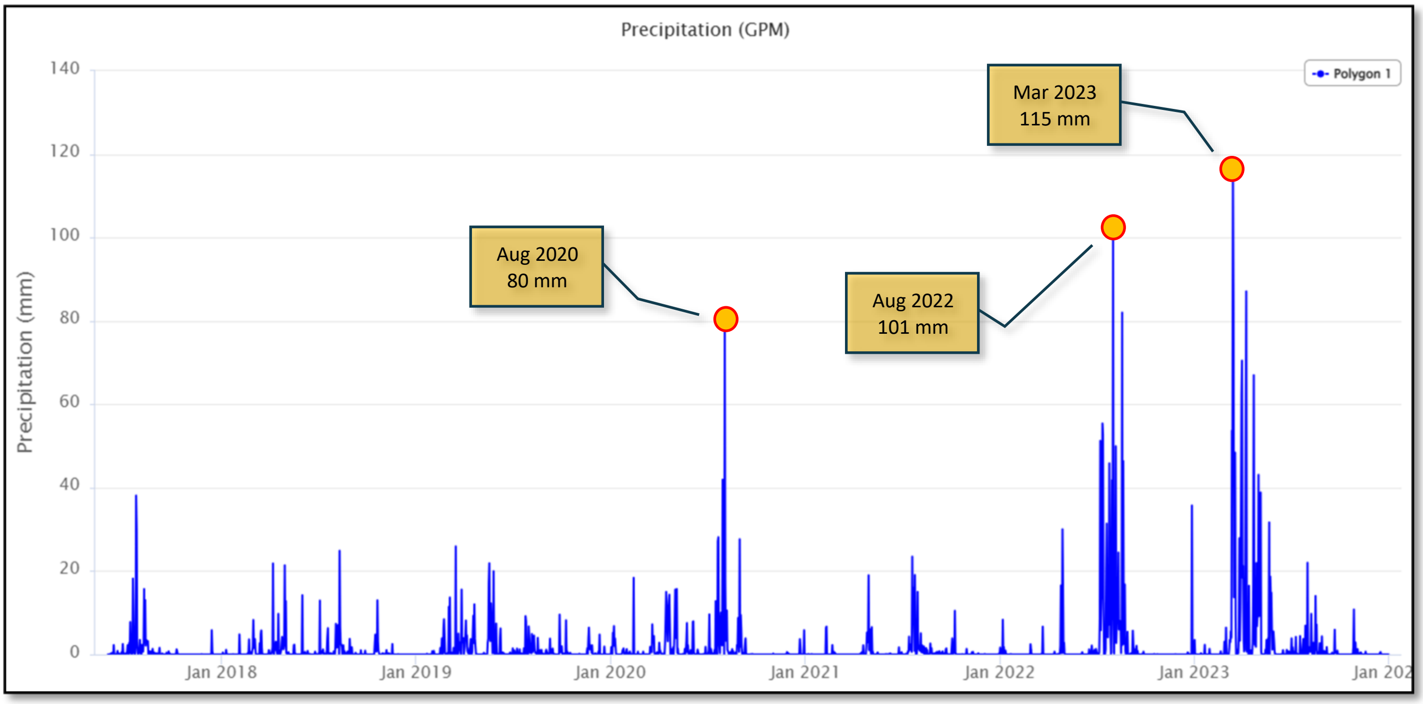


Fig. 33: Shows the rainfall distribution within **Marib Governorate** from **2017 – 2023**. (Source: **Giovanni**). https://giovanni.gsfc.nasa.gov/giovanni/#service=VtPf&starttime=&endtime=&dataKeyword=Precipitation

Raster Precipitation Data Analysis

Fig. 34 is a thematic map showing the annual rainfall distribution (in **mm**) from **2017** to **2023** for a region, likely in **Yemen**, as indicated by the labeled districts such as **Marib City**, **Al Jubah**, and **Harib**. Key observations include:

Description

1. **Rainfall Ranges:**

The map (**Fig. 33**) uses a color gradient to display annual rainfall ranges: Red (**124-170 mm**) represents areas with the least rainfall, predominantly in the northern and eastern parts; Orange to Yellow (**171-262 mm**) indicates areas with slightly higher rainfall, covering much of the central region; Light Green to Dark Green (**263-354 mm**) shows moderate rainfall regions; and Light Blue to Dark Blue (**447-539 mm**) highlights areas with the highest rainfall, concentrated in the southern and southwestern areas.

2. **Geographical Layout:**

The map illustrates distinct rainfall patterns across the region, highlighting clear geographic variations. **Northern** and **eastern** parts, such as **Majzar** and **Raghwan**, experience the lowest rainfall levels, as shown by the red and orange zones. Central areas, including **Marib City** and its surrounding districts, receive moderate rainfall, represented by yellow and green shades. In contrast, southern areas, like Al **Abdiyah** and **Mahliyah**, stand out with significantly higher rainfall, depicted in blue tones. This marked increase in rainfall in the south could be attributed to orographic effects or specific climatic conditions influencing the region.

Suggested Actions and Insights

1. **Climatic Analysis:**

The fluctuation in rainfall reveals potential climatic changes across the region, recommending specialized resource management techniques. **Southern** locations with higher rainfall could benefit from improved agricultural initiatives and water resource management projects to help them reach their potential. **Northern** and eastern locations, which receive less rainfall, may require targeted drought mitigation activities, such as water conservation, harvesting techniques, and sustainable resource planning.

2. **Data Usability:**

The map (**Fig. 33**) provides specialized information for hydrological planning, urban growth, and environmental conservation based on rainfall availability in each **district**.

3. **Policy Implications:**

Sustainable techniques such as enhancing groundwater recharge or introducing drought-resistant crops should be focused in regions with low rainfall, whilst high-rainfall areas might focus on implementing flood management systems to decrease hazards during periods of heavy rainfall.

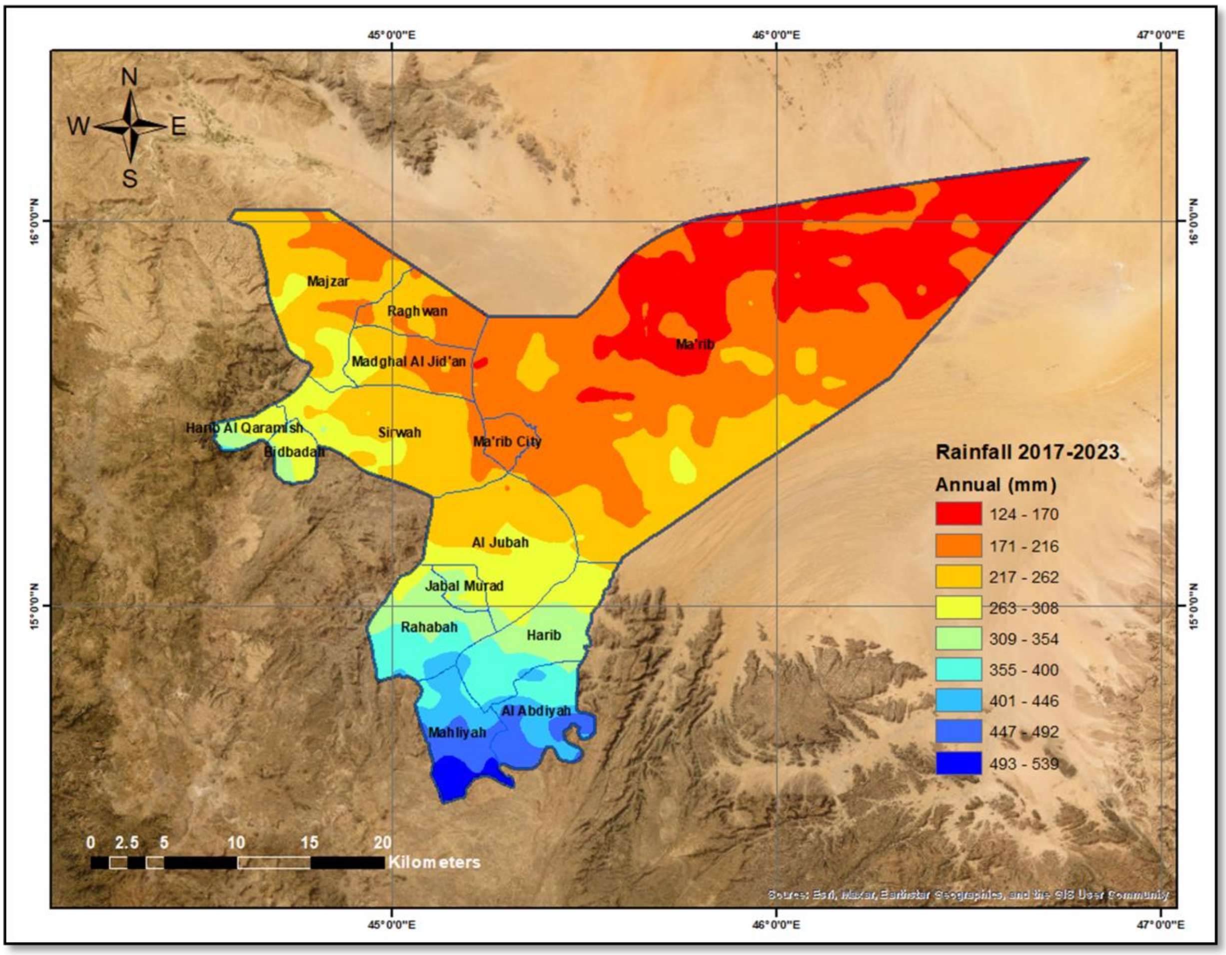


Fig. 34: Shows the max. annual rainfall distribution within **Marib** **districts for the years 2017-2023.** (Source: **the author**).

Overview of the Flood hazard Map

From **Fig. 35**, the flood hazard assessment map for Internally **Displaced Persons (IDP)** sites in **Marib governorate**, **Yemen**, is based on a model produced in **January 2023**. It employs hydraulic modeling using **HEC-RAS** to estimate flood depth and hazard levels across different areas, providing critical insights for disaster preparedness and risk mitigation. The classification of flood hazards follows the **US Federal Emergency Management Agency (FEMA)** guidelines, which categorize hazards based on depth and velocity, ensuring a standardized approach to assessing flood risks[40]. Such modeling is essential for identifying vulnerable populations and implementing effective flood response strategies[41].

Key Observations

The **Flood Hazard Classification** map categorizes flood severity into five levels: **Low** hazard (**0-0.2 m^2/s**), **Medium** hazard (**0.2-0.5 m^2/s**), **High** hazard (**0.5-1.5 m^2/s**), **Very high** hazard (**1.5-2.5 m^2/s**), and **Extreme** hazard (**>2.5 m^2/s**). The **Marib Dam** and its reservoir exhibit extreme flood hazard levels, with a large red area indicating the highest risk. The **IDP** Sites and Flood Exposure analysis identifies internally **displaced person (IDP)** sites based on their flood exposure: **23** sites in high hazard areas, **20** in **medium** hazard areas, **29** in **low** hazard regions, and **21** with unknown hazard levels, requiring further analysis. **Regarding Geographical Risk Distribution**, the **western** and **southern** parts of the **governorate**—especially around **Marib Dam**—face the highest flood risks, while the eastern and northeastern regions are less prone to severe flooding, with lower hazard levels and scattered **IDP** settlements.

The map emphasizes the need of disaster preparedness and **early warning**, with authorities directed to use this data to relocate high-risk **IDP** camps or construct flood protection measures.

Suggestions for Use

[40] Federal Emergency Management Agency. (2021). *Guidance for Flood Risk Analysis and Mapping – Floodway Analysis and Mapping*. FEMA.

[41] REACH, 2023.

In terms of infrastructure planning, **humanitarian** organizations and **government** agencies should prioritize flood-resistant infrastructure in high-risk areas. Furthermore, regular updates and monitoring are critical due to the dynamic nature of climate change and extreme weather, which necessitate periodic revisions to the flood model. In conclusion, the **Marib governorate** flood danger map is an important tool for disaster risk management, particularly for **IDP** protection. However, improvements in data resolution, field verification, and infrastructure mapping would make it more effective. **Humanitarian** agencies should use this approach to select interventions and protect vulnerable communities from flood-related disasters[42,43].

How Can the Nexus Approach Be Implemented with Climate Change?

1. Water Security & Flood Management

To enhance flood resilience in **IDP** camps, a multi-layered approach combining technology, ecological restoration, and infrastructure planning is essential. IoT-based flood monitoring sensors can be deployed to detect rising water levels in real time, triggering early warnings to alert communities before flooding occurs. At the same time, nature-based solutions, such as watershed restoration, reforestation, and wetland conservation, help reduce runoff and improve water retention. Additionally, **climate-resilient infrastructure**—including elevated housing, reinforced drainage systems, and flood barriers—should be prioritized, with relocation strategies considered for high-risk areas. By integrating smart monitoring, sustainable land management, and resilient construction, this approach ensures long-term water security and flood preparedness for vulnerable populations.

2. Energy Security & Climate Adaptation

Ensuring reliable energy access in flood-prone **IDP** sites requires **renewable and decentralized solutions** that enhance resilience to climate extremes. Solar-powered water pumps and desalination systems can provide a stable water supply during

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[42] Federal Emergency Management Agency (FEMA). (2021). *Flood Depth and Analysis Grid Guidance*. Washington, D.C.

[43] REACH. (2023). Yemen - Flood Hazard of IDP Sites, Ma'rib Governorate.

extreme weather events, reducing dependency on vulnerable infrastructure. Additionally, mini-grids and solar panels can offer decentralized energy solutions, ensuring uninterrupted power for essential services such as lighting, communication, and medical facilities during disasters. By integrating **renewable energy with climate adaptation strategies**, this approach strengthens both water and energy security, enhancing the sustainability and self-sufficiency of displaced communities.

3. Food Security & Sustainable Land Use

Enhancing food security in flood-prone areas requires climate-smart agricultural practices that adapt to changing environmental conditions. Flood-resilient farming techniques, such as hydroponics, floating farms, and raised-bed agriculture, can sustain food production even in waterlogged conditions. Additionally, managed water retention systems can harness floodwaters for irrigation, improving water availability during dry periods. By integrating innovative farming methods with sustainable water management, this approach ensures long-term food security while enhancing ecosystem resilience in vulnerable regions.

4. Data-Driven Policy & Climate Resilience

Effective flood risk management requires **data-driven decision-making** that integrates geospatial analysis, disaster planning, and cross-sector collaboration. **ArcGIS and remote sensing** can be used to map climate change impacts on flood frequency, helping to identify high-risk zones and guide mitigation efforts. Integrated disaster planning, in coordination with **humanitarian** agencies, ensures that **IDP** site selection incorporates flood risk models to minimize exposure. Additionally, **Nexus-based governance** promotes a balanced approach to water management**,** agriculture, and flood mitigation, fostering resilience through multi-sector cooperation. By leveraging advanced analytics and coordinated policies, this approach strengthens climate adaptation strategies for vulnerable communities.

Integrating **IoT, GIS, RS and Nexus approaches** can enhance climate resilience in flood-prone **IDP** areas. This requires **multi-sectoral cooperation** among environmental agencies, **humanitarian** organizations, and **government** authorities.

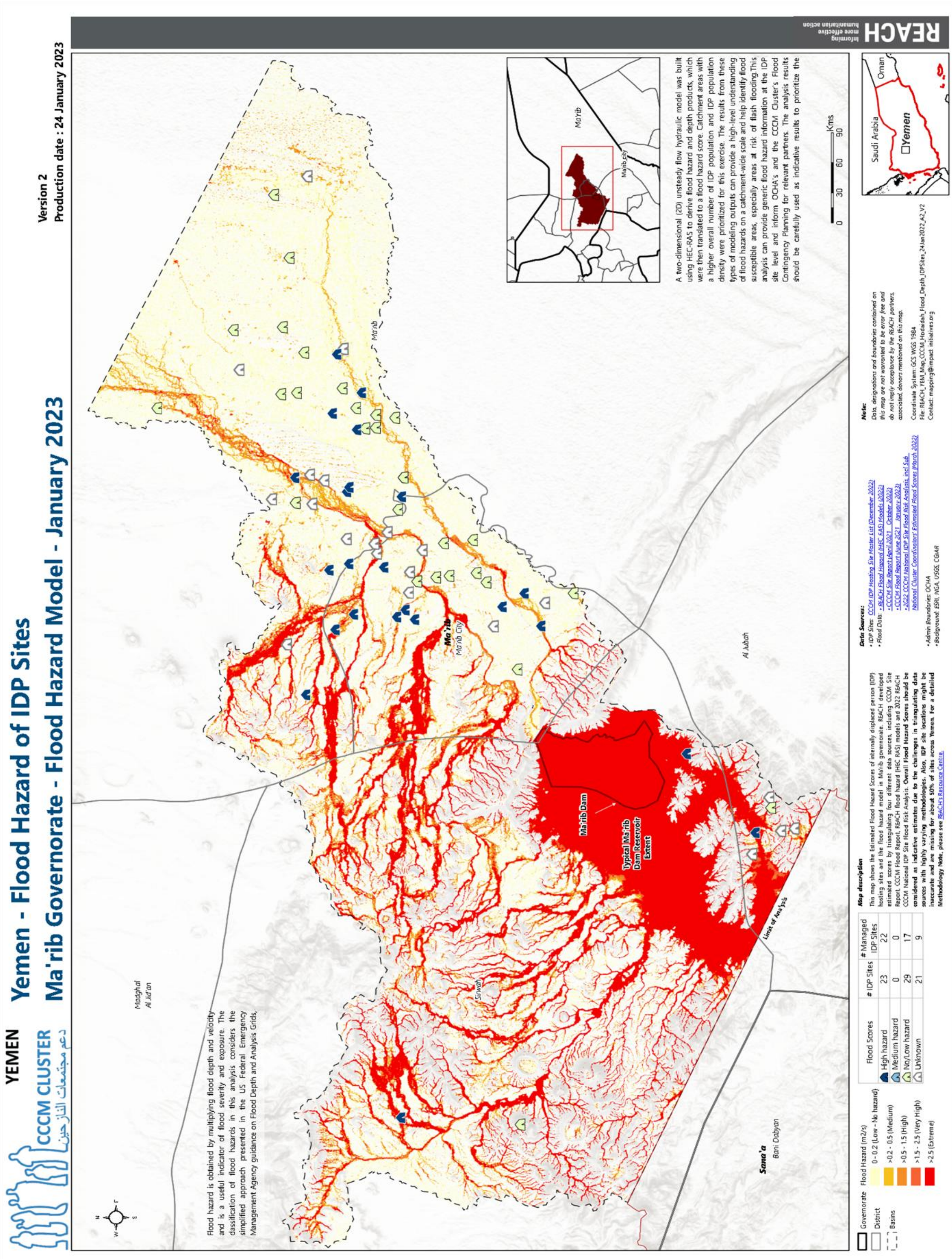

Fig. 35: Shows the flood hazard sites in **Marib Governorate.** (Source: **REACH**).

Hajjah Governorate

VI. Climate Change Impacts: Hajjah

VI.1. Overview

Geography of Hajjah Governorate

Hajjah Governorate, located in northeastern **Yemen** (**Fig. 36**), has a diversified geography that includes rugged highlands and low-lying coastal plains along the **Red Sea**. This diverse landscape increases the region's susceptibility to seasonal flooding[44] (**Figs. 37** & **38**).

In recent years, **Hajjah** has experienced substantial flooding, particularly during the rainy season. For example, in **August 2024**, heavy rains caused widespread flooding in various **Yemeni governorates**, including **Hajjah**, leading in infrastructure destruction and community displacement[45].

The impact of these floods is amplified by **Yemen's** ongoing humanitarian crisis, where prolonged conflict has already stretched resources and infrastructure. Flooding ruins houses, disrupts livelihoods, and raises the danger of waterborne infections, further testing impacted populations' resilience.

Implementing **early warning systems**, strengthening infrastructure, and promoting sustainable land management techniques are among the efforts being made in **Hajjah**

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44 https://yemen.unfpa.org/en?utm_source=chatgpt.com

45 Berghof Foundation & Political Development Forum, 2021. https://yemenlg.org/governorates/marib/?utm_source=chatgpt.com

to reduce flood risk. However, continuous conflict and inadequate resources provide substantial hurdles for these projects.

Box 2: How Other Organizations Report Flood Impacts?

"Flooding in **Yemen** has left at least **57** people dead and thousands displaced, the **UN** has said. More than **34,000** families were affected by the heavy rains, which began in late June and intensified in early **August**, according to the UN humanitarian affairs office (OCHA).

It has worsened the country's "already dire humanitarian situation" as millions grapple with the impact of a civil conflict that began nearly **10** years ago, the UN body added."

"The magnitude of this disaster is overwhelming, and the humanitarian needs are enormous," said **Matt Huber**, the International Organization for Migration (IOM)'s acting chief of mission in **Yemen**."

"Regions affected by the flooding include **Hodeidah**, **Hajjah**, **Taiz** and **Marib**. **Hodeidah** is among the hardest hit areas. Flooding there has displaced more than **6,000** families and caused widespread destruction to homes and essential services, according to the UN. Roads were closed and access to affected areas remained challenging, the body added. The IOM says it is ramping up emergency operations in the country (**Source: BBC New**)."

In **2020**, the situation was particularly grave, with over half a million people directly affected by water by September. A total of **189** districts in **19** governorates were affected, with about **44** persons killed. The **Ministry of Public Health and Population** in **Sana'a** estimates **250** casualties and **131** deaths in northern **Yemen** alone. Several international assessments suggested that the lives of tens of thousands of **Internally Displaced People (IDPs)**, many of whom were already in hazardous shelters as a result of the violence, were significantly harmed. **Marib**, **Hajjah**, **Al-Hodeidah**, and **Sana'a** were the most hit **governorates** in this case. According to the **August 2022 OCHA** Situation Update, heavy rains have affected more than **51,000** households across the country since **mid-April 2022**, with **Marib** and **Hajjah governorates** being the worst-hit, with over **13,000** and **9,000** households affected, respectively, and the majority of those affected reportedly living in displacement sites. Along **Yemen's** western coast, **Abs** in **Hajjah governorate** is one of the most devastated districts, with one of the biggest concentrations of **IDPs** and vulnerable people in the country. Since **2019**, **Hajjah** has had a series of torrential rains that have devastated shelters in **IDP** sites and infrastructure, leaving thousands of people in need and hampering **humanitarian** shipments[46] (**Figs. 39** & **40**).

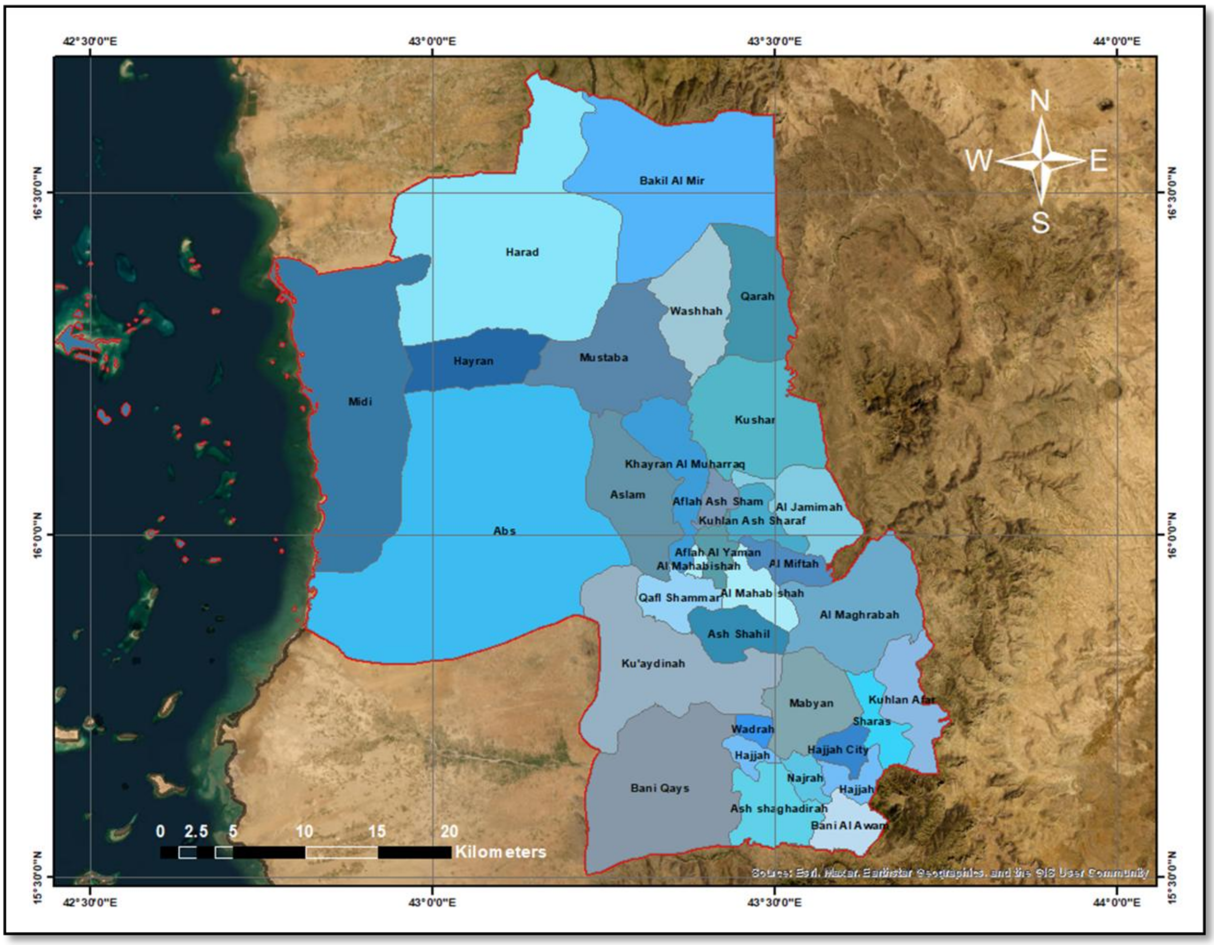

Fig. 36: Shows displaced families affected by rain and floods in **Hajjah** province (Source: **the author**).

46 REACH, 2022. https://data.unhcr.org/es/documents/details/91763

Fig. 37: **Hajjah** City (Source: https://it.pinterest.com/pin/511228995215395583/).

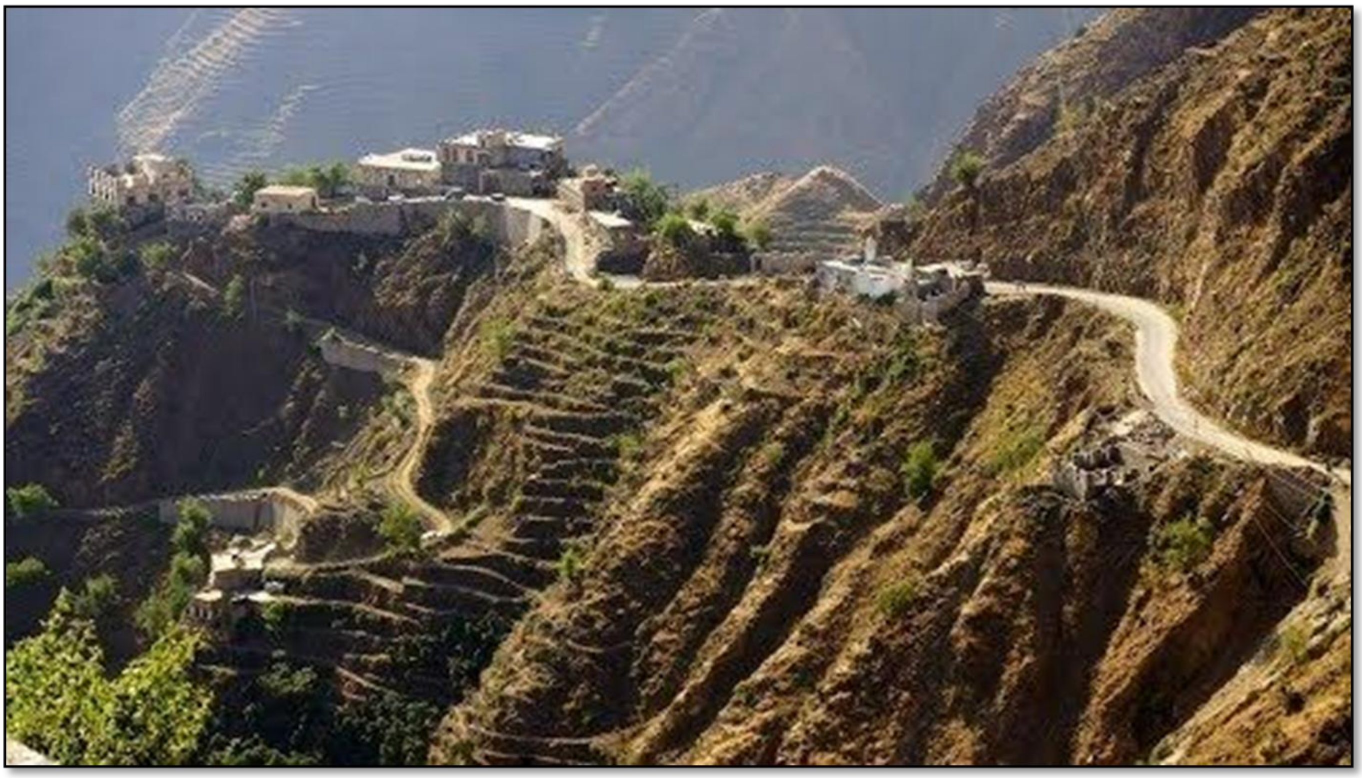

Fig. 38: **Hajjah governorate** (Source: **Alchetron**). https://alchetron.com/Hajjah-Governorate

Fig. 39: Damage Caused by Rain and Floods in the Displaced Persons Camps in **Hajjah governorate**. (Source: **exuye.org**). https://www.exuye.org/en/2088

Fig. 40: Shows displaced families affected by rain and floods in **Hajjah** province (Source: **YemenTV**). https://en.yementv.tv/report-around-2000-displaced-families-affected-by-rain-and-floods-in-hajjah-province.html

VI.2. Rainfall Analysis

Analysis of the Rainfall Chart (Precipitation - GPM)

1. **Data Overview:**

The chart represents daily precipitation data from **January 1, 2017**, to **December 31, 2023** (Fig. 41). The y-axis (Precipitation in **mm**) indicates the daily rainfall amount, while the x-axis represents the timeline from **2017** to **2023**.

2. Observations:

The rainfall data shows high variability with alternating dry spells and intense precipitation events. A noticeable increase in extreme precipitation events is observed starting in early **2022**, with several peaks exceeding **140 mm**. Recurring wet and dry seasons are evident, though variability exists within each year. The highest rainfall peaks occur in **2022** and **2023**, suggesting a possible intensification of extreme weather events.

3. **Potential Implications:**

The increase in extreme precipitation events in recent years may be linked to climate variability or **climate change** impacts, leading to heightened flood risks, particularly in **2022** and **2023**. More frequent and intense rainfall spikes can exacerbate flooding, causing damage to infrastructure and disrupting ecosystems. Additionally, excessive rainfall creates favorable conditions for vector-borne diseases such as malaria and dengue, as stagnant water provides breeding grounds for mosquitoes, increasing public health concerns.

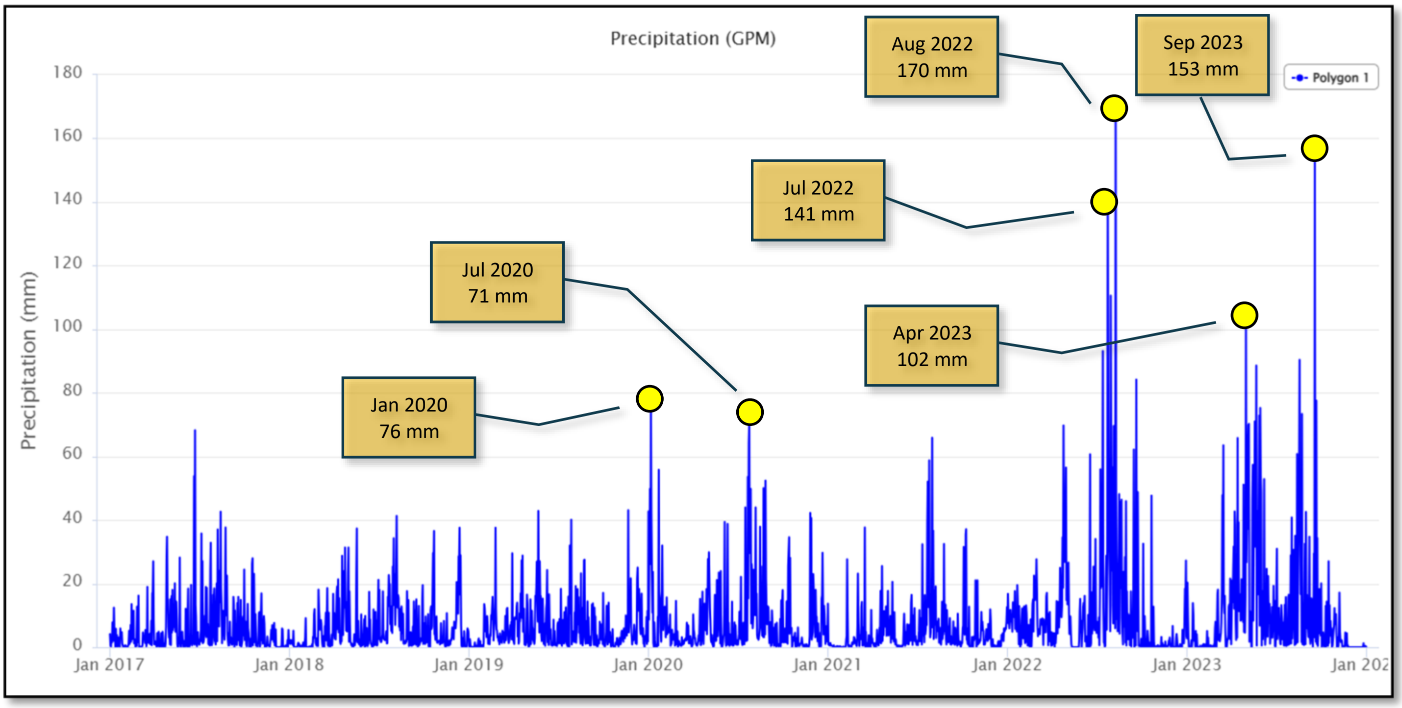

Fig. 41: Shows the historical rainfall intensity within **Hajjah Governorate** from **2017** – **2023**. (Source: **GPM**).

4. Hydrological & Climatic Context

The rainfall chart (**2017–2023**) indicates high variability in precipitation, with extreme rainfall events increasing from **2022** onward. The map provides a spatial representation of the terrain, showing how precipitation patterns may interact with geographical features such as coastal and mountainous areas (**Fig. 41**).

Key Linkages Between Rainfall and Geography

1. Mountainous Areas and Rainfall Intensity

The eastern mountainous region, influenced by orographic lifting, likely receives significant rainfall as moist air rises over the terrain, enhancing precipitation. Heavy rainfall in **2022–2023**, as indicated in the chart, may have triggered landslides, flash floods, and increased runoff, leading to soil erosion and sediment transport downstream. The presence of a river system further suggests that excess water flows toward coastal areas, potentially heightening flood risks in low-lying regions.

2. Coastal Areas and Flood Risks

Coastal zones are prone to flooding due to excess runoff from upstream rainfall events, especially when high rainfall coincides with tidal surges. The rainfall spikes observed in **2022** and **2023** suggest possible extreme weather events, such as storms or cyclones, which could have intensified coastal inundation and erosion.

3. Climate Change and Rainfall Variability

The increase in extreme precipitation in recent years, likely linked to **climate change**, is affecting both the mountains—leading to landslides and vegetation loss—and the coast, contributing to flooding and sea-level rise. The variability in rainfall further suggests unpredictable water availability, which could negatively impact agriculture, water resources, and public health, increasing the risk of disease outbreaks, such as vector-borne illnesses due to stagnant water in coastal flood zones (**Fig. 42**).

Implications for Hydrological and Climate Risk Management

To address flood and erosion risks, implementing watershed management strategies in mountainous areas can reduce runoff and landslides, while enhancing coastal flood protection through measures like mangrove restoration and seawalls. The increased frequency of extreme rainfall emphasizes the importance of **early warning systems** and climate-resilient infrastructure to mitigate flash floods and storm surges. Additionally, high rainfall in low-lying areas creates breeding grounds for disease vectors, such as mosquitoes and waterborne pathogens, necessitating integrated environmental health monitoring to support effective epidemiological surveillance (**Fig. 42**).

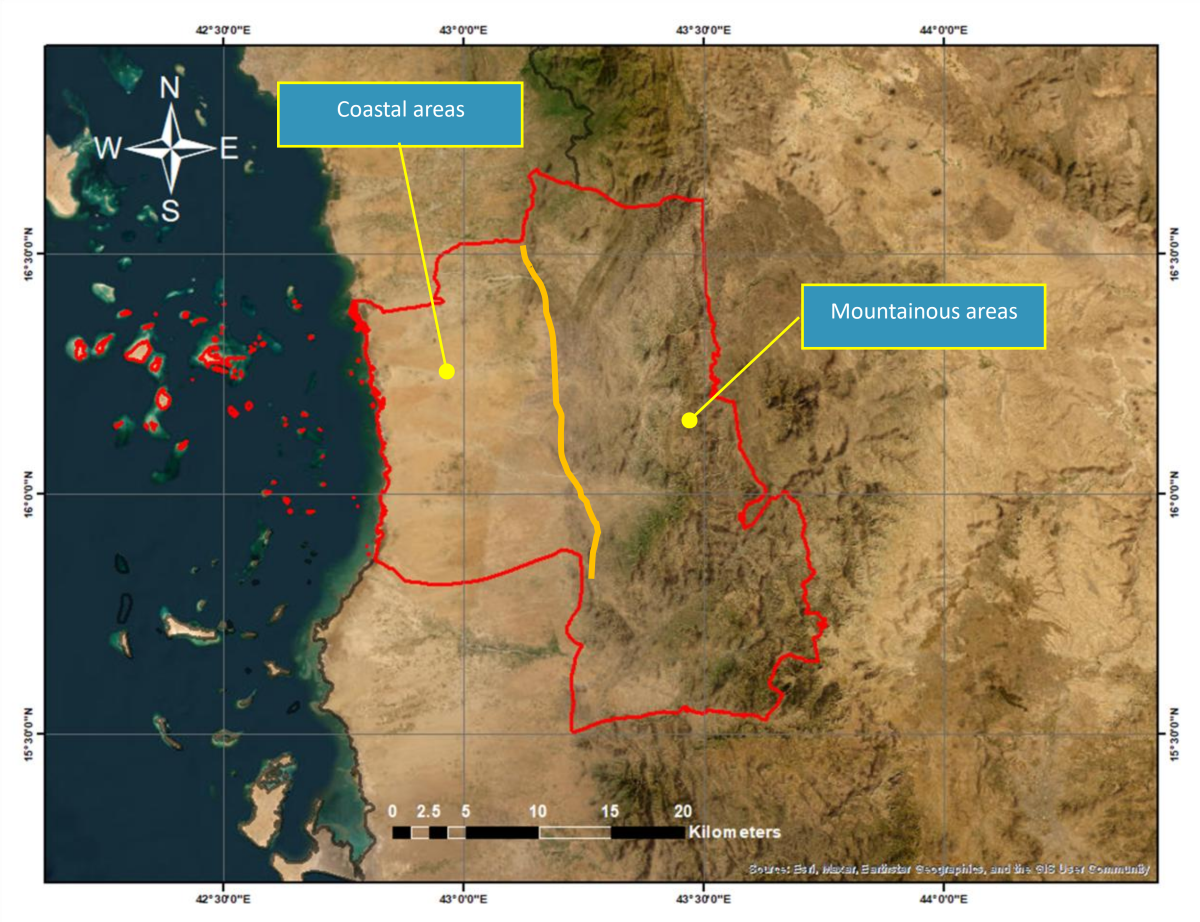

Fig. 42: Depicts the geographic varities of **Hajjah** province (Source: **the author**).

Analysis of Rainfall Patterns, Geography, and Climate Trends of Hajjah Area

1. Rainfall Distribution and Geographic Influence

The rainfall distribution map (**Fig. 43**) reveals distinct geographic influences on precipitation patterns, with higher rainfall (dark blue shades) concentrated in central areas and lower precipitation (red/orange) in the eastern mountainous and western coastal regions. The eastern mountains experience reduced rainfall (yellow to red areas) due to rain shadow effects, where moist air loses its moisture before reaching higher elevations. Meanwhile, the western coastal region, despite receiving moderate rainfall, remains highly vulnerable to flooding as its low-lying terrain exacerbates the impact of upstream runoff during extreme precipitation events.

Comparing the Rainfall Map with the Time-Series Chart (2017–2023)

Comparing the rainfall map (**Figs. 41** & **43**) with the time-series chart (**2017**–**2023**), highlights both long-term spatial patterns and recent extreme events. The time-series data indicate a rise in extreme rainfall events in **2022** and **2023**, which likely intensified storms in high-rainfall areas (blue zones) despite the map showing multi-year averages. Even in lower rainfall regions, such as the coastal and eastern areas, short but intense downpours may have triggered flash floods and erosion. Seasonal and interannual variability observed in the time-series chart aligns with spatial rainfall distribution, where transition zones (blue to yellow) experience fluctuating wet and dry periods, impacting agriculture, water resources, and ecosystem stability.

Potential Implications and Risks

A. Climate Change & Hydrological Risks

The increasing frequency of extreme rainfall events, as shown in the time-series chart (**Fig. 41**), combined with high rainfall accumulation in central areas, as seen in the map of **Fig. 43**, indicates an elevated risk of flash floods, particularly in valleys and lowland regions. The reduced rainfall in the mountainous areas may lead to drought conditions and decreased groundwater recharge, which could negatively impact water security and agriculture in the eastern regions. These hydrological risks highlight the potential consequences of **climate change** on both flood and drought occurrences.

B. Flood & Erosion Hazards

Downstream flooding is a significant hazard as the river, originating from high rainfall zones, flows toward the coast, making low-lying coastal settlements particularly vulnerable to runoff-driven floods during extreme rainfall years. Additionally, high rainfall variability could exacerbate soil erosion in the mountainous regions, with sediment being transported downstream to lowlands, resulting in sedimentation in rivers that can degrade water quality and disrupt local ecosystems.

C. Epidemiological & Public Health Concerns

Flood-related diseases pose a significant public health concern as stagnant water from extreme rainfall events (peaking in **2022–2023**) in high-rainfall areas creates ideal mosquito breeding grounds, increasing the risk of malaria, dengue, and waterborne diseases. Meanwhile, drought-affected areas in the mountainous regions may face water scarcity, malnutrition, and a rise in heat stress-related illnesses, further exacerbating public health challenges.

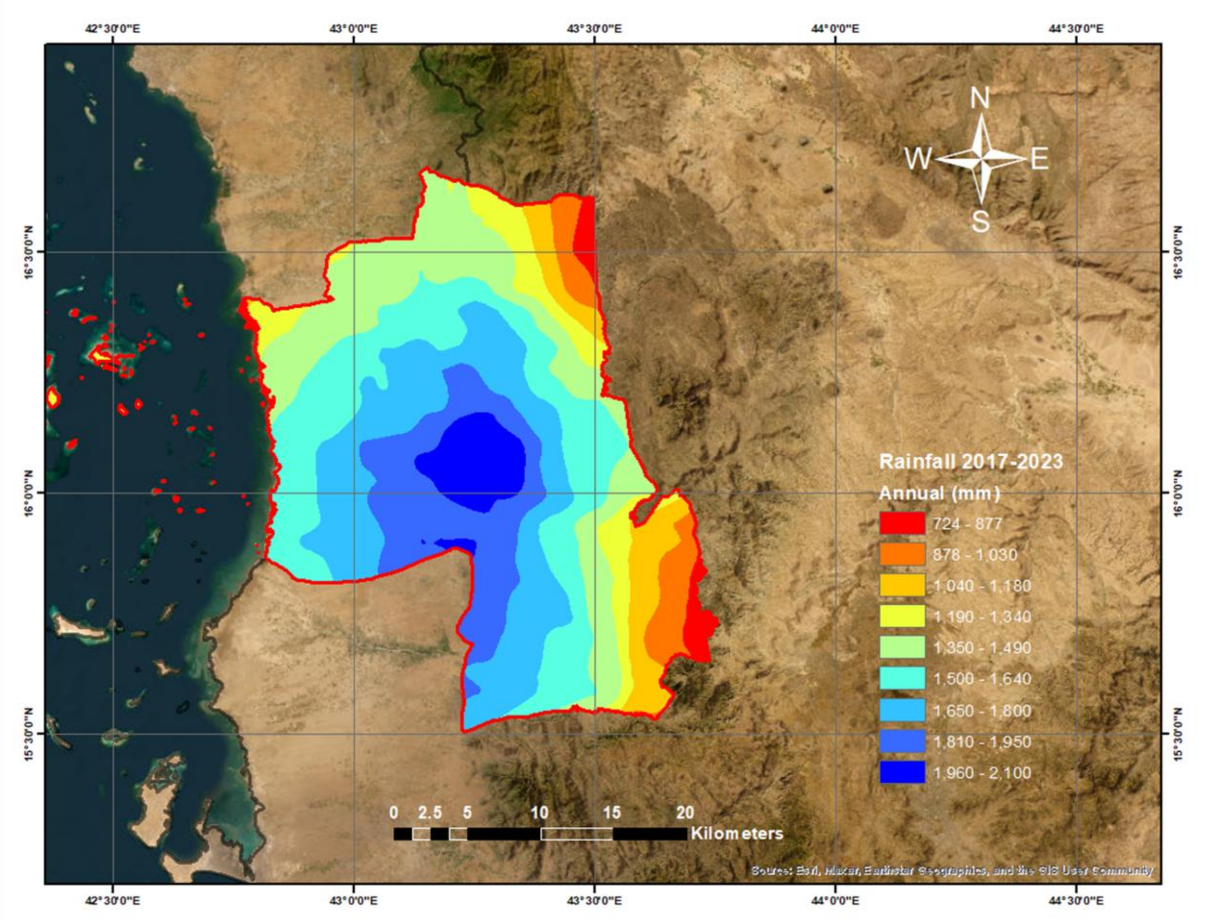

Fig. 43: Shows the intensity of rainfall distribution in Hajjah province (Source: **the author**).

Enhancing Climate Resilience with the Nexus Approach

Implementing the **Nexus Approach** in the context of **climate change** entails integrating water, energy, and food management to improve sustainability and resilience. This approach recognizes the interdependence of these sectors and encourages policies and practices that maximize resource usage while mitigating climate impacts.

Essential Strategies for Applying the Nexus Approach with Climate Considerations

1. **Integrated Resource Management**: Addressing the interdependence of the water, energy, and food sectors is critical. For example, sustainable wastewater management in agriculture exhibits the Water-Soil-Waste Nexus, in which cleaned wastewater is used for irrigation, conserving freshwater resources and lowering pollution[47].
2. **Using Modeling techniques**: Environmental modeling techniques help to comprehend complicated interactions inside the Nexus. The Nexus Tools Platform (NTP), created by the UNU Institute for Integrated Management of Material Fluxes and Resources (UNU-FLORES), is a web-based inventory of models that examine environmental resource management from a Nexus standpoint. This platform aids users in picking relevant tools for their research needs, promoting informed decision-making[48].
3. **Promoting Policy Coherence**: Ensuring that policies across sectors are consistent with climate goals is critical. The Water, Energy, and Food Security Nexus viewpoint promotes multidisciplinary solutions that improve sectoral cooperation rather than standalone initiatives. This technique aids in identifying synergies and balancing trade-offs between water, energy, and food security development goals[49].

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[47] https://en.wikipedia.org/wiki/Nexus_Tools_Platform?utm_source=chatgpt.com
[48] https://en.wikipedia.org/wiki/Nexus_Tools_Platform?utm_source=chatgpt.com
[49] https://en.wikipedia.org/wiki/Water%2C_energy_and_food_security_nexus?utm_source=chatgpt.com

4. **Engaging Stakeholders**: Active participation by government agencies, the commercial sector, and civil society is required. Collaborative initiatives aid in avoiding unforeseen negative repercussions and devising policies, plans, and investments that capitalize on synergies and address trade-offs between sectors[50].
5. **Managing Climate and Trade Policy Intersections**: Recognizing the relationship between climate action and trade policies is becoming more crucial. For example, debates at COP29 focused on how trade policies such as carbon taxes might influence global emissions reduction efforts and the economic ramifications of the energy transition[51].
6. **Balancing Climate Action and Biodiversity Conservation**: Concentrating primarily on climate change mitigation may unintentionally harm biodiversity. The United Nations warns against such an approach, instead advocating for comprehensive solutions that address numerous environmental concerns at the same time, ensuring that climate policies do not jeopardize natural habitats and biodiversity[52].

50 https://en.wikipedia.org/wiki/Water%2C_energy_and_food_security_nexus?utm_source=chatgpt.com
51 https://time.com/7178427/climate-trade-policy-baku-cop29/?utm_source=chatgpt.com
52 https://www.thetimes.co.uk/article/dont-focus-on-climate-action-at-expense-of-nature-says-un-bwzln7lj8?utm_source=chatgpt.com

General Recommendations for Flood Risk Management

1. **IDP Site Management**:
   - Relocate high-risk **IDP** sites to safer places with lower flood risk.
   - Offer flood-resistant shelters for **IDPs** in medium-risk areas.
2. **Infrastructure Resilience:**
   - Build flood defenses, such as embankments, around essential infrastructure and metropolitan areas.
   - Improve drainage systems to prevent water collection in high-risk areas.
3. **Agricultural Adaptation:**
   - Promote flood-resistant crops in flood-prone agricultural areas.
   - Implement soil conservation practices to reduce erosion.
4. **Early Warning Systems:**
   - Create flood **early warning systems** to alert communities and **IDPs** of approaching flood hazards.
   - Carry out regular flood hazard assessments and update maps to reflect changing threats.
5. **Community-Based Disaster Preparedness:**
   - Teach local communities about flood risk mitigation, emergency response, and evacuation protocols.
   - Make sure **IDPs** are included in catastrophe preparedness planning.
6. **Environmental Protection:**
   - Reforest erosion-prone regions to help stabilize soils and lessen flood damage.

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