Yemen National Probabilistic Risk Assessment

Historical Hazard Data Review, Analysis and Data Quality Assessment

A report prepared for the World Bank with support from GFDRR

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Executive Summary

The Historical Hazard Data Review, Analysis, and Data Quality Assessment report for Yemen National Probabilistic Risk Assessment Task-1 covers a review of available historical information and records for Yemen, relating to the occurrence of all hazards under study in this project: earthquake, flash flood, flood (coastal storm surge and tsunami), rockslide/landslide and volcanic eruption. The report describes the data that has been collected: the sources, their accuracy and their format. It also covers whether the hazard data from various sources is sufficient to perform the respective probabilistic loss estimation.

It is noteworthy that the RMSI team undertook several missions to the country to collect data with the active participation of the local counterpart. The team also compiled these data using archives available from international and national institutions involved in systematic archiving of hazard event data. These datasets were compiled to support and calibrate the probabilistic analysis of the hazards. It also undertook comprehensive review of existing studies, hazard assessments and hazard maps at the national level. The results of this review are being used to complement the systematic data sets.

During this activity, the RMSI team worked closely with the project counterpart team at the Yemen Geological Survey and Minerals Research Board (YGSMRB), in the identification of local hazard information and hazard impact areas. This should result in improved data availability for the selected high-risk areas.

The historical analysis includes consideration for mega-scale events identified from geological records as well as more contemporary events provided in historical records. The quality of data collected, from the perspective of performing the required modeling, varies for the different hazards and may be summarized as follows:

For earthquake, input data such as event catalog, historical records of earthquake events are available and the quality of such data is good. Local site conditions were developed from geological maps on 1:250k scales. Event records for developing Yemen specific attenuation functions are not available, so global or other similar region specific attenuation functions will be used in the model. Seismic fault map and Seismicity rate of known faults is not available in Yemen. In absence of this, seismicity of Yemen will be modeled as area source, instead of fault line source.

The available volcanic database in Yemen is sufficient for the basic catastrophe modeling approach, which requires stochastic event set frequencies and loss consequences.

For landslides the soil conditions have to be derived from the geological maps as no country level soil map could be obtained. In addition, the record of historical events has no loss and frequency information. This information is not enough to develop a landslide probabilistic risk model, so hazard susceptibility maps will be prepared.

For flood modeling the elevation data is available from SRTM for the entire country and rainfall data from NWRA is insufficient and will be augmented from global sources. Observed discharge and flow levels are not available and flood footprints are available only for recent events. These will be supplemented by published reports and information from local people for recent flood events for validation of model results. Loss information in terms of affected population and damages available from EMDAT for the major events from 1981-2008 will be used for validation of modeled losses. With this information, national level flood risk assessment study can be carried out; though there is further scope of improving the model with detailed data in terms of rainfall, runoff, elevation, and flood levels.

Cyclones are rare in Yemen, so it is difficult to get a large number of actual storm events with well documented meteorological and storm surge histories. It is even rarer to find adequate and reliable measurement of storm surge elevations. Besides the two rare tsunamis - the 2004 Indian Ocean Tsunami and the Tsunami in 1945, no specific historical records have been available of tsunamis. This information is not sufficient to develop a probabilistic model of storm surges and tsunamis.

As a whole, the lack of data and in some cases the delays in getting access to existing data or non-accessibility to data due to the proprietary nature of the information have proven to be a significant impediment in the course of the project. This has led to long delays and, at times, to the need of resorting to alternate analysis approaches and to less reliable sources of information

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Abbreviations & Acronyms

Abbreviation / Acronym	Definition
AAL	Average Annual Loss
ARI	Average Recurrence Intervals
A.V.S.	Aden Volcanic Series
CDS	City Development Strategy
CSO	Central Statistical Organization
DAD	Depth-Area-Duration
DEM	Digital Elevation Model
DFD	Depth-Frequency-Duration
FEMA	Federal Emergency Management Authority (U.S.)
FTP	File Transfer Protocol
GFDRR	Global Facility for Disaster Reduction and Recovery
GDP	Gross Domestic Product
H&H	Hydrologic and Hydraulic
IFD	Intensity-Frequency-Duration
ISWMP	Integrated Storm Water Management Plan
ISWMS	Integrated Storm Water Management System
LC	Loss Cost
LEC	Loss Exceedance Curves
LoB	Line of Business
LULC	Land Use and Land Cover
MDR	Mean Damage Ratio
Mb	Body wave magnitude
ME	Energy magnitude
Ms	Surface wave magnitude
Mw	Moment magnitude
MWE	Ministry of Water and Environment
PML	Probable Maximum Loss
SCR	Stable Continental Region
ToR	Terms of Reference
YGSMRB	Yemen Geological Survey & Mineral Resources Board
YTS	Yemen Trap Series
YVS	Yemen Volcanic Series

1 Introduction

1.1 Background

Yemen is prone to various types of disasters caused by earthquakes, flash floods, floods (coastal storm surge and tsunami), landslides/ rockslides, and volcanoes. On an average, at least one disaster strikes the country every year with estimated economic Average Annual Loss (AAL) to the order of USD 70 million (World Bank). The post disaster response in the country is still in its infancy and decision makers presently lack information necessary to evaluate risk and support risk mitigation.

The Yemen National Probabilistic Risk Assessment Project is funded by The World Bank, Global Facility for Disaster Reduction and Recovery (GFDRR).

The World Bank has appointed RMSI in association with Tetra Tech EM Inc. and Rayman Engineering as consultants to undertake the study, henceforth this association has been referred to as the RMSI team.

During and following the first mission to Sana'a (April 26 to May 14, 2009), a significant amount of data has been collected. This includes the flood extents of recent events and elevation data from detailed surveys, rain gauge data, information on historical landslides, land use data, and geological maps. During this mission, a visit to Dhamar Observatory was also made to collect earthquake data and reports, published literature on volcanoes and tsunami.

A second mission was organized between June 07 and July 25, 2009 to collect field data. A DGPS field-survey was carried out for collecting about 300 point locations (latitude, longitude, and vertical height) data and corresponding flood-heights (based on watermarks left on buildings) during Storm 03B. Another field-survey was conducted along with geologists from YGSMRB for collecting landslide/rockslide data during June 07– July 04, 2009 in the affected districts of Hadramout and Al Mahara governorates. Field survey details are not presented in this report.

This report is the Historical Hazard Data Review, Analysis, and Data Quality Assessment for Yemen National Probabilistic Risk Assessment Task-1 and has been prepared at the end of data collection phase referred above.

1.2 Objectives of the Report

The Objectives of the report as defined in the Terms of Reference (TOR) are:

- Compilation and Analysis of historical Hazard Event Data - the scope covers a review of available historical information and records for Yemen, relating to the occurrence of all hazards under study in this project: earthquake, flash flood, flood (coastal storm surge and tsunami), rockslide/landslide and volcanic eruption. The report describes the data that has been collected, their sources, their accuracy and their format.
- Use and Integration of existing Hazard Assessments and Hazard Maps: each hazard section describes how the hazard data from various sources has been used.

2 Historical Flood Hazard Data Review, Analysis and Quality Assessment

Based on the flood data availability, decisions have been made regarding the approach to be followed in areas where data is insufficient. This section describes the sources of data identified in order to perform the flood hazard identification. The data required falls into the following main categories:

- Hydrological Data
- Hydraulic Data
- Historical flood records

Each subsection details the data sources, quality, and ultimate decision on whether to use the data.

2.1 Hydrological Data

Hydrologic modeling is used to simulate the hydrologic processes in the basin and estimate the design flows. It is the first step in identifying the flood hazard and mapping the floodplain. In order to develop a hydrologic model for Yemen, the following model inputs and corresponding data sets were needed:

1) Precipitation from rain gage data, satellite or hypothetical storms
2) Basin and sub-basin delineation from a Digital Elevation Model (DEM) and a stream network system
3) Soil hydrologic groups based on soil runoff characteristics and soil taxonomy
4) Curve numbers from land use and soil characteristics
5) Time of concentration requires a slope map derived from the DEM and the stream network system
6) Routing parameters and routing methods

The following sections describe the input data available based on past studies and other datasets obtained for basin characterization, precipitation, soils, landuse, and topography.

2.1.1 Past Studies

A review of previous studies was performed at the beginning of the hazard identification task. Studies were collected from the Ministry of Water Resources, Ministry of Agriculture, National Water Resource Authority, and Sana'a University. Table 2-1 describes the hydrological information discovered from each relevant study.

Table 2-1: Relevant Hydrology Information from Past Studies

Studies	Relevant Information (Hydrology)
Yemen Irrigation Improvement Project, Working Paper 14 - Hydrological Analysis, Interim Report. March 2003. By Arcadis Euroconsult	• Daily rainfall information for 37 stations • Regional flood frequency analysis based on 30 stations • Flood frequency curves based on observed annual maximum flows • Probability distribution of daily rainfall and floods is log-normal
Soil Survey of the Yemen Arab Republic. Dept of Agronomy, Cornell University. May 1983. Jack W. King II, Terrence R. Forbes, Abdul Elah Abu Ghanem. Contract Number	• Soil survey data

Studies	Relevant Information (Hydrology)
AID/NE-C-1665.	
Surface Water Final Report. Technical Secretariat of the High Water Council UNDP/DTCD Project YEM/88/001. January 1992.	• Identification and assessment of rainfall and flood gages • Daily-runoff model • Recommended CN
The Water Resources of Yemen – a summary and digest of available information (WRAY-35). March 1995. Jac A.M. van der Gun and Abdul Aziz Ahmed.	• Surface water data - catchments, hydrographs, flow volumes, peak flows, quality, and sediment transport • Climate data - precipitation, ET, and climate zones
Rainfall and Runoff in Yemen. F.A.K. Farquharson, D.T. Plinston, J.V. Sutcliffe. Hydrological Sciences, October 1996	• Climate, precipitation, evaporation, runoff and landuse characteristics for Yemen • Relationship between rainfall and runoff for selected catchments in Yemen

2.1.2 Precipitation Data

Daily rainfall data were obtained in digital format from three sources: (1) National Water Resource Authority (NWRA), (2) U.S. National Oceanic and Atmospheric Administration (NOAA) and (3) the National Aeronautics and Space Administration (NASA). The NOAA and NWRA data came from the stations shown in Figure 2-1. The daily rainfall data spans from 2003 to 2008 and was available for 14 gage stations. In addition, rainfall data was collected from two international sources namely, TRMM and Santa Clara University data sets.

The Tropical Rainfall Measuring Mission (TRMM) is a joint U.S.-Japan satellite mission to monitor tropical and subtropical precipitation and to estimate its associated latent heating. TRMM is designed to monitor and study tropical rainfall and the associated release of energy that helps to power the global atmospheric circulation, shaping both global weather and climate. The rainfall data is available at 0.25° resolution and for the period 1998-2008. It is spatially distributed in raster format. Spatial map showing grid locations are given in Figure 2-2. Data has been downloaded from the following link:

(http://mirador.gsfc.nasa.gov/cgibin/mirador/presentNavigation.pl?tree=project&project=TRMM.)

Santa Clara University data has gridded rainfall data at 0.5° resolution and is available for the period 1950-1999 (Maurer et.al., 2002). Data is available on internet at (Source: http://www.engr.scu.edu/~emaurer/data.shtml). Since the data has no specific name, it has been named on the university at which it was generated i.e., Santa Clara. Spatial map showing grid locations are given in Figure 2-3.

Both data sets were used to enhance data collected from weather monitoring stations of Yemen.

A comprehensive network of rainfall gage stations with historical rainfall records (more than 30 years ideally) and fine temporal resolution rainfall data are needed to develop intensity-duration-frequency (IDF) curves and isohyets showing the distribution of rainfall.

From the stations shown above, there were none that had more than three years of daily records. The stations had major data gaps and only had a few years of data. To support the rainfall analysis, TRMM and Santa Clara data sets were used which provided a more complete record of rainfall. Design storms have not been previously developed for these basins. Therefore, a statistical frequency analysis is being performed on the maximum annual rainfall for each sub-basin to develop the design storm events.

Figure 2-1: Rainfall Stations

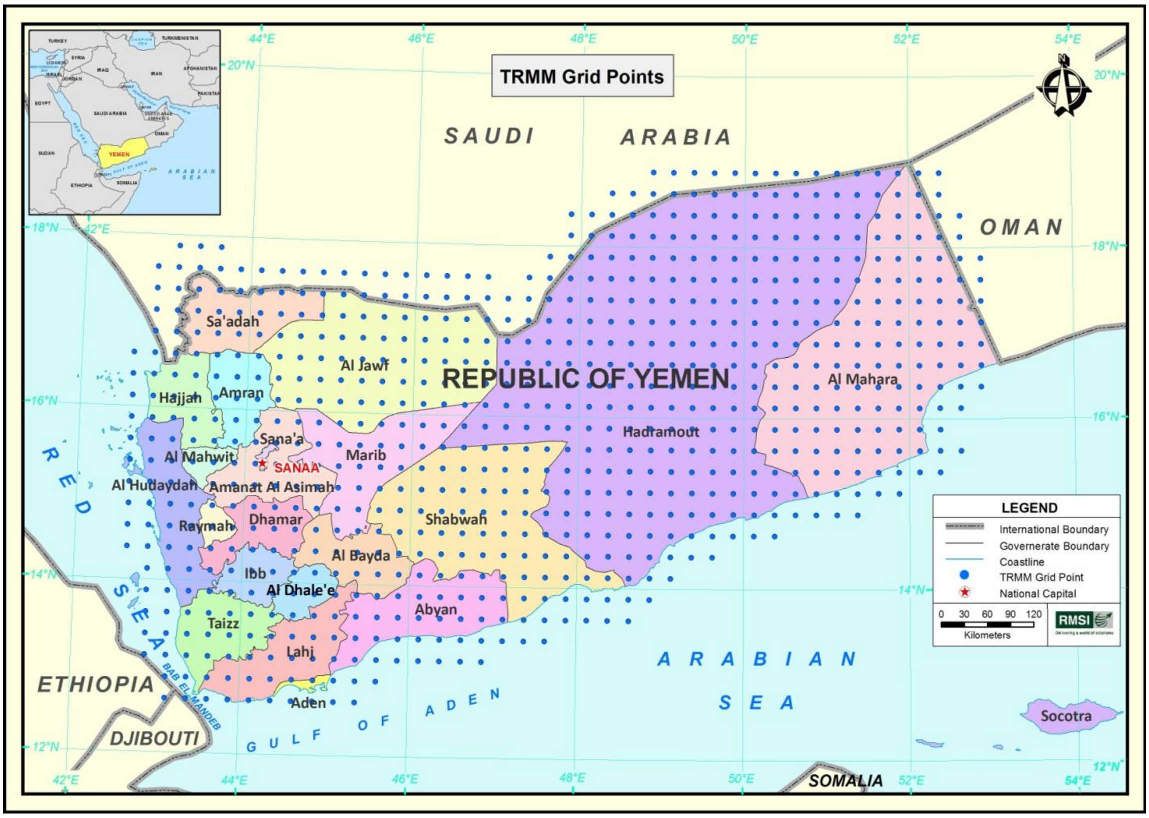


Figure 2-2: Map showing TRMM grid points over Yemen.

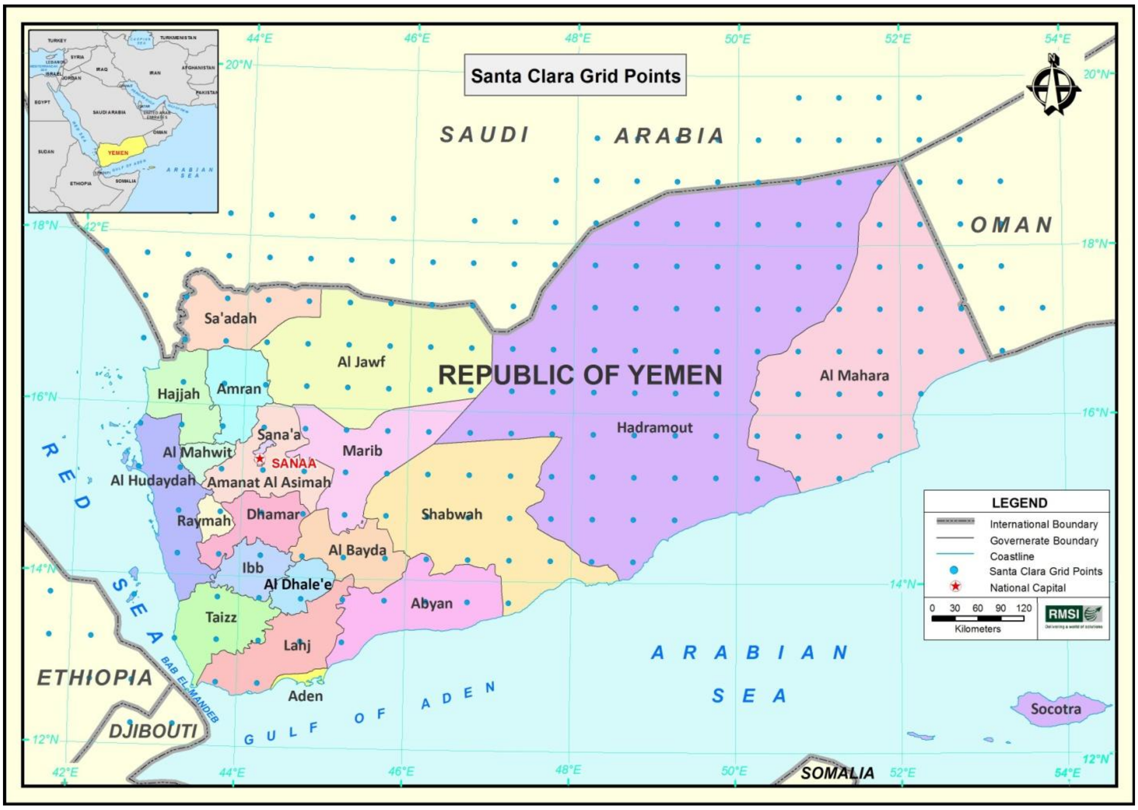


Figure 2-3: Map showing Santa Clara University grid points over Yemen.

2.1.3 FLOW DATA

In the present study, flow data is not available for calibration of the hydrological model. Mean rainfall and runoff values are available for various basins across Yemen, based on 20 years of simulation. This data is taken from the paper "Rainfall and runoff in Yemen (F.A.K. Farquharson et.al 1996).

2.1.4 SOILS AND LAND USE DATA

Soils related data was collected from several sources listed in the past studies section above as well as from the Survey Authority. It was found that FAO soil maps are the best source for soil related properties.

Other useful information in assigning soil groups is the runoff characteristics map (Figure 2-4) which separates the basin into two main zones: a runoff producing zone and a runoff absorbing zone. The runoff producing zones included areas with steep slopes, bared rock, or flat slopes with impervious soils. The runoff absorbing zones included flat and sandy alluvial areas, terraces on plains and low slopes with natural vegetations. Soil hydrologic groups were assigned to producing and absorbing zones.

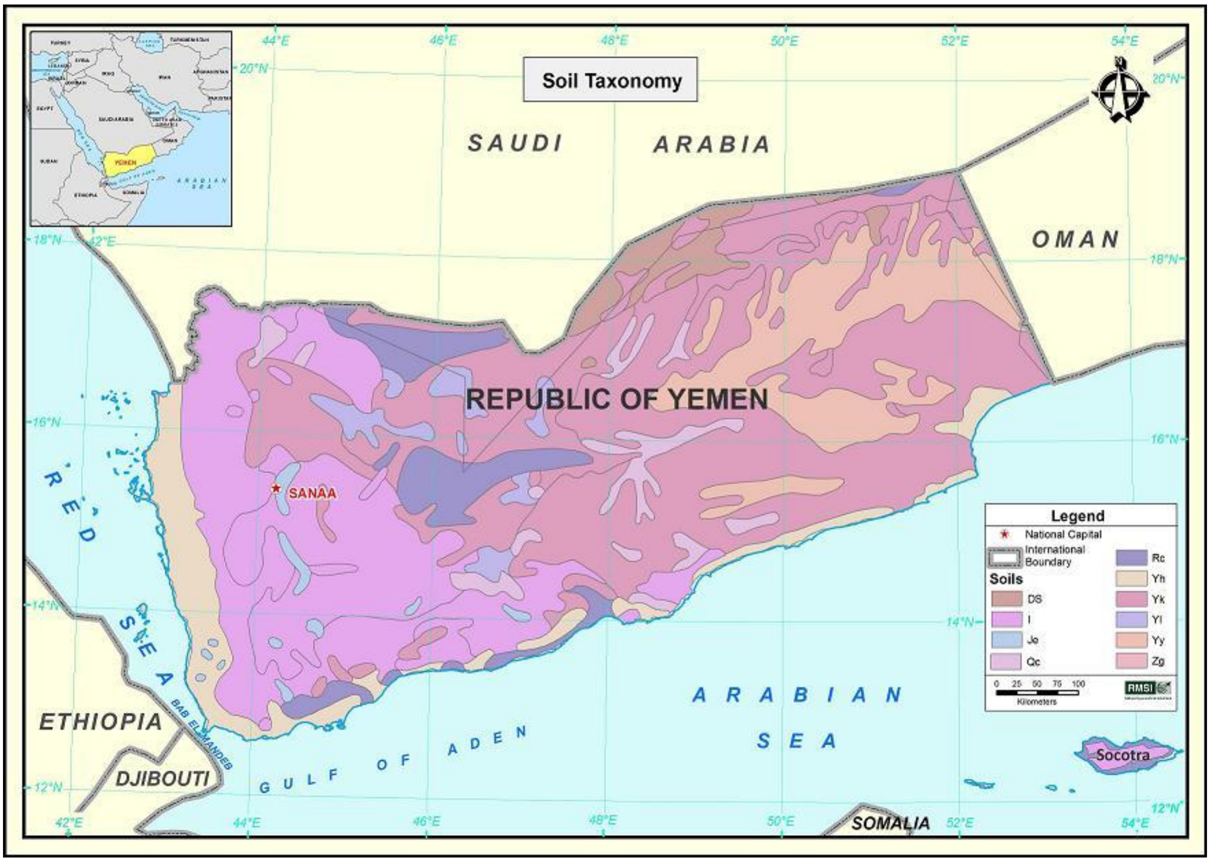


Figure 2-4: Soil Taxonomy

Table 2-2: Soil Taxonomy

Name	Map Symbol (Fig 2)	Texture
Inceptisols (37.8% of Basin)		
Typic Ustropepts	Iuu	-
Entic Ustropepts	Iuu	fs, fl
Aridisols		
Ustollic Calciorthids	Iuu	Fl
Ustollic Camborthids	Iuu	Cl
Entisols (33.6% of Basin)		
Typic Ustifluvents	Ehu, Eho, Eub, Ruo	cl, fl
Typic Torriorthents	Ehu, Eto, Muh, Rtc	ss, cl, fl
Typic Ustorthents	Ehu, Eto, Eub	ss, cl, fl, fs

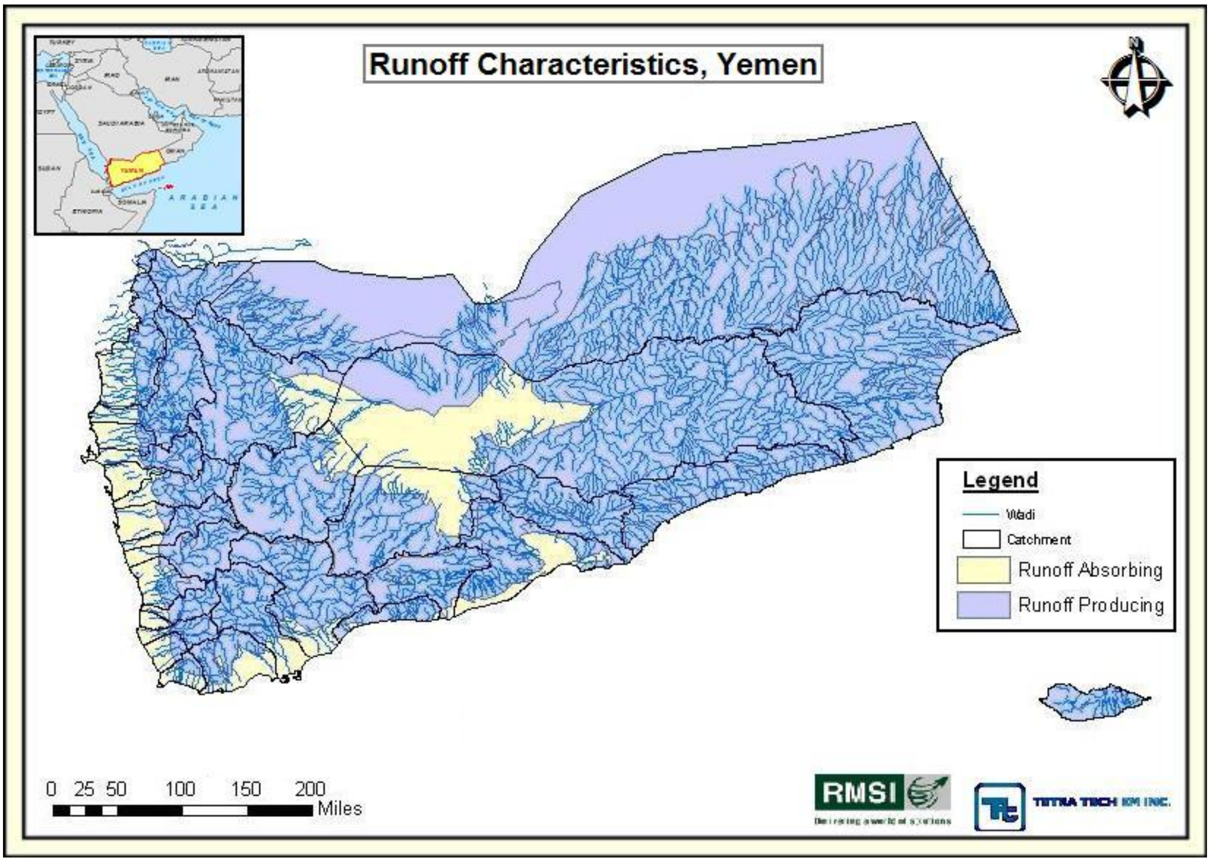


Figure 2-5: Runoff Characteristics

Land use data for the basins were obtained from the LandSat dataset, which covered the entire basin at a 28.5 m resolution taken in 2000. The land use data was classified into eight categories as shown in Table 2-3.

Table 2-3: Existing land use categories in the Basins

Land use class	Land use type
1.	Residential
2.	Industrial/Commercial
3.	Vegetation/Agriculture
4.	River Bed/ Flood Plain
5.	Coast/Sea
6.	Rocky terrain
7.	Sand dunes
8.	Road Network

Soil hydrologic groups and landuse data were overlaid to determine curve numbers. The curve number is an empirical parameter used in hydrology for predicting direct runoff.

2.1.5 Topography

The elevation data is important to several tasks in this project. It is important that the data be easily available and fits within the schedule of this project and be accurate enough for use in the flood modeling task. Digital elevation data from the Shuttle Radar Topography Mission (SRTM) at 90 m was available for this project and it covered all basins. The resolution was fine enough that watershed sub-basins could be delineated and water flow paths could be defined.

2.2 Hydraulic Data

Hydraulic modeling simulates the stream conveyance and provides the flood depth and velocity for a flood study. The model requires mainly geometry data and discharge data. The geometry data includes (1) cross section stations and elevations, (2) bridge and culvert data, and (3) friction factors.

2.2.1 Past Studies

A review of previous studies was performed at the beginning of the hazard identification task to identify any relevant hydraulic data. Studies were collected from the Ministry of Water Resources, Ministry of Agriculture, National Water Resource Authority, and Sana'a University. Table 2-4 describes the hydraulic information discovered from each relevant study.

Table 2-4: Relevant Hydraulic Information from Past Studies

Report	Relevant Information (Hydraulics)
Soil Survey of the Yemen Arab Republic. Dept of Agronomy, Cornell University. May 1983. Jack W. King II, Terrence R. Forbes, Abdul Elah Abu Ghanem. Contract Number AID/NE-C-1665.	• Soil survey data
The Water Resources of Yemen – a summary and digest of available information (WRAY-35). March 1995. Jac A.M. van der Gun and Abdul Aziz Ahmed.	• Surface water data - catchments, hydrographs, flow volumes, peak flows, quality, and sediment transport

2.2.2 DETAILED TOPOGRAPHY

The high resolution DEM from Remote Sensing and GIS (RS & GIS) center, Sana'a, Yemen has not been made available to date. This makes hydrological and hydraulic analyses tasks difficult. As an alternative, the SRTM 90 m DEM has been interpolated to 30 meter and quality has been improved with the help of DGPS survey elevation data to make it satisfactory for hydrological and hydraulic analyses for the Hadramout and Al Mahara Basins.

2.3 Historical Flood Records

Historical flood event records available from CRED EM DAT are presented in Table 2-5. Besides this, historical flood data such as depth, extent, and duration is of critical importance to calibrate the hydrologic and hydraulic models. Such information was unavailable at MWE and NWRA. In addition, flood maps from earlier events were not available. Flow measurements for streams in the basins were not available.

Table 2-5: Historical events (CRED EM-DAT, 2008)

Start Dates	End Dates	Location	Killed Persons	Affected Population	Estimated Damage (US$ Million)
23/10/2008	24/10/2008	Tarim, Sah, Shibam, Qatun	90	25,064	400
1/8/2007	27/08/2007		50		
23/03/2007	30/03/2007	Hadramout, Ibb	36	618	
1/1/2007	4/1/2007	Rayma, Dhamar province	7	2,000	
3/4/2006	5/4/2006	Dhamar, Hodeida, Manakhah	25	320	
20/02/2006	23/02/2006	Ma'arbar (Dhamar province)	5	2,000	
20/08/2005	21/08/2005		12	6	
25/04/2005	27/04/2005	Sanaa, Hodeaida regions	10	715	
19/06/2003	21/06/2003	Hijja, Taaz province	15		
22/08/2002	6/9/2002	Taëz, Houdaida, Hadramout	28		
24/07/2002	26/07/2002	Raima region	13		
6/7/2002	8/7/2002	Salafiyah region	10		
11/4/2002	11/4/2002	Shahar district (Hadramout)	2	700	
26/07/2001	29/07/2001	Omrane, Hadramout, Saada	33		
4/12/1999	4/12/1999	Socotra		19,750	

Start Dates	End Dates	Location	Killed Persons	Affected Population	Estimated Damage (US$ Million)
		Archipelago			
14/08/1998	30/08/1998	Siham valley Red Sea port	70	240	
14/03/1998	16/03/1998	Tihama Valley in Al Hodei		3,000	
14/05/1996	18/05/1996	Hudayda, Taiz regions	7	5,000	10
13/06/1996	25/06/1996	Shabwa, Mareb, Hadramout	338	238,210	1200
5/2/1993	10/2/1993	Lahej, Abyan, Aden Govern	31	21,500	1.5
00/12/1991	00/12/1991	Socotra Island		30,000	
6/4/1989	6/4/1989		38	150,000	
24/08/1975	24/08/1975	Sanaa region	52	50,000	12.7
4/8/1973	4/8/1973	Hugaryah Area (Taiz province)	60	2,862	
19/03/1989	19/03/1989	Saiyoon district	25	340,000	33
29/03/1982	29/03/1982	Nationwide	482	350,000	975
00/09/1981	00/09/1981	Abyan		3,000	16
00/03/1981	00/03/1981			12,000	16.2

3 Historical Earthquake Hazard Data Review, Analysis and Quality Assessment

During and following the first mission to Sana'a (April 26 to May 14, 2009), a good amount of data has been collected.

3.1 Earthquake

The collision zones between the Arabian and Eurasian plates are the principal cause of earthquakes in Yemen. The seismic hazards in the country are mainly due to the proximity of the Red Sea Rift, which is more pronounced due to the seismicity along the spreading ridges. However, a low level of seismicity, characterized by small to moderate - size events, occurs within the Arabian Plate within 200 to 300 km of the axis of the Red Sea in Yemen and extends into adjacent areas southward, and the Asir region of southwestern Saudi Arabia (Ambraseys and Melville, 1983; and Plafker et al., 1987).

The documentation of historical earthquake activity in the Arab region dates back over 4,000 years in a wide range of forms and includes historical chronicles (Alsinawi and Aydrus, 1999). As historical data are not based on instrumental observations, the earthquake magnitude, intensity and epicenter in this database have been estimated based on the description in historical documents. Therefore, the accuracy of estimation and the lower limit of scale of earthquakes vary widely from time to time (Razak et al., 1997).

Documented historical seismicity of Yemen goes back to an earthquake that struck the desert of Sheba in 742 AD. The historical seismicity records included damaging earthquakes in various locations of Yemen. Seismic history of Yemen indicates the occurrence of large earthquakes with 20 to 30 years recurrence periods (Alsinawi and Alaydrus, 1999). The development in instrumental seismology in Yemen began after the occurrence of the December 13, 1982, Dhamar earthquake (Al-Saud, 2008). The National Yemeni Observatory started earthquake monitoring in November 1994. Appendix A details the studies considered for the earthquake hazard. Table 3-1 describes the earthquake information discovered from each relevant study.

Table 3-1: Relevant Seismic Information from Past Studies

Report	Relevant Information (Earthquakes)
Seismicity of Yemen. 1999. By Alsinawi, S. A. and Aydrus, A. Al, Faculty of Science, University of Sana'a	• Geology and Tectonics • Macroseismicity of Yemen • Earthquake data evaluation • Seismotectonics and seismological engineering
The Seismicity of Egypt, Arabia and the Red Sea – a historical review. 1994, Ambraseys, N. N., Melville, C. P. and Adams, Cambridge University Press	• Macroseismic information and related data assessment • Earthquake catalog • Completeness of historical earthquake catalog and regional distribution of seismicity
Evaluation of Seismic Ground Motion for Sana'a Region. January 1997, Razaq, N. A. A. et al. Ministry of Oil and Mineral Resources, Republic of Yemen	• Historical and recent seismicity • Earthquake engineering design consideration

Report	Relevant Information (Earthquakes)
Seismic and Volcanic Risks in the Yemen Arab Republic. August 1976. By UNDRO, Geneva	• Seismic hazards in Yemen • Physiography and tectonics • Seismic activity and risk
Survey of Damages During the Dhamar Earthquake of 13 December 1982 in the Yemen Arab Republic. Bulletin of the Seismological Society of America, Vol. 75, No. 2, pp. 597-610, April 1985, Arya, A. S., Srivastava, L. S., and Gupta, S. P.	• Description of Dhamar earthquake • MMI distribution map
A Basis for Evaluation of Seismic Hazard and Design Criteria for Saudi Arabia. Earthquake Spectra, Vol. 10, No. 2, 1994. By Haddad, M. et al.	• Seismicity and seismotectonics • Seismic source regionalization • Seismic hazard analysis
Surface Effects and Tectonic Setting of the 13 December 1982 North Yemen Earthquake. Bulletin of the Seismological Society of America, Vol. 77, No. 6, pp. 2018-2037, December 1987, by Plafker, G. et al.	• Tectonic and geologic settings • Shaking damage
Report of Earthquake Reconstruction Joint Mission –Proposal for a reconstruction Program, Yemen Arab Republic, Feb 25, 1983	• Damages in Dhamar earthquake • Reconstruction Plan • Economic aspects of Reconstruction Plan

3.1.1 Historical Earthquake Events records

The objective of the present study is to provide a uniform account of the seismicity of Yemen. Being located alongside one of the main sea trade routes, Yemen has a long and relatively documented history of important past earthquake events chiefly from medieval Arabic chronicles as well as European travel literature and technical studies. After 1900, the instrumental records from various seismological stations and bulletins supplement these macro-seismic data. These include records from ANSS - Advanced National Seismic System as shown in Figure 3-1.

Though earthquakes from time to time along and adjoining the Red Sea have affected Yemen, systematic historical records of these events are not readily available (Alsinawi and Alaydrus, 1999). An attempt has been made to compile a catalog of important historical earthquakes of Yemen from various sources such as Alsinawi (1999), Ambraseys et al. (1994), Razaq (1997), Al-Heety (2005).

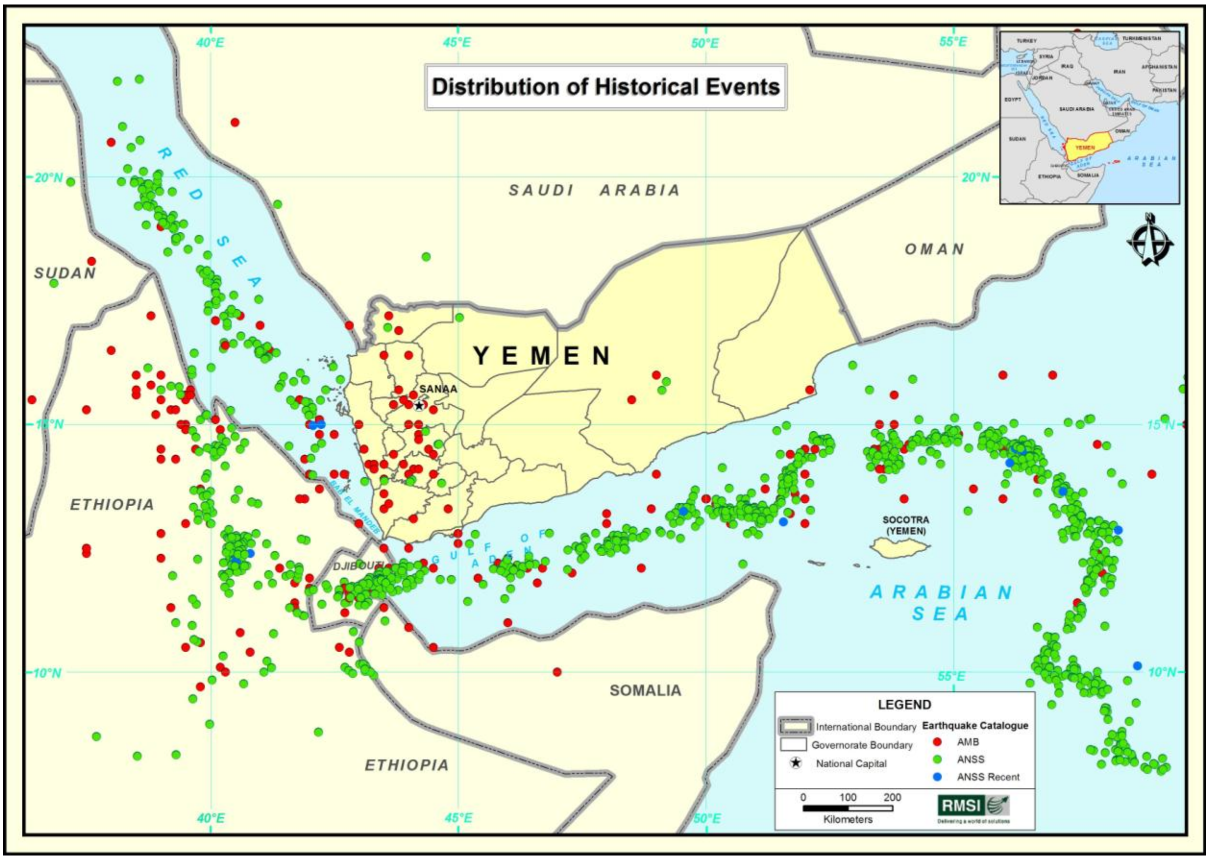


Figure 3-1: Distribution of historical events

The macroseismic data retrieved from various sources have been interpreted in order to find out the epicentral locations, assessment of maximum observed intensities and calculation of magnitudes as defined by their reported felt area. Attention is given to the role of population distribution, communications, and availability of historical documents and completeness of datasets as a whole (Ambraseys et al., 1994). Table 3-2 provides a catalogue of significant historical earthquakes that occurred in Yemen.

Table 3-2: Catalogue of significant historical earthquakes

Year AD	Date	Description/ affected areas	Estimated Intensity	Approx. Location of Co-ordinates	Ref.
1993	Jan 09	Occurred in Haidan with an estimated magnitude Mw 4.5		17.16N, 45.025E	11
1993	Nov 02	Occurred at Haidan near Sadah	V-VI	13.863N, 43.509E	11
1991	Nov. 22	Occurred 140 km south of Sana'a, 10 people killed and about 450,000 affected	VII	13.9N, 44.1E	10
1982	Dec. 13	Located 70 km south of Sana'a, heavy damage. Collapsing buildings caused the death of about 2,500 people and injury to 1,500. shock also felt in Jizan, Najran and Ta'izz	VIII	14.7N, 44.2E	10
1975	Oct.	Azal al-Radma of Ibb province, 38 houses evacuated in Bait Badr village and 12 houses in Khaulan	VI	14.0N, 44.2E	10
1959	Aug. 16	Located teleseismically near Bait al-Faqih, felt in al-Mukha, Ta'izz and Ibb, caused damage to cultivable land, dwellings, multistory buildings,		14.5N, 43.1E	10
1955	Oct. 17	Mild earthquake without damage in region east of Sa'da	VI	17.2N, 43.6E	10
1941	Jan. 11	Devastating earthquake, extending from Sana'a and up north to Jizan on the Red Sea, 1,200 people were killed and 200 injured	VIII	16.4N, 43.5E	10
1911	May 13	Considerable damage and collapsing of houses in Zabid	VI	14.1N, 43.3E	10
1898	Sept.	Probably caused by meteorite strike, Tihama		15.4N, 43.7E	10
1896	Dec. 11	Sana'a	VI	15.6N, 39.5 E	10
1895	Aug. 2	Series of shocks felt at al-Mukha and Ta'izz	V	13.1N, 44.1E	10
1895	Feb. 8	Series of 3 shocks. Extent of damage unknown. Mukha- Taiz	VII	13.4 N, 43.6 E	6,10
1887		Aden	VI	12.8N, 45E	10

Year AD	Date	Description/ affected areas	Estimated Intensity	Approx. Location of Co-ordinates	Ref.
1884	July 2	ME= 5.9 Massawa	VI	16N, 41E	2,4
1881		Saada	VI	16.9N,43.8E	10
1878		Dhamar- Yarim	VIII	14.5 N, 44.4 E	6,10
1861	22-2	Caused by volcanic eruption	IV	13.74N,41.55 E	10
1850		300 houses demolished in Sana'a	IX	15.4 N, 44.2 E	10
1810		Jabal Nar between Yemen and Asir	VII	17.0 N, 42.8 E	10
1789	July	Red Sea, Jabal Al-Dukhan	VIII	12.5 N, 44 E	2,4,5,9,10
1788		Large shock affecting Bayt Qsr and Bayt Hindi - Houses and buildings destroyed.	VIII		2,4,5,9,10
1775		Hais Area	VI	13.9N, 43.5E	10
1675		North of Dhawran	VI	15 N, 44.2 E	2,3,10
1674		About 30 shocks, culminating in a major shock - split many houses and caused rock falls from jabal Dawran. Felt in Sana'a	VIII	14.8N, 44.2E	10
1667	March	Damaged houses, shocks felt throughout most parts of Yemen, Sana'a	VIII	14.4 N, 44.5 E	10
1666		Sana'a	VI	15.5N, 43.9E	10
1647		Shocks felt at Sana'a and else where	V	15.5 N, 43.9 E	0
1644	22	Strong tremor caused rock fall. May have been a landslide East of Sadah at Al Ashshah	VI	15.4 N, 43.9 E	2.3.4,9,10
1631	2 10	Volcanic activity of doma foot of Doma Ali ME 5.7	IX	11.25N, 41.70E	6,10
1631	2 25	Volcanic activity of doma foot of Doma Ali ME= 5.7	IX	11.25N, 41.70E	2,4,3,9
1619		ME=5.8 between Saada and Kawkaban	VII	16.4N, 44.0E	10

Year AD	Date	Description/ affected areas	Estimated Intensity	Approx. Location of Co-ordinates	Ref.
1613		Made ground swell in waves, possibly offshore epicenter. Aden	VI	13.2 N, 44 En	6,10
1511	Feb. 27	Zabid	VII	14.2N, 43.3 E	10
1511	11	ME=5.6. Zabid	VI	13.6N, 43.5 E	10
1509		Series of large and small shocks	VII	14.2 N, 43.31	2,4,5,9
1504		ME=6.6. Red Sea-Zabid, Zaila' (Bab Al-Mandab)	VII	12.5 N, 43.5 E	10
1502		Series of shocks. Panic in Zabid, no damage	V	142 N, 43.3 E	2,4,9,10
1501		Series of shocks continue to 1502. Zabid	V	14.2 N, 43.3 E	2,4, ,9,10
1485		Great Earthquake-Swarms	VII	14.2N, 43.5E	10
1484		Great Earthquake	VII	14.2 N, 43.3 E	10
1466		Zabid	VII	14.3N, 43.3 E	10
1463		Series of shocks over 3 days, 50 houses destroyed in Zabid, 10 killed. Zabid	VIII	14.3N, 43,3E	2,4, 5,9,10
1432		ME= 5.7 Tihama, Surdud	VI	15.1N, 43E	10
1427		Main shock & numerous aftershocks destroying many houses and killing 60 people in Zabid	VIII	14N, 44E	2,4, 5,9,10
1413		Himyar (Sana'a Yarim)	IX	14.1N, 44.2E	10
1400		Dubbi volcano ME=6	VIII	13.4N, 41.8 E	6,10
1394	March - April	Sequence of about 40 shocks in Mawza Region	V	13.3 N, 43.5 E	2,4,5,9,10
1387.	Spt.	Destroyed many houses without loss of life. Followed by other shocks that lasted several days, caused damage in Hajar, Aden	VIII	13.3N, 44.8E	2,4, 9,10
1381		Hadramout (Wadi Amd)	VII	15.5 N, 48.5E	10

Year AD	Date	Description/ affected areas	Estimated Intensity	Approx. Location of Co-ordinates	Ref.
1359		Shocks continued intermittently from mid-day to early evening. Many houses destroyed. 51 killed in Zabid and a few in Sana'a and Aden. Zabid, Sana'a and Aden	VIII	14.2N, 43.9E	10
1349		Caused panic, no apparent damage. Zabid	V	14.3N, 43.5E	2,4,5,9
1265		Shocks felt. Sana'a	V	15.4N, 44.9E	2,4,9,10
1259	End	Slight shock, no damage. Sana'a	V	15.4 N, 43.7 E	2,4,9,10
1259	10th Dec.	Damage to many places in mountains west of Sana'a	VII	15.5N, 44 E	2,4,9,10
1195		Hadramout (Tarim, Shibam, Region)	VI	16.0N, 49.05E	10
1154	11th	Destroyed many villages, a castle and dwellings. 300 killed. Between Sana'a & Aden	VIII	14.1 N, 44.1 E	10
1072		Destroyed houses and killed about 50 people. Sana'a, Zabid and Mukha	VIII	14.5N, 43.7E	2,3,4, 9,10
859		Wadi Dhar/ Aden	VIII	15.4 N, 44.3 E	1,10
827		Destroyed houses and villages and caused many deaths. Aden - Sana'a	VII	14.0 N, 44.5 E	2, 9,10
742		Many villages overwhelmed by collapsing mountains, possibly Ma'rib Dam damage, between Shabwah and M'arib	VII	15.4N, 45.4 E	2,3,4
		Shocks left no house undamaged, poorly constructed ones suffered extensive Damage. Cracks appeared in fields and wells muddied. Zabid - Mawza			

References cited in Table 3-2	
Ref. No	**Source**
1	Alsinawi (1983-a), Alsinawi (1986)
2	NRP (1992)
3	Yemen National Earthquake Mitigation (1993)
4	Ambraseys and Mellvile (1983)
5	Hais Seismicity (1993)

References cited in Table 3-2	
Ref. No	**Source**
6	Gouin (1979)
7	Al Thour (1993)
8	Poirier and Taher (1980)
9	Ambraseys (1971)
10	Ambraseys et al. (1994)
11	ANSS (2009)

3.1.2 MACROSEISMIC INFORMATION ON MAJOR EARTHQUAKES IN YEMEN

From 1900 onwards, almost all earthquakes having macroseismic data have been described and three significant earthquakes have been identified that caused a large number of deaths, affected a large number of people, and caused considerable economic losses.

3.1.2.1 The Sadah Earthquake of January 11, 1941

The Jan 11, 1941 earthquake is considered amongst the largest earthquakes in the recent history of Yemen (Al Munifi, 1993; and Al Aydrus, 1997). The earthquake was preceded by a foreshock on January 9, 1941 felt in Al-Hudaida. The region worst affected lay west of Sa'da, in the area around Razih, where a number of villages were destroyed, accompanied by minor loss of life. Landslides blocked the road at the head of the Razih Valley. To the north, between Jizan and Razih, at Arida near Abu Arish in Saudi Arabia, the shock caused rockfalls and the drying up of spring water. In Sa'da and Rahban, and especially Wadi Azar, many houses were destroyed: old and new houses developed cracks in Sa'da, but there was no loss of life. The inhabitants abandoned their homes and camped in tents. In the district of Majz, many Jews were killed by the collapse of the roof of their synagogue. Damage also extended south to Kuhlan and Hajja, where a few houses were demolished (Ambraseys et al., 1994).

Recalculations from surface wave data utilizing 17 stations using the Prague equation yielded a surface wave magnitude (Ms) 6.0 (Alsinawi and Alaydrus, 1999). The location of the earthquake epicenter is marked at 16.4°N and 43.5°E with an estimated seismic intensity of VIII. The devastating earthquake caused 1,200 deaths, injured 200 people, damaged 1,700 houses of which 300 were destroyed, 400 were damaged beyond repair and the rest received minor damage (Ambraseys et al., 1994).

3.1.2.2 The Dhamar Earthquake of December 13, 1982

A large area of Dhamar province of Yemen was rocked by a destructive earthquake on 13 December 1982 (Mb = 6.0) (Alsinawi and Alaydrus, 1999). The epicenter of this earthquake was located at 14.7°N and 44.2°E. This moderate, shallow earthquake that occurred in a densely populated region about 70 km south of Sana'a, resulted in 2,500 deaths and injured 1,500 people (Ambraseys et al., 1994). More than 70,000 dwellings were damaged and 500,000 people were affected. However, number of deaths reported by Ambraseys et al. (1994) differs with those reported by NGDC. Casualties were more in the highly populated village centers rather than better-built and engineered structures in modern centers. The damage was more severe for houses built adjacent to steep slopes due to rock falls and slides. The shock was perceptible as far as Jizan, Najran and Ta'izz, all at an average distance of 230 km, but it was not reported from Aden or from Yemeni and Ethiopian ports on the Red Sea. The main shock and its aftershocks were associated with tension cracking of the ground, with 1 cm wide cracks in the ground, along a zone 15 km long by 10 km wide, trending 350°, presumably the result of dip-slip along normal faults responsible for the earthquake (Ambraseys et al., 1994).

Name	Year	Month	Day	Hour	Minute	Second	Latitude	Longitude	Depth	Mag	MMI Int	Number of Deaths	Number of Injuries	Damage in $Mill
YEMEN: DHAMAR	1982	12	13	9	12	48	14.701	44.379	5	6	8	2800	1500	2000

Source: NGDC, Significant Earthquakes

The survey reveals individual ground fractures, with openings from a few mm to about 10 cm extending over 50 to 100 m. The earthquake caused heavy damage to most of the random rubble stone masonry and unburned brick construction in Dhamar-Ma'bar region. Such constructions suffered heavy damage in the form of large and deep cracks in walls, and the collapse of the outer and inner masonry walls, and resulted in partial or complete collapse of the construction.

3.1.2.3 The Al-'Udain and Hazm Al-'Udain (Ibb) Earthquake of November 22, 1991

The November 22, 1991 earthquake (13.9°N, 44.1°E) of Ms 4.5 caused widespread damage to housing and infrastructure in Yemen. The most affected areas were the al-'Udain and Hazm al-'Udain districts in the Ibb region (UNDHA, 1991). The earthquake affected a mountainous region where it triggered rockfalls and slides from steep slopes (Ambraseys et al., 1994). The sub-districts of Jabal Bahri and Bani Zuhair experienced the worst damage. In Jabal Bahri, 17 houses were destroyed causing 11 deaths and wounding more than 30 people. Preliminary surveys indicate that 7,150 buildings were damaged and 1,578 were destroyed (UNDHA, 1991). However, the reinforced concrete structures in the epicentral area suffered no structural damage indicating the high vulnerability of traditional buildings, especially those constructed on slopes without proper foundation (Ambraseys et al., 1994).

3.1.2.4 The Haidan Earthquakes of January 9, 1993

A major event struck the Haydan area of Sadah Region with an estimated Mw of 4.5 on 9 January 1993. Most of the aftershocks of this event are located at Wadi-Haidan, which represents a major fault in the area (Alsinawi and Alaydrus, 1999). The seismicity of the area for the period 11 January- 26 February 1993, reveals aftershock events of the major shock of January 9 1993, rather than earthquake swarm activity, as in Al-Udayn region (Abdul Jabbar and Fari, 1993).

From various available reports, thesis, past studies and other documents it is clear that potential earthquake risk exists in Yemen. In addition to the direct effects of earthquakes, their indirect consequences like rockslide/landslide and fire, should also be taken into consideration.

4 Historical Rockslide/Landslide Hazard Data Review, Analysis and Quality Assessment

Mass movements (rockslides/landslides) in Yemen are not uncommon. The recent rockslide in Al-Dhafeer village, Bani Matar district is one such example (Figure 4-1), which occurred about 50 km from Sana'a on December 28, 2005. More than 90 people were killed and about 20 houses were destroyed. The Yemen Geological Survey & Mineral Resources Board (YGSMRB) team surveyed and discussed the scientific reasons for the event. The team explained that the rockslide happened due to the increasing weight of the emerging rock in the Al-Dhafeer mountain summit on its base, which consists of sedimentary rocks that are sandy and vulnerable to erosion. In this event, several blocks of about 70m x 20m x 10m were dislodged from the mountain cliff.

After the Al – Dhafeer incident, people of Yemen have observed slopes and informed local governments. There is one such case from people of Bani Hammad, Taiz province, who informed about landslides that threaten their life. NewsYemen learned about rifts/large cracks about 20 meters in depth found in the mountain. Taiz is one of the provinces, which is prone to rockslides/landslides due to torrential rains and fragile geology. The examples are areas of Gabal Habashi and Qadas in Taiz, which show cracks on the ground in the front of a landslide (Figure- 4-2). The YGSMRB is active and conducting field surveys in all populated and geologically fragile stretches of Yemen.

In Yemen, variations exist in topography, geology, climate and living conditions and the overall scenario suggests that most of the communities/settlements are located at the toe of mountains or under cliffs and are, therefore, vulnerable to rockslides/landslides. Slope failures occur due to both natural and manmade causes. The natural causes include fragile geology, tectonic activity, climate changes, severe variations in temperature and precipitation. The manmade causes include cutting the mountain toe for house construction, road construction, and blasting at mining sites.

Figure 4-1: Rockslide at Al-Dhafeer village

As discussed above, the topography and living conditions suggest that most of the settlements are located under cliffs and the toe of mountains. Particularly, in case of Hadramout, the settlements are stretched along the toe of mountains since the valleys are used for cultivation (Figure 4-3). The spatial extents of a majority of settlements are under dangerous massive cliffs. One such example of the spatial distribution of settlements in the Hadramout valley is shown in Figure 4-4.

Figure 4-2: The high concentration of cracks in the front of the sliding area in Gabal Habashi (Sayed A.E. et al, 2003)

Figure 4-3: Settlement in Hadramout valley: (A & B) in Syoun at the toe of mountain front; (C & D) in Tarim at the toe cutting in Hadramout valley

Figure 4-4: Al-Dhafeer village is situated under the massive cliff

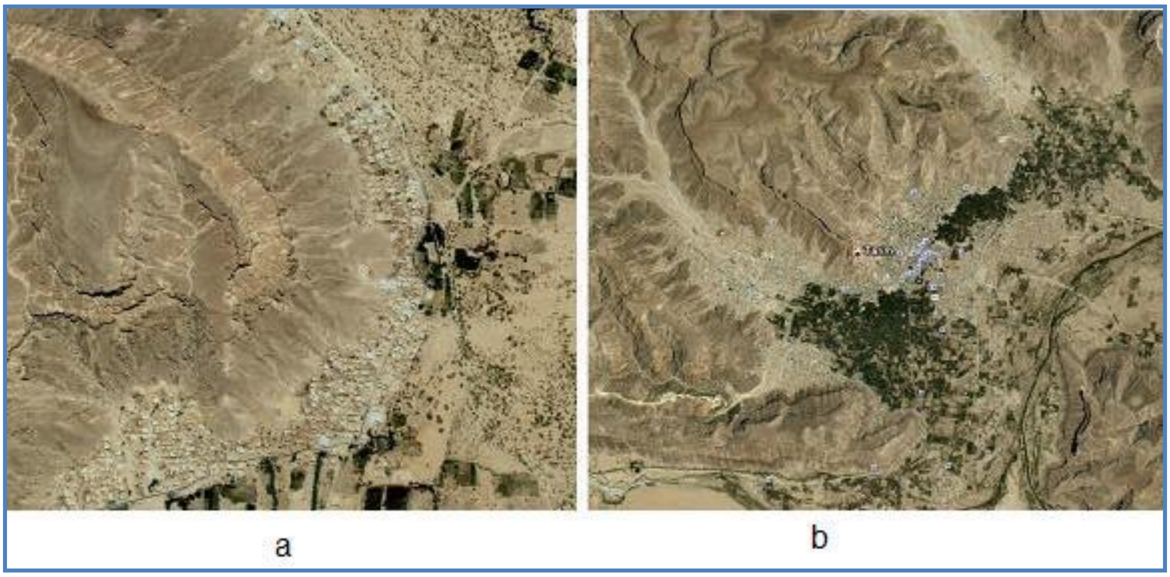


Figure 4-5: a and b show the settlements established under and along cliffs in Hadramout (Tarim, Syoun valleys)

4.1 Data Review and Analysis

In order to develop a rockslide/landslide probabilistic hazard model, the following geospatial datasets are being analyzed (after Cees J. van Westen et.al, 2008):

1) Landslide inventory data -inventory, monitoring,
2) Environmental factors - geology, soil, morphology, geomorphology, LULC, hydrology
3) Triggering factors - earthquake zones, weather data (rainfall, temperature)
4) Elements at risk - roads, agricultural areas, buildings, population

4.1.1 Rockslide/Landslide inventory, monitoring

Rockslide/Landslide inventory: YGSMRB is the nodal agency for capturing and studying rockslide /landslide occurrences in the country. The spatial distribution of these are shown in Figure 4-6, which indicates that occurrences are correlated with mountain topography, morphology, fragile geology, rainfall, seismic activity, and human settlements. For example, Taiz and its surrounding area have steep valleys and tectonically active geological structures, and experience heavy rainfall. In addition, agricultural activity degrades the stability of land surfaces on the slopes.

Another example is Dhamar and its surrounding areas, which have tectonically active geological structures such as faults, fractures and joints. Moreover, Hadramout region is also composed of a fragile geology and secondary structures like faults and joints.

Due to severe weathering, various sets of joints and fractures develop in sandstone and limestone rocks. Climate change and human encroachments also trigger rockslides. Field investigations support the correlation between the geo-environment and the spatial distribution of rockslide and landslide in Yemen. However, the inventories of all the locations of rockslides/landslides are not available. Table 4-1 shows the historical rockslides/landslides in Yemen.

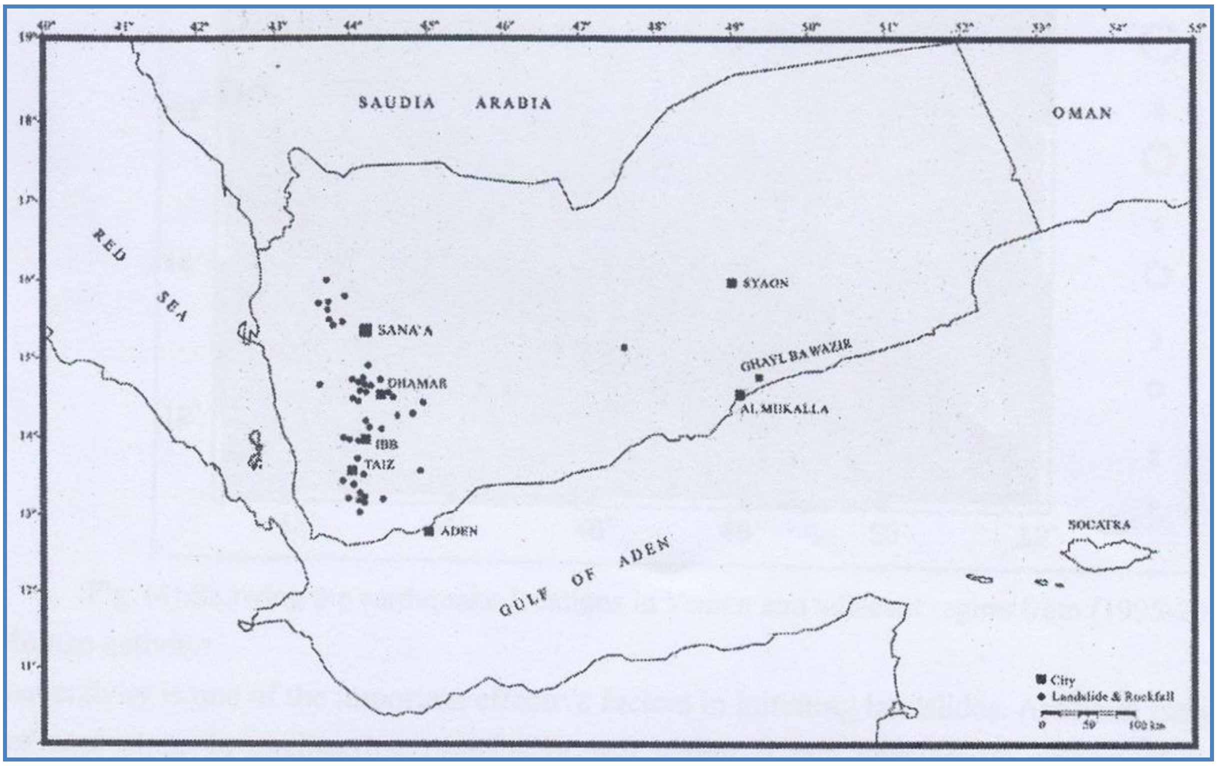


Figure 4-6: Locations of landslides/rockslides in Yemen (after Hussein et.al. 2008)

Table 4-1: Inventory of historical rockslides/landslides (collected from YGSMRB)

Year	Location	Province	Causalities	Cause
1982	Jabal Al-Lisi	Dhamar		Debris sliding of volcanic ash materials from steep slope occurred due to Dhamar earthquake of 1982 of M=5.9
1982	Mankhdh	Dhamar		Rock fall happened due to Dhamar earthquake 1982
1983	Sahaf-Maswar	Amran		Rock fall occurred from cliff after a heavy rainfall, where 15 houses were destroyed, and some animals died.
1983	Yasleh road	Sana'a		Rock slump and sliding of debris happened due to Dhamar earthquake aftershocks.
1983	Kirbat Jaharan	Dhamar		Sliding of slope debris happened after Dhamar earthquake.
1983	Jabal Sama-Bani Ahmed	Taiz		Rock slump and creep of slope debris occurred due to water action after heavy rainfall and after Dhamar earthquake of 1982. The landslide of high steep slope caused destruction of agriculture terraces.
1983	Adraah	Dhamar		Rock fall caused damage to some houses due to Dhamar earthquake of 1982.
1983	Nakil Al-Masnah	Dhamar		Rock fall happened due to Dhamar earthquake of 1982.
1983	Bait Al - Jashari	Dhamar		Rock fall occurred due to Dhamar earthquake of 1982.
1985	Hammam Ali	Dhamar		Rock fall and slump caused by heavy rainfall.
1985	Al-Dawahra	Dhamar		Rock fall caused by heavy rainfall.
1986	Kalabah	Taiz		Hill sliding and subsidence of houses caused wall cracks of some houses. The failure happened due to human activities, (loading of slopes, increased water content after heavy rain, and bad sanitation.
1986	Bab Al-Lazeq Doba	Taiz		Mudflow occurred after heavy rain causing damage to houses, agriculture terraces, and animal deaths.
1986	Asser	Sana'a		Rock falls and debris sliding occurred due to rainfall.
1986	Mabyan	Hajjah		Human activity resulted in sliding of slope debris due to excavation and heavy rainfall.
1987	Jabal Al_Masrabah Otomah	Dhamar		Rock fall and slump occurred after flash floods, which caused damage to roads and agriculture land.
1990	Al-Juruf -Maswar	Amran		Rock fall and slump occurred due to water action, threatening some houses from rockfall.
1991	Bait Al Shaber-Jabal Bahri-Al Udyn	Ibb		Rockfall and slump occurred due to Al Udyn Earthquake of 22 Nov 1991 of M=4.6

Year	Location	Province	Causalities	Cause
1992	West Jabal Bahri-Al Udyn	Ibb	1 child	Rock slump occurred due to aftershocks of Al Udyn earthquake, which caused damage to one house and agriculture terraces.
1992	Jabal Al Kohiza-Al Radmah	Ibb		Sliding of slope debris from steep slope caused a cut in non- asphalted road. The failure occurred due to the slope degree of approximately 65 degrees, and weathering action.
1993	Jabal Munif	Taiz		Creep of boulders and slope debris occurred from high slope area. The creep was continuous for about 4 months and resulted in covering the water source. The dust was seen from a distance.
1993	Al Ramah-Kabaita	Lahj		Liquefaction and quick mudflows due to heavy rainfall destroyed agriculture land, crops, 5 houses, and 10 wells.
1993	Jabal Al-Azani-Yatar	Dhamar		Sliding of slope debris happened by water action after a heavy rainfall. The flow materials cut the asphalted road, and affected agriculture land.
1993	Bait Al Omaisi	Dhamar		Sliding of slope debris occurred due to heavy rain affecting some houses.
1993	Hajrat Al-Thari Anis	Dhamar		Sliding of slope debris due to removal of toe to construct a road caused damage to some houses.
1993	Al-Daha	Hajja		Sliding of soil occurred due to flash flood, which caused a 3 meter vertical subsidence, damaging one house, a water pool, road cut, and agriculture lands.
1993	Al Janadiah Al Aulia	Taiz		Creep of slope debris after heavy rainfall.
1995	Bait Ishba-Dhawran Anis	Dhamar		Sliding of slope debris caused wall cracks in some houses.
1995	Thi Houd Al-Manar –Anis	Dhamar		
1995	Jabal Al-Manar-Al-Ragmah-Badan	Ibb		Slumping of slope debris after continuous rainfall for 20 days caused damage to some houses and agriculture land
1995	Jobran Akahila-jabal Al-Jaiah	Lahj-Taiz		Complex landslides (rock fall, toppling, slump and rolling), frequently occurred from very high cliffs after rainfall, where jointed layers overhung eroded weathered silt bed. The failure, which happened under gravity action, caused damage to agriculture terraces.
1997	Al-Dahboah	Taiz		Big rock and debris sliding on lubricant soil of Montmorillonite and Kaolin occurred due to slope cutting using blasting materials for urban expansion. Other reasons were bad water and sanitary drainage.

Year	Location	Province	Causalities	Cause
1997	Bani Omar-Yarim	Ibb		Loading of slope and action of water runoff caused land subsidence and damage to houses.
1997	Al-Metbabah-Otomah	Dhamar		Flash floods caused rock falls, debris flow and mudflow resulting in damage to agriculture terraces and road cut.
1997	Bani Al-Kaisi Al-Radma	Ibb		Sliding of rock and slope debris that occurred after heavy rainfall threatened some houses, but no damage was reported.
1997	Bait Marih-Ans	Dhamar		Rockslides occurred due to water saturation and run off.
1998	Al-Sarwah Ahkoom	Taiz	2 children injured	Rockfall under the gravity action catalyzed by water infiltration through discontinuities. The impact caused damage to a small water pool and agriculture terraces.
1998	Somarah (Sanaa-Taiz road)	Ibb		Toppling of rocks onto the Sana'a - Taiz main road was due to slope cut, vibration, discontinuities, and an eroded bed at the base. The failure was catalyzed by heavy rain.
1998	Bait Raid Kohlan	Hajjah		
1999	Karyate Al-Halila Dowran Anis	Dhamar		Sliding of slope occurred due to water action after a heavy rainfall. The flow materials cut the asphalted road, and affected agriculture land and some houses partially.
1999	Wadi Maaker	Al-Mahwit		Sliding of slope debris occurred from highly fractured and weathered marl bed that was overlying a lubricant surface. The failure occurred due to slope cutting for road construction purposes.
1999	Babe Al-Ahjor	Al-Mahwit		Sliding of slope debris occurred from highly fractured volcanic rock, weathered beds, and landfill materials. The failure occurred due to slope cutting for road construction purpose
2000	Al-Khebah Al Baraha Jabal Habashi	Taiz		Creep of slope debris took place after heavy rain.
2001	Jabal Al-Fala Akroud Kadas	Taiz		Creep of slope debris happened after heavy rains.
2002	Al-Nobigah	Ibb		Overloading of slopes and crest caused subsidence and creep of materials, destroying some houses and damaging agriculture land.
2002	Klabah Al-Mlahy - Lahab-Manakhah	Sana’a		Rock fall caused damage to agriculture terraces of coffee trees, water pools and springs due to heavy rainfall, highly fractured rocks and joints of high slopes.

Year	Location	Province	Causalities	Cause
2003	Jabal Bani Molad Magreb Ans	Dhamar		Rock falls from a cliff and continuous extension of fissures happened in the area causing subsidence of agriculture land. The failure occurred due water and gravity action.
2003	Sah - Wadi Hadramout	Hadramout		Rock fall happened due to earthquake of M=4.3. No damage was reported.
2003	Al Mokar-NW Al Tawilah	Al- Mahwit		Rockfall damaged one house.
2003	Thulla	Amran		Rock fall happened from a cliff due to gravity action. The failure caused destruction to water pipes and partially damaged a concrete water tank.
2003	Al Batina-Qadas	Taiz	3 children	Rockfall and slump from cliff occurred due to water and gravity actions causing destruction of one house and affecting agriculture terraces.
2003	Akabat Agzar-Amd	Hadramout		Rock fall of hanging blocks due to slope cut for road construction. The failure occurred because of erosion and weathering actions of slope toe by rain water.
2004	Nakil Citran-Bait Al Rakhami	Dhamar		Creep of slope debris occurred due to toe cut in high slope area. The failure occurred after heavy rainfall causing asphalted road cut, damage to one house, and mosque.
2005	Mashwarh	Ibb		Probably rotational creep landslide of intensely fractured boulders in weak matrix and artificially cut slope. The failure resulted in damage to one house.
2005	Al Dafir-Bani Matar	Sana'a	64 people	Complex landslides (rockfall, toppling, and slump) of huge rocks from cliff of high slope with big discontinuities and hanging due to excavation of stores in the toe and water pools at top of the slope.
2005	Babe Al-Ahjor village	Al-Mahwit		Rockfall, toppling and rolling of huge sandstone rocks from high and nearly vertical slopes due to eroded layers under jointed bed which were catalyzed by rainfall.
2006	Bait Naser Al-Ear Al-Hyma Al Dakhliah	Sana’a		Rotational landslides of vertical displacement approximately 4 meters caused a road cut in two places and destroyed agriculture terraces. The failure happened due to unstudied construction of the road.
2006	Bait Al Thre-Hobaish	Ibb		Complex failure of rock and soil happened due to water action after heavy rainfall. This impact was heard as a thunder and a shock was felt by villagers. The failure caused wall cracks in one house and damaged a small water barrage.

Year	Location	Province	Causalities	Cause
2006	Salah- Jabal Al Domalah- West Al Saeed hotel	Taiz		Creep happened due to slope cut off, in addition to overloading on slope, vibrations of vehicles, and bad sanitation. The slope materials are of Montmorillonite & kaolinite. Four houses were destroyed and a road also subsided.
2006	Bani Gabr Magreb Ans	Dhamar		Rotational Soil creep of vertical movement approximately 4 meter due to heavy rainfall (flash flood), which damaged a road, covered a water source, destroyed water pipes and drove a huge quantity of debris onto agriculture land.
2006	Al Qaeda town	Ibb		Rotational sliding happened after heavy rainfall and due to loads of slope, residual soil, and lubricant surface. The failure totally destroyed 4 houses and some others were partially destroyed.
2006	Al-Manakh Jabal Al-Tarf	Al-Mahwit		Planar sliding of big rocks occurred due to cut of toe, heavy rain, water leakage from water barrage, and vibration of vehicles. The landslide cut the main asphalted road (Al Mahweet-Al kanawes) and the walls of two houses built on the top of the hill slope.
2006	Jabl Sadad Lahab Manakhah	Sanaa		Rock fall caused damage to agriculture terraces of coffee trees, water pools and springs. It occurred due to heavy rainfall and fractures and joints of high slopes.
2006	Bait Homaitha-Manayn-	Al Mahwit	1 child	Two houses were destroyed and agriculture land affected due to rock fall and slump, which took place after heavy rainfall.
2006	Bait Al Nihmi Amran-Al swedah road	Amran		Rotational landslides caused a cut in the asphalted road (Al Swedah-Amran). It happened because of rainfall and due to bad road construction planning.
2006	Daraimah-Bani Hamad	Taiz		Creep of slope debris and soil happened due to water action after heavy rainfall causing damage to all the village houses.
2006	Kobal Bani Sheba	Ibb		Rockfall and slump from high cliffs caused partially destruction of one house, and affected agriculture land, electric power, and water supply.
2006	Al Ghahf-Bani Ahmed-Wasab Al Safil	Dhamar	4 children	Rockfall from jointed and highly fractured cliff caused damage to 2 houses and agriculture terraces and killed some livestock.
2006	Wadi Al kadi- Al Jabal Al Abyad	Taiz		Overloading of slopes and crest caused subsidence and creep of hill materials damaging some houses.
2006	Al Sharaf-Hofash	Al Mahwit	1 woman	Rockfall and slump of granite rocks from high slope located near a quarry (60 meter).The failure occurred after heavy rainfall, which caused damage to agriculture terraces and one cattle head was lost.
2006,	Al Mokbil village-	Amran		3 successive rock falls in 2006 caused damage

Year	Location	Province	Causalities	Cause
2007	Maswar			to one house and mosque. In 2007, rockfall also occurred and resulted in damage to one house. The failures were due to heavy rainfall and gravity action.
2006, 2007	Lemnah-Bait Joail-Maswar	Amran		Rockfall of granitic rocks occurred in 2006 and in March 2007, but no damage was reported.
2006	Hyghat Al Abd- Al Makatira Road	Lahaj		Frequent rockfalls and slope debris occurred especially after rainfalls. The road was constructed on high slope area. Slopes have been cut vertically.
2008, 2009	Hyghat Al Abd- Al Makatira Road	Lahaj		Frequent rockfalls and slope debris occurred especially after rainfalls. The road was constructed on high slope area. Slopes have been cut vertically.
2007	Al-Rebat Al-Gabin Road	Rimah	1 died and 2 injured	Toppling happened due to slope cut for road construction by using blasting material. This failure caused one car crash.
2007	Al Jaafara Al Manar Anis	Dhamar		Toppling and rolling of rocks, which struck one house and damaged a water tank. The failure was due to rainfall, high slope, and gravity action.
2007	Gorab-Wadi Alayn	Hadramout		Sliding of slope debris and big blocks due to a flash flood caused total damage to some mud and others were partially damaged. The material also caused broken water and sanitary pipelines, and affected agriculture land.
2007	Al Osailah Sharab Al Salam	Taiz		Creep sliding of rocks occurred due to high slope and highly fractured rocks.
2007	Al Oshah-Bani Muslim	Ibb		Wedge sliding of rocks due to slope cutting for road construction affecting some houses and agriculture land.
2007	Yadhil-Otmah	Dhamar		Rockfall caused wall cracks in schoolrooms and some houses.
2007	Al Juruf-Bait Al Jahdari- Maswar	Amran	1 child	Rock fall and slump occurred due to water and gravity actionsaffecting some houses considered to be vulnerable to rockfall.
2008	Al Mukhala-Khalaf	Hadramout		Rock fall from a cliff damaged two houses.
2007	Al Kholabah-Hofash	Al Mahwit	2 Children died, some injured	Landslides involving huge rocks near a quarry after rainfall resulted in destruction of one house of two floors and a road cut. It crushed one vehicle, two water pumps, electric motors, and some properties.
2008	Jabal Al Damigha-Hobaish	Ibb		Sliding of rocks and slope debris after rainfall occurred due to slope cutting for road construction.
2008	Yadaor Bani Muslim-Al Qafer	Ibb		Rockfall and slump after heavy rainfall affected a water source and damaged agriculture terraces.

Year	Location	Province	Causalities	Cause
2008	Bait Boss	Sana'a		Rockfall from a cliff of nearly vertical slope
2008	Al Rithaay-Al Shaear	Ibb		Toppling and slump of big rocks occurred due to water and sanitation penetration into the joints and fissures and erosion of the underneath layer. The impact caused damage to 3 houses of 1-3 floors. Water tank, electric lines, and some properties were also damaged.
2008	Bahozil- Wadi Bin Ali	Hadramout		Rock slump took place due to the storm, which struck the eastern part of Yemen in 2008.
2008	Hadiah wadi Hadiah	Hadramout		Rock fall and slump took place due to the storm, which struck the eastern part of Yemen in 2008.
2009	Al Madawer – Malhan	Al Mahwit	11 people died	Sliding of agriculture terraces after heavy rainfall damaged one house.
2009	Al Wahr- Gorban-Kamer road	Amran	2 died, 6 injured	Rockfall took place due to cut of slope toe for road extension purposes and resulted in a car crash.

During the fieldwork from June 07 to July 25, 2009 in Hadramout and Al-Mahara areas, historical rockslide/landslide data were also collected. Figures 4-7 A, B show damaged houses due to rock falls in the city of Al-Mukalla. Such types of rock falls take place in many places in the city. Figure 4-7 C shows a rockslide that occurred due to road excavation located on the way to Hoaf from Al-Gayada (eastern Yemen). Similar situations exist along many national highways in the country that cut across massive and fragile mountains. Figure 4-7 D provides another indication of cracks that developed on the same road, probably due to failing rock or wave action from the sea.

Landslide/Rockslide monitoring

The focus on rockslide/landslide studies in Yemen is comparatively slow and few steps have been taken to carry out any scientific study. Figure 4-8 shows the landslide distribution in Yemen prepared by the World Health Organization (WHO).

Under the Litho Cover Hazard Mapping Project (LCHMP) program of YGSMRB, the potential rockslide and landslide areas are being surveyed in detail. The recently initiated LCHMP is an ongoing project of YGSMRB, which has so far covered only a few areas of Yemen. Ten parameters described in Figure 4-9 were used to assess the susceptibility of the terrain and the chosen area was divided into 0.5 km X 0.5 km grids for fieldwork. Figure 4-10 presents the work carried out at Al-Mukalla. The scope of work includes developing susceptibility maps and recommends the potential sites for detailed study. Figure 4-11 presents the urban encroachment and a quote from a local person, who takes such hazards as their fate. The probability parameters as measured in the field by the geologists are then transferred to GIS format. The indexes of all parameters are summed up to give a final rating to each grid. In this way, potential and critical places are indentified and recommended for detailed study.

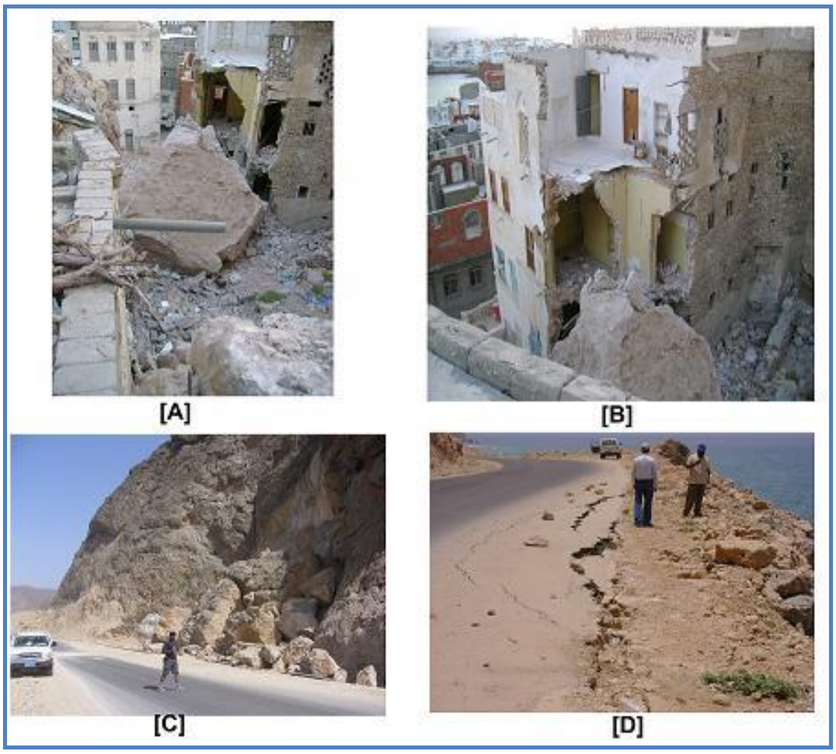


Figure 4-7: A, B: Rockfall destroyed houses in Al-Mukalla city. C Rockslide occurred along the road between Al-Ghayada and Howf. D Cracks developed on the road

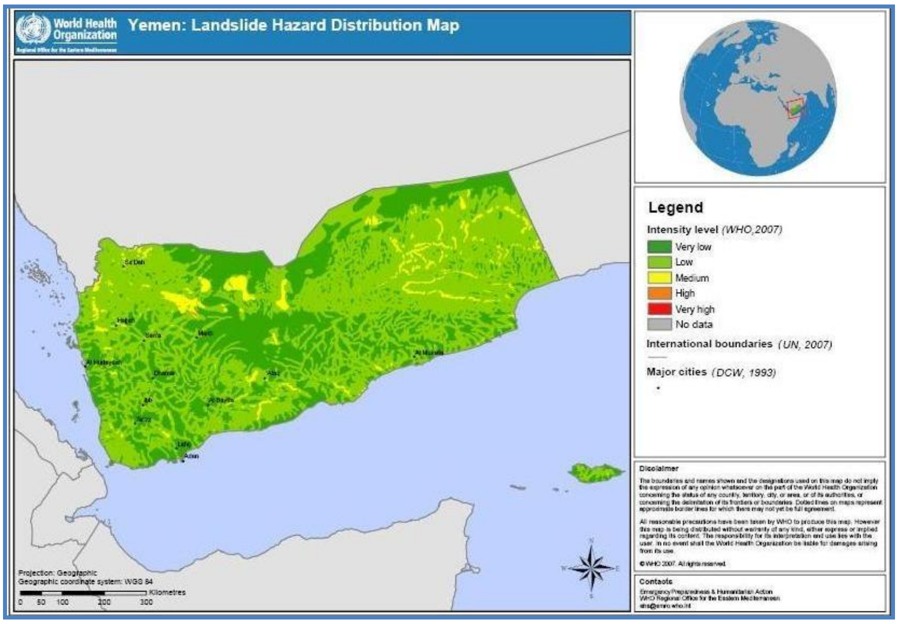
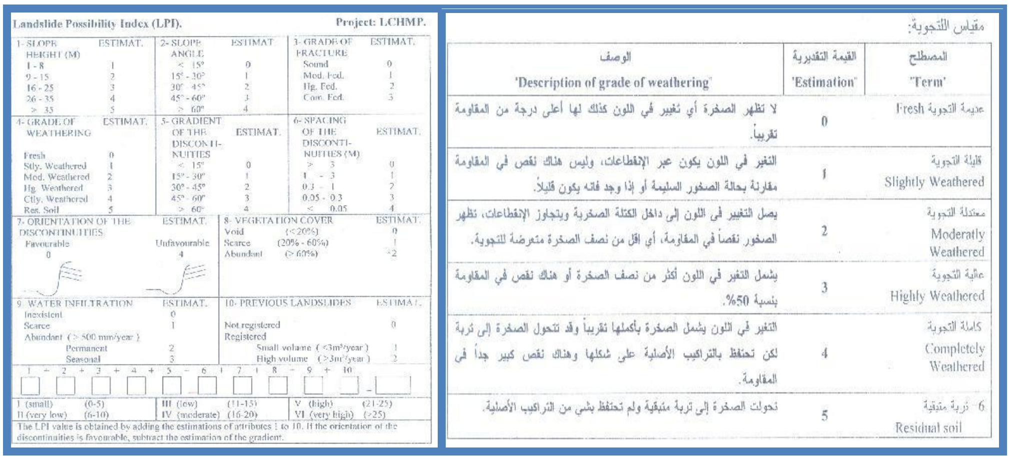


Figure 4-8: Landslide hazard distribution map of Yemen prepared by WHO

The LCHMP is a ongoing project of YGSMRB, which has so far been able to cover only a few regions of Yemen.



Landslide Possibility Index (LPI). **Project: LCHMP.**

1- SLOPE HEIGHT (M)	ESTIMAT.	2- SLOPE ANGLE	ESTIMAT.	3- GRADE OF FRACTURE	ESTIMAT.
1 - 8	1	< 15°	0	Sound	0
9 - 15	2	15° - 30°	1	Mod. Fed.	1
16 - 25	3	30° - 45°	2	Hg. Fed.	2
26 - 35	4	45° - 60°	3	Com. Fed.	3
> 35	5	> 60°	4		

4- GRADE OF WEATHERING	ESTIMAT.	5- GRADIENT OF THE DISCONTI-NUITIES	ESTIMAT.	6- SPACING OF THE DISCONTI-NUITIES (M)	ESTIMAT.
Fresh	0	< 15°	0	> 3	0
Stly. Weathered	1	15° - 30°	1	1 - 3	1
Mod. Weathered	2	30° - 45°	2	0.3 - 1	2
Hg. Weathered	3	45° - 60°	3	0.05 - 0.3	3
Ctly. Weathered	4	> 60°	4	< 0.05	4
Res. Soil	5				

7- ORIENTATION OF THE DISCONTINUITIES	ESTIMAT.	8- VEGETATION COVER	ESTIMAT.
Favourable	0	Void (<20%)	0
Unfavourable	4	Scarce (20% - 60%)	1
		Abundant (> 60%)	2

9- WATER INFILTRATION	ESTIMAT.	10- PREVIOUS LANDSLIDES	ESTIMAT.
Inexistent	0	Not registered	0
Scarce	1	Registered	
Abundant (> 500 mm/year)		Small volume (<3m³/year)	1
Permanent	2	High volume (>3m³/year)	2
Seasonal	3		

1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9 + 10 =

I (small) (0-5)	III (low) (11-15)	V (high) (21-25)
II (very low) (6-10)	IV (moderate) (16-20)	VI (very high) (>25)

The LPI value is obtained by adding the estimations of attributes 1 to 10. If the orientation of the discontinuities is favourable, subtract the estimation of the gradient.

مقياس التجوية:

المصطلح 'Term'	القيمة التقديرية 'Estimation'	الوصف 'Description of grade of weathering'
عديمة التجوية Fresh	0	لا تظهر الصخرة أي تغيير في اللون كذلك لها أعلى درجة من المقاومة تقريباً.
قليلة التجوية Slightly Weathered	1	التغير في اللون يكون عبر الإنقطاعات، وليس هناك نقص في المقاومة مقارنة بحالة الصخور السليمة أو إذا وجد فانه يكون قليلاً.
معتدلة التجوية Moderatly Weathered	2	يصل التغيير في اللون إلى داخل الكتلة الصخرية ويتجاوز الإنقطاعات، تظهر الصخور نقصاً في المقاومة، أي اقل من نصف الصخرة متعرضة للتجوية.
عالية التجوية Highly Weathered	3	يشمل التغير في اللون أكثر من نصف الصخرة أو هناك نقص في المقاومة بنسبة 50%.
كاملة التجوية Completely Weathered	4	التغير في اللون يشمل الصخرة بأكملها تقريباً وقد تتحول الصخرة إلى تربة لكن تحتفظ بالتراكيب الأصلية على شكلها وهناك نقص كبير جداً في المقاومة.
6- تربة متبقية Residual soil	5	تحولت الصخرة إلى تربة متبقية ولم تحتفظ بشي من التراكيب الأصلية.

Figure 4-9: Landslide Probability Index (LPI) parameters used in project LCHMP by YGSMRB

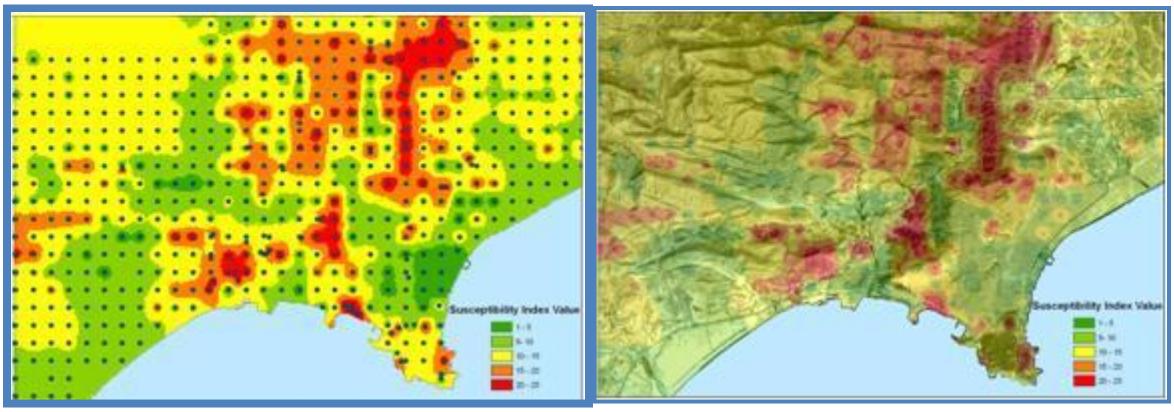


Figure 4-10: Rockslide hazard map of Al-Mukalla region (LCHMP program, YGSMRB)

Mr Thabt from a village Al-Hawta, Shibam district spoke on potential rockslide *"We moved from centre of valley to under cliffs because land here is less expensive and not prone to floods but we were not aware that this place is prone to rockslides/landslides. We never know, when those big rockslides may take place, everything is in God's hand. We heard many times in the Hadramout valley that rockslides happened.*

Figure 4-11**:** Shows the urban encroachment and comment from a local resident in Hadramout valley

4.1.2 ENVIRONMENTAL FACTORS

As can be seen in the following paragraph very little new local information was available to the RMSI team. Aside from the geological maps provided by YGSMRB, the general geological information was extracted from existing reports. Other information such as slope assessment and land use will have to be derived from databases accessible through the internet.

Morphometric parameters:

Slope angle, aspects, internal relief and flow accumulation are being developed using SRTM 90m interpolated to 30m DEM for Yemen.

Lithology and Structures:

Lithological units are to be captured from available geological maps of scale 1:250k. There are 35 sheets covering the whole geography of Yemen. Figure 4-12 shows the extent of geological formations, age, and lithological composition.

The Precambrian basement rocks of the area were subjected to intensive folding and metamorphism. Afterwards, in the Paleozoic Era, the basement was strongly eroded, leveled to a peneplain and warped. Subsequently, sediments covered it during the Cambro-Ordovician, Permian, Jurassic and Cretaceous periods. Parts of these sediments are of continental origin, others were deposited in shallow marine or neritic environments. Rapid subsidence started during the Jurassic period along the line, which now defines the Al Jawf graben. It enabled the accumulation of organic-rich shales with petroleum source potential.

At the end of the Cretaceous and continuing during the Tertiary, the present-day western part of the Arabian Peninsula and neighboring East-Africa was uplifted and started to break into separate blocks. Lava extruded through faults and fissures and thickness extended. Strata of tuffs and lavas (andesites, basalts, syenites, rhyolites, etc.) covered the Precambrian basement and the overlying -predominantly Mesozoic- sediments. During the Tertiary, the Arabian plate drifted north-eastward and caused the folding of the Zagros Mountains in Iran. To the west and south, the rift valleys of the present Red Sea and the Gulf of Aden opened between the peninsula and north-eastern Africa. Intensive block-faulting caused the mountains of Yemen and Ethiopia to break into numerous blocks, separated by faults running parallel to the axis of the Red Sea (NNW), the Gulf of Aden (ENE) and the Eritrean rift valley (NNE). The vertical displacement varies from one block to another; in some locations, it exceeds 2,000 m. In the eastern part of the country, thick blankets of predominantly carboniferous sediments were deposited during the Tertiary period. They dip slightly towards the east-north-east. Near the end of the Tertiary, local granitic and granodiontic laccoliths, plutons and stocks intruded through the older rocks in several zones of the country. At the beginning of the Quaternary, a new and still continuing phase of volcanic activity started. It produced mainly basaltic eruptions along the major fault systems.

The morphological features of the country, formed largely as a result of the tectonic and volcanic activities during the Tertiary, were modified to some extent during the Quaternary period. The main present-day drainage systems developed; river terraces, alluvial plains and coastal plains were formed; and aeolian deposition took place in the lowlands, on the plateau and in the vast areas of the Rarnlat-as-Sabatayn and Rub-al-Khali (WRAY -35).

Geological Structures: Figure 4-12 shows the geological structure of Yemen. The Arabian Peninsula is in a structural sense part of the Africa-Arabian plate. In Late Cretaceous and Cenozoic times, this plate moved both eastward and northward with respect to the Eurasian plate. The subsequent collision of the two plates had a profound impact on the regional geology: in the north and east of the Arabian plate, the basement is depressed and thickly covered with relatively young sediments (platform zone),

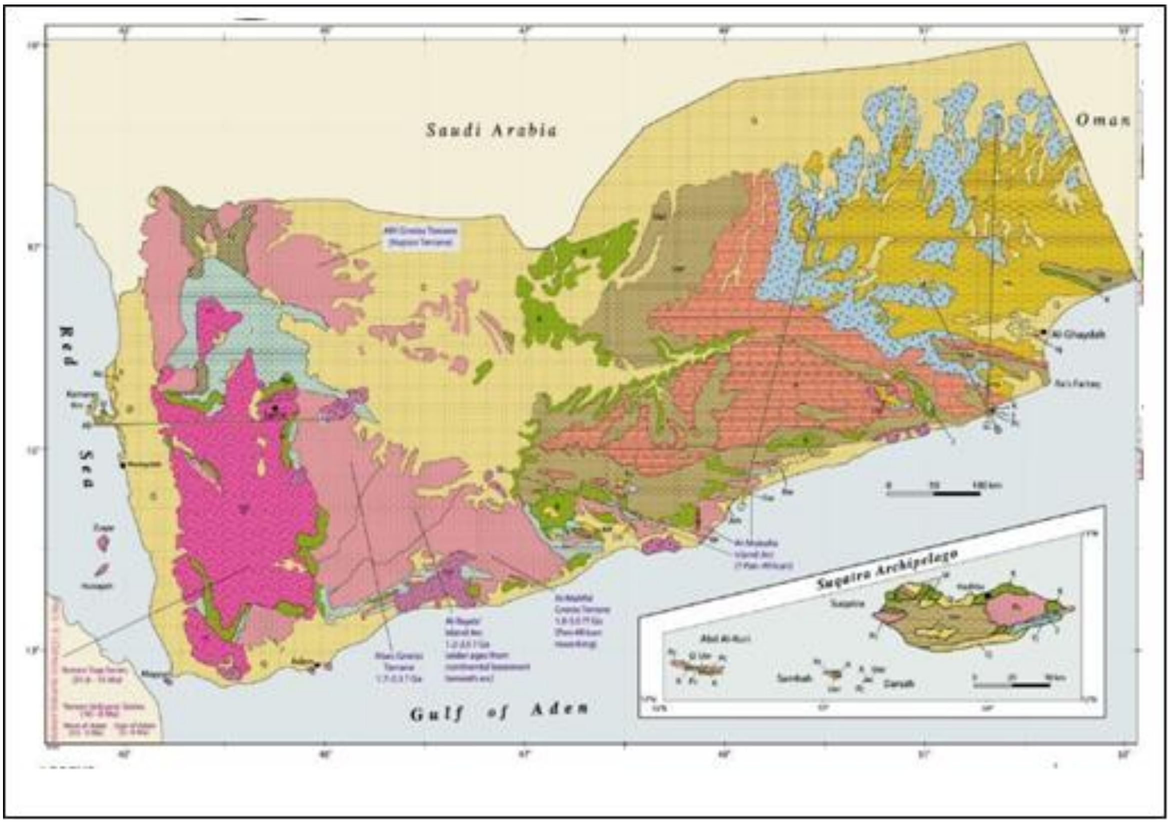


Figure 4-12: Geological map of Yemen

Whereas further south and west, the Precambrian crystalline basement and its older sedimentary cover are uplifted and partly exposed (Arabian Shield-zone). The overall geological structure of Yemen is dominated by the Precambrian Arabian Shield in the western part of the country and an extensive and thick cover of Phanerozoic sub-horizontal sediments further east. The uplifted shield ('Yemeni horst') is steep-sided to the west and south, but slopes gently north-eastwards. It mainly consists of crystalline basement, and is partly covered by sediments and volcanic rock. Prominent regional tectonic features include the *anticlinals* known as the southern and northern *Hadramawt arches*, the rift valleys of the Red Sea and the Gulf of Aden, the Sadah-Al Jawf-Balhaf graben System ('Sabatayn structure'), and the Al Ghaydah Depression (WRAY -35)

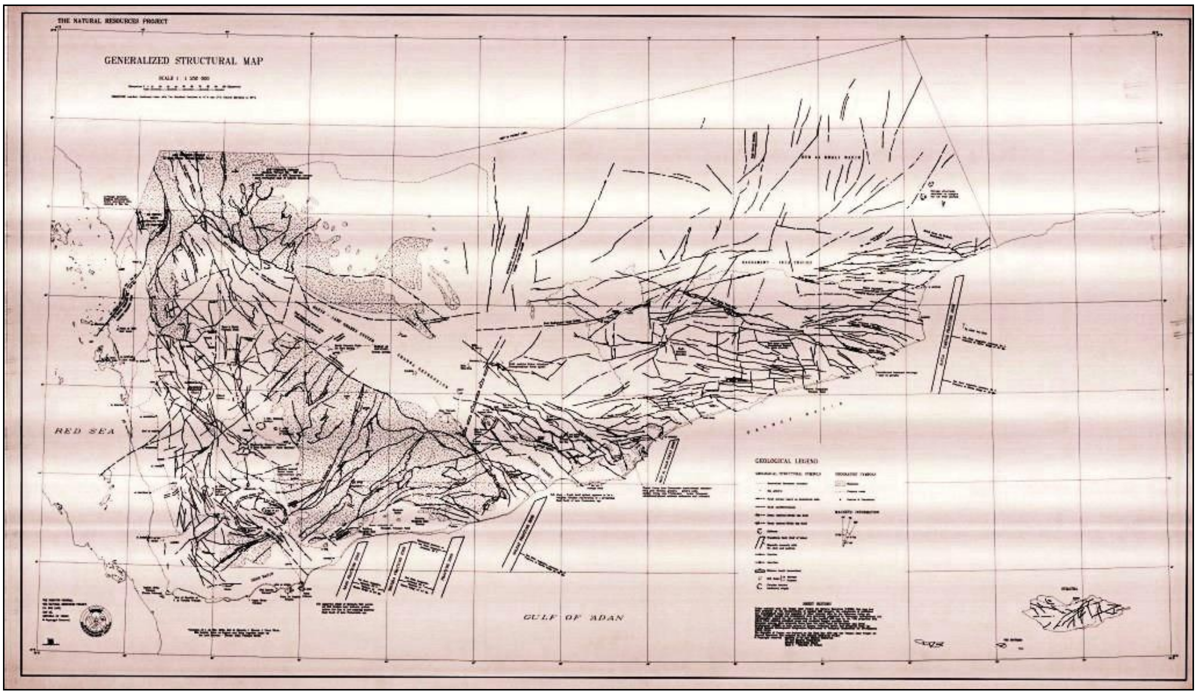


Figure 4-13: Structural map of Yemen

Soil types: The soils map obtained from the Geological Survey was developed in 1990 at a scale of 1:250K. In order to use the soils map, the soil types need to be converted into the U.S. National Earthquake Hazard Reduction Program (NEHRP) standard shown in Table 4-2. A geologist converted the Geological Survey values into NEHRP values and generated the table, which will be used to modify the soils GIS data layer.

Table 4-2: NEHRP Soil classification scheme

Soil Index value	NEHRP /CDMG Class	Brief Description
1.0	AB	Very hard to firm rocks mostly metamorphic and igneous rocks
1.5	BC	Firm sedimentary rocks (mid Miocene age) and weathered metamorphic
2.0	C	Sedimentary Formation Mid-Lower Pleistocene age
2.5	CD	Weak rock to gravelly soils - Deeply weathered and highly fractured bedrock
3.0	D	Holocene Alluvial soils
3.5	DE	Young alluvium / Water-saturated alluvial deposits
4.0	E	Non-engineered artificial fill, soft clays, peat and swamp deposits

Land use types: Figure 4-14 shows the land use map developed using satellite images.

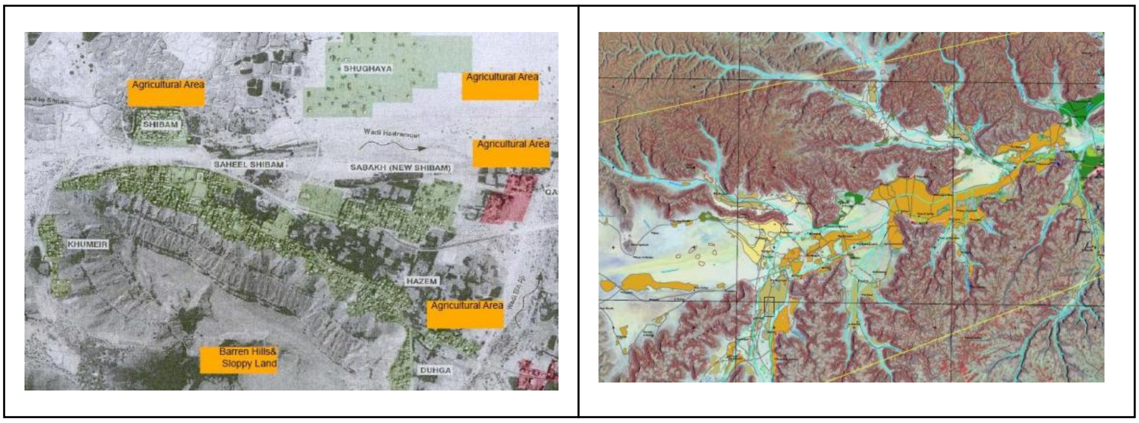


Figure 4-14: schematic lands use map, which is detailed from high resolution satellite imageries

4.1.3 TRIGGERING FACTORS

Rainfall: The Tropical Rainfall Measuring Mission (TRMM) satellite was launched on November 27, 1997 (EST). TRMM is a joint U.S.-Japan satellite mission to monitor tropical and subtropical precipitation and to estimate its associated latent heating. TRMM data will be enhanced using data collected from weather monitoring stations of Yemen. Figure 4-15 shows the rainfall distribution for the Storm 03B event.

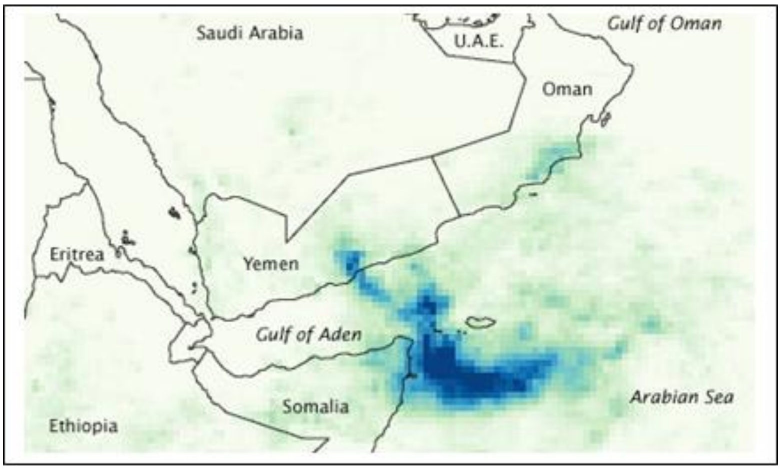


Figure 4-15: TRMM rainfall grid for Storm 03B event

Temperature/evapo-transpiration: Data to be collected from weather monitoring stations of Yemen and free satellite imageries.

Earthquake catalogs and ground acceleration: Data being taken from the earthquake module

4.1.4 ELEMENTS AT RISK

The elements at risk describe the types of buildings and infrastructure subjected to the hazard. To be useful, the description should be done at the highest level of resolution possible both spatially and structurally. Since, in most cases, it is not possible to identify each building specifically, the exposure is usually defined within administrative boundaries such as census tracks, postal codes, created grids or other recognized boundaries. For Yemen, the highest available resolution is district administrative boundary maps. Within each boundary, the exposure is represented by a distribution of building types in terms of their construction material, number of stories and design philosophy, and other relevant building characteristics. It is assumed that buildings are uniformly distributed within each boundary. The survey will record the construction types and use of structures in the area and try to capture the approximate replacement cost of damaged or undamaged structures. This information will be used to generate the exposure.

The elements at risk are to be covered in sub-task 3 of this project and will be presented in a future report titled: “Development and Compilation of the Inventory of Assets, Their Classification and Valuation”.

5 Historical Volcano Hazard Data Review, Analysis and Quality Assessment

Approximately one-tenth of the total area of Yemen is covered with rift volcanism (Mattash and Bilik, 1990), of which a majority of the outcrops are found in the western part of the country. The Yemen region has had a prolonged history of volcanic activity since the Tertiary period, followed by the Yemen volcanic series (till Quaternary) and up to recent times though on a relatively smaller scale. Recent volcanic activity around the Red Sea appears to be confined to the Arabian side. The volcanic activity in the Cenozoic period in and around Yemen is roughly contemporaneous with the two-stage opening of the Red Sea – 30-15 Ma and 5 Ma to present (Al Aydrus, 1997).

Volcanic rocks in Yemen can be divided into two series:

1. Yemen Trap Series (YTS), which were extruded from the late Oligocene to early Miocene (synrift phase);
2. Yemen Volcanic Series (YVS), which evolved during the post-rift or late Miocene-Recent phase;

The YTS series is composed of thick volcanic units like lava flows, dykes, sills, mainly of basaltic composition, whereas the YVS is mainly composed of basaltic volcano characterized by strato-type volcanoes, cones, domes, sheets and lava flows (Mattash, 2007).

As a whole, about 20 volcanic eruptions have affected Yemen (and the adjacent Red Sea) in proto-historical and historical time, and four of these took place within 30 km of capital Sana'a (Hughes and Collings, 2000). Several eruptions are indicated to have occurred in the Sana'a area over the last 1,500 years, and the area is vulnerable to future eruptions. An event in about AD 200 is indicated by archaeological work and is said to have overwhelmed several religious sites 20 km north of Sana'a (Hughes and Collings, 2000; Ambraseys et al, 1994).

Appendix B describes the studies considered for the volcano hazard in Yemen. Table 5-1 provides the information on volcanoes discovered from each relevant study. Figure 5-1 shows the volcanic distribution in and around Yemen.

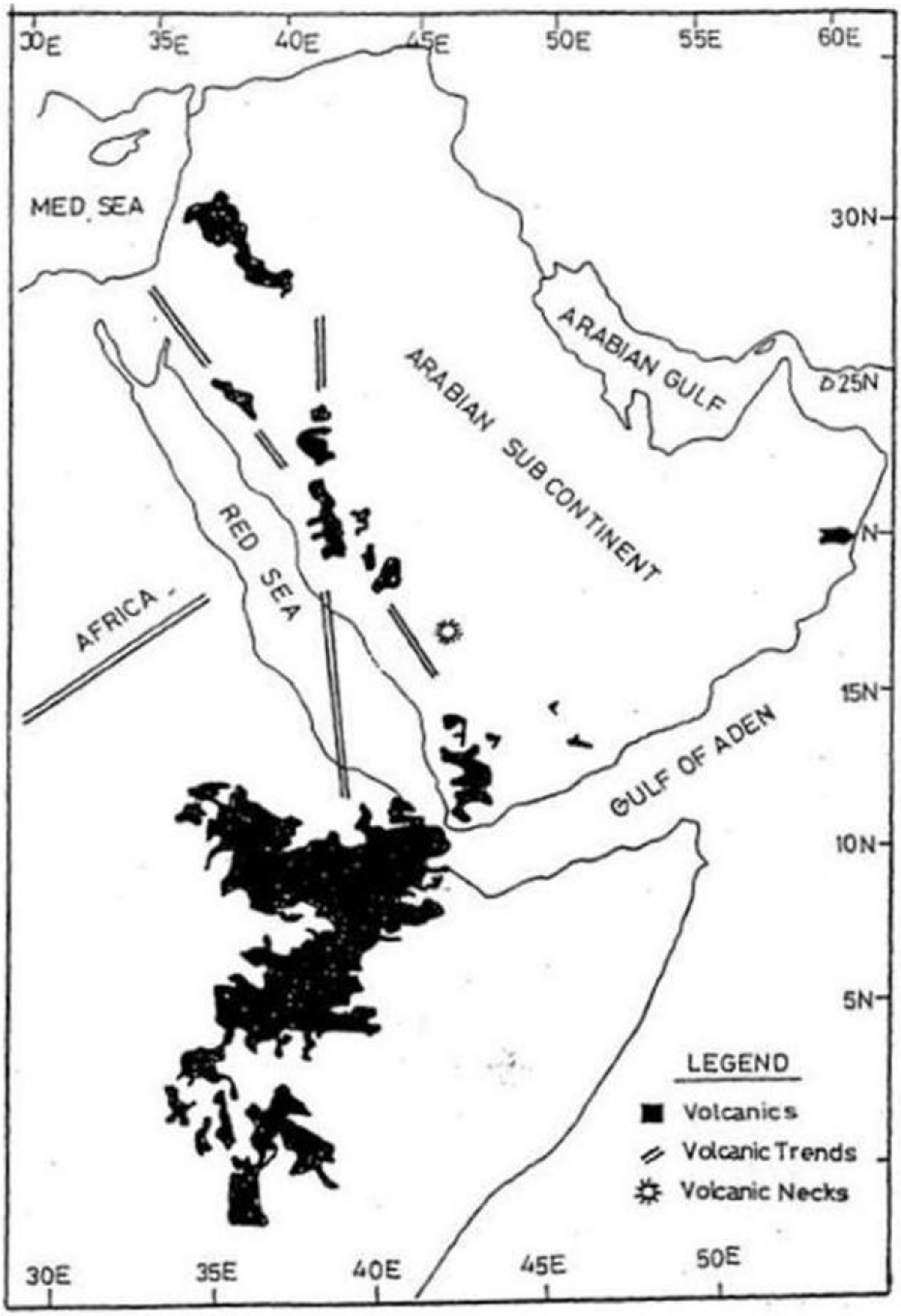


Figure 5-1: Major volcanic distribution in and around Yemen (After Al Aydrus, 1997)

Table 5-1: Relevant information on volcanoes in Yemen from past studies

Report	Relevant Information (Volcanoes)
Seismic and Volcanic Risks in the Yemen Arab Republic. August 1976. By UNDRO, Geneva	• Major volcanic fields • Volcanic risks in different volcanic fields
The Seismicity of Egypt, Arabia and the Red Sea – a historical review. 1994, Ambraseys, N. N., Melville, C. P. and Adams, Cambridge University Press	• History of volcanism in Arabian sub-continent/ Yemen • Major volcanic fields
Seismicity of Yemen. 1999. Alsinawi, S. A. and Aydrus, A. Al, Faculty of Science, University of Sana'a	• History of volcanism in Arabian sub-continent/ Yemen • Major volcanic fields • Volcanism, tectonism and seismicity • Thermal springs
Evaluation of Seismic Ground Motion for Sana'a Region. January 1997, Razaq, N. A. A. et al. Ministry of Oil and Mineral Resources, Republic of Yemen	• Historical and recent seismicity • Earthquake engineering design consideration
Younger Volcanic Fields of Yemen with Focus on Jabal At-Tair Active Volcano., 2007, Mattash, A. M., Ministry of Oil and Minerals, Geological Survey and Minerals Resources Board, Republic of Yemen.	• Volcanic activity and structural geology • Yemen volcanic series and younger volcanic fields • Eruption history of different volcanic fields and active volcanoes in the Red Sea
The Western Part of the Shuqra Volcanic Filed, South Yemen. 1977, Cox, K. G., Gass, I. G. and Mallick, D. I. J., Lithos 10, 185-191, Oslo	• General Geology • Composition of volcanic rocks in the Shuqra area
Jabal An Nar: An Upper Miocene Volcanic Centre Near Al Mukha (Yemen Arab Republic) . August 1986, Capaldi et al. Journal of Volcanology and Geothermal Research, 31 (1987) pp. 345-351	• Geology and Geochronology • Analysis on Lava composition in Jabal An Nar

5.1 Major volcanic fields in Yemen and their brief history

Eight major volcanic fields are known in Yemen, out of which three are found in the western province, four along the coastal plain of the Gulf of Aden and the last is the Island Groups of the southern Red Sea (Mattash, 2007). The western Yemen volcanic province is characterized by several hydrothermal features like thermal springs, condensates and fumaroles, which indicate relatively shallow felsic magma chambers (Mattash, 1994). Important features of different volcanic fields are discussed below:

5.1.1 SANA'A AMRAN VOLCANIC FIELD:

This volcanic field to the north of Sana'a, extending approximately 70 km in length (N – NW) and 30 km in width, is composed of monogenic cinder cones and associated basaltic lava flows (UNDRO, 1976). It covers an area of about 1,271.6 km² (Mattash, 2007). In this area, two recent eruptions were located at Kaulet Hattab (400-600 AD) and Jabel Jebib (200 AD). The other important volcanic center with a recent eruption is Jabel el-Marah (Holocene) located 11 km south of Sana'a (Alsinawi and Alaydrus, 1999).

5.1.2 SIRWAH-MA'RIB VOLCANIC FIELD:

This recent Quaternary volcanic field extends over 60 km in length and 20 km in width at the boundary of the Yemeni Plateau (UNDRO, 1976). This volcanic massif, similar in form and composition to the Sana'a-Amran field, is composed of tephritic cones and basaltic lava flows. It covers an area of about 821.1 km² (Mattash, 2007). Around 60 to 100 volcanic cones are present here, some of which have been raised in alternates of scories, cinders and lava. As per anthropological evidence, the last reported eruptive activity was probably later than 1200 BC (Alsinawi and Alaydrus, 1999).

5.1.3 DHAMAR-RADA VOLCANIC FIELD:

This Quaternary volcanic massif (1477.1 km²), extending East of Dhamar, is a compound volcano with mostly basaltic lava flows and widely dispersed basaltic monogenic cinder cones (UNDRO, 1976). The volcanism is characterized by a sequence of pyroclastic flow deposits followed by outpouring of basalt through fissures. Subsequent central activity produced cones, ash rings and pyroclastic fall deposits (Mattash, 2007). Recent eruptions were reported from Harras of Dhamar (1937) and Hammam Ez Zebib (Holocene). In addition, fumarolic activity was reported at J. Al Isi, J. Isbil. In Hammam Demt, located 40 km ESE of Yarim, the fumarolic activity is associated with a number of sinter cones (Alsinawi and Alaydrus, 1999).

5.1.4 SHUQRAH VOLCANIC FIELD:

This basaltic compound volcanic field mainly consists of lava flows and widely dispersed monogenic cinder cones. A recent eruption was reported from Es-Sawad volcano, probably located in the western end of this volcanic field (Alsinawi and Alaydrus, 1999).

5.1.5 ATAQ VOLCANIC FIELD:

Little is known about the recent volcanic activity associated with this small field of basaltic vents and flows.

5.1.6 BALHAF-BIR ALI VOLCANIC FIELD:

This is a basaltic, compound volcano consisting mainly of lava flows and widely dispersed monogenic cones. Unspecified Holocene activity from this volcano under the name of Harra of Bal-haf is reported (Alsinawi and Alaydrus, 1999).

5.1.7 AL MASILAH FLOWS:

The Al Masilah volcanic field is characterized by basalt flows along the coastal plain between Wadi Ma'bar and Wadi Masilah as well as along wadi floors and inland depressions up to 70 km. No recent volcanic activity is associated with this area (Alsinawi and Alaydrus, 1999).

5.1.8 RED SEA VOLCANIC ISLANDS:

Jabel at Tair, the Zubair and Hanish islands are important volcanic islands of Yemen located along the central axis of the Red Sea. Historically eruptive and fumarolic activities were reported for Jabel at Tair (erupted in 1750, 1833, 1863 and 1883 AD) and eruptive and solfataric activity reported for Zubair (erupted in 1824, 1846 and 1914 AD) (Alsinawi and Alaydrus, 1999).

5.1.9 RECENT ERUPTION: JABEL AT TAIR

Jabel at Tair is a volcanic island of Yemen located in the Red Sea at 15°33' N and 41°50' E. Significantly, the island has renewed its volcanic eruption most recently in September 30, 2007.

Jabel at Tair is composed of relatively thin basaltic lava flows covering a total area of 10 km². During the past volcanocity in the 19th century, eruption took place from a central vent at some 244 m a.s.l. (Gass, et. al., 1969), whereas the latest eruption is from new central vents located north of the former one at less than 230 m a.s.l. The recent activity is characterized by basaltic lava flows dominated by pahoehoe with thickness between one to three meters. Besides lava flows, the volcano emits fumaroles, sulfur dioxide and less commonly carbon dioxide (Mattash, 2007).

As per reports, fire fountains erupted from a fissure on the NE flank and lava flowed into the sea. Eight fatalities have been reported among military personnel on the island as the eruption destroyed a naval base there. Ash and pumice rafts floated 10 km from the island (http://www.volcanolive.com/).

As Figure 5-1 indicates, volcanic rocks cover a considerable area in the region. They are also of considerable thickness. They are associated with the rifting of the Red Sea and the Gulf of Aden that are still spreading, causing accumulation of stress in the region as a whole. This suggests geothermal activity at depth and conduction of heat to the available aquifers in the region.

6 Historical Tsunami Hazard Data Review, Analysis and Quality Assessment

The Indian Ocean is one of the regions in the world, which is frequently affected by natural disasters such as storm surges associated with tropical cyclones, tsunamis, tides, and sea level rise. The Indian Ocean tsunami on December 26, 2004 is considered to have been one of the worst natural disasters in history, affecting twelve countries, from Indonesia to Somalia. 175,000 people are believed to have lost their lives, almost 50,000 were registered as missing and 1.7 million people were displaced. As well as this horrendous toll on human life, the tsunami destroyed property worth billions of dollars and ruined many local economies. Relative to the countries of Southeast Asia, damage in Yemen was much less, mainly because of its distance from the epicenter of the earthquake, and the protection it receives from the Indian Peninsula and Horn of Africa. Nevertheless, the impacts on the livelihoods of local people, especially fishermen, were significant, as many of them lost their main form of income. The two main areas identified as the most affected include Socotra Island and the coastline of Al Mahara Governorate, especially the area extending from Saihut to Wadi Hauf (Ministry of Agriculture and Irrigation, 2004).

Natural hazards have always been a challenge to the modelers, particularly tsunamis and storm surges are at the top of the list. Accurate prediction of tsunamis in the coastal waters is highly essential for countries around the Indian Ocean. Various techniques such as empirical, statistical, analytical and numerical are employed for the prediction of coastal flooding associated with tsunami around the world. In general, empirical and statistical methods require several years of observations on vast shelf areas, which are difficult to obtain.

6.1 Historical Perspective of Natural Disaster Tsunami

Yemen is located in the southwest Arabian Peninsula adjacent to active faults. Figure 6-1 shows the major tectonic plates over the Indian Ocean. Of the converging boundaries, only Makran and Sunda Arc are capable of producing basin-wide destructive tsunamis. The Makran Subduction Zone produced the majority of the earthquakes in Pakistan and Iran including the 8.1-magnitude earthquake on November 27, 1945 that was accompanied by a regional tsunami with a run-up in the 5 to 10 m range (Ambrasys and Melville, 1982). The 9.3-magnitude Sumatra-Andaman earthquake at the northern Sunda Arc on December 26, 2004 generated a devastating tsunami across the Indian Ocean with recorded run-up of 6 m on Socotra Island and 3.3 m near the Yemen-Oman border (Okal et al 2006; and Fritz and Okal, 2008). The Indian subcontinent shielded most of the Arabian Peninsula from the brunt of the tsunami. Should the tsunami occur further south, the resulting wave action could have significant impacts on Yemeni coast.

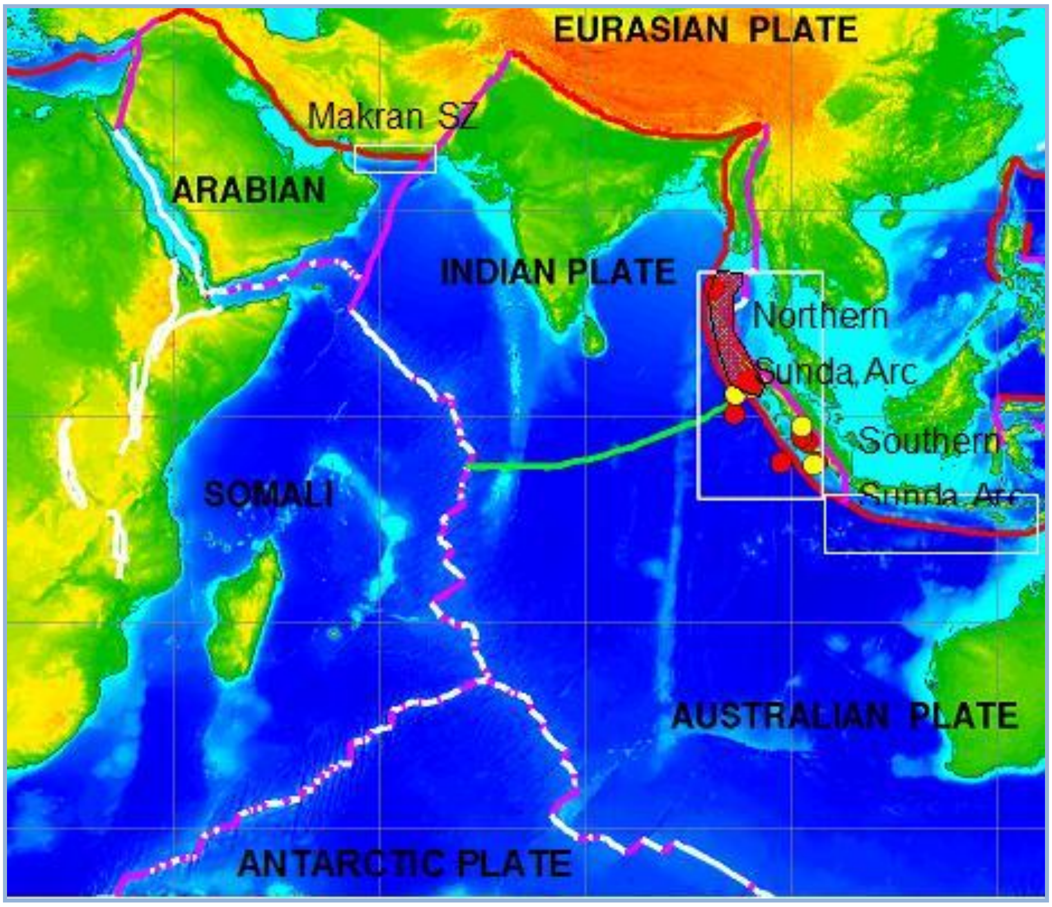


Figure 6-1: Tectonic plates in the Indian Ocean (white lines = diverging boundaries, purple lines = transform boundaries, red lines = converging boundaries, red shaped area = source of the 2004 Indian Ocean Tsunami)

The 2004 Sumatra-Andaman earthquake has led scientists to a reassessment of the concept of a maximum expectable earthquake at a given subduction zone. Stein and Okal (2007) recompiled earthquake source and tectonic data and concluded that the commonly accepted approach of Ruff and Kanamori (1980) based on fault age and convergence rate underestimates the maximum expectable earthquakes at subduction zones in the Indian Ocean. Okal and Synolakis (2008) subsequently estimated the maximum expectable earthquakes in the Makran and Sunda Arc subduction zones using a new paradigm based on continuous fault length. The new earthquake estimates and recent historical events allow an assessment of tsunami hazards along the Yemeni coasts.

The tectonics of the Indian Ocean, the historical records compiled by Jordon (2008), and the unique location of the Arabian Peninsula have led to the conclusion that destructive tsunamis to Yemen will likely come from the Makran Subduction Zone and the northern Sunda Arc.

6.1.1 Historical Tsunamis impacting the Arabian Peninsula include:

The following are recorded tsunami events that have impacted the Arabian Peninsula. They are organized by geographic and oceanographic regions and are summarized in Table 6-1.

Persian Gulf

978 – Siraf, Iran. On 17 June 978 A.D. the port town of Siraf, Iran, located in the Bushehr Province along the northeastern Persian Gulf coast near the present port of Taheri was struck by an earthquake that killed about 100 people. According to historical records, the land shook for seven days and that some of the buildings of the town fell into the sea (McEvilly and Razini, 1973). Although there is no mention that this event generated a specific tsunami, forty years later in 1008 A.D. another earthquake (see event below) reportedly did.

1008 – Siraf, Iran. In the spring of 1008 A.D., an earthquake occurred in this region and reportedly generated waves that sunk a number of ships. Also, McEvilly and Razani (1973) indicate that many people were killed when "the sea inundated the land". Although, Ambraseys and Melville (1982) concur on the loss of several ships, they state that there is no evidence of waves inundating the land. According to them, at least one other source refers to the sinking of the ships but did not associate the waves with the earthquake. Other records show that high winds affected the region during this same time-period, thus the reported flooding and destruction of ships could have been caused by storm surge. Also, there is no definitive record that waves were generated when the more destructive 978 A.D. earthquake occurred in the same location (McEvilly and Razini, 1973; Ambraseys and Melville, 1982, p. 39, 107, 176). It is possible that the reported waves may have been generated by an earthquake-triggered coastal landslide – although the historical records do not indicate that one occurred in conjunction with this particular event, or any other earthquake in the Persian Gulf region. Given these uncertainties, it is difficult to evaluate what possible effects from such a tsunami may have had along the Arabian coast or to estimate its maximum height and runup. Given the fact that wave activity was only reported in the earthquake's epicentral region, the implication is that this event was localized and if a tsunami was indeed generated, its energy was quickly attenuated, given the shallowness of the Gulf.

The Red Sea

1879 – Tor (present-day El Tor), Egypt. On 11 July 1879, three moderate earthquake shocks were felt in Upper Egypt. Although the exact locations of these earthquakes are not known, it was reported that a tsunami flooded the village of Tor on the Sinai Peninsula in the Gulf of Suez (Ambraseys et al., 1994). A landslide is a possible source for this tsunami, but there is no such documentation in the historical records.

1884 – Massawa (present-day Mitsiwa), Eritrea. On 20 July 1884, an earthquake occurred offshore from Massawa. Reportedly, sea waves built up in the Massawa harbor, mostly between the localities known as Taulud and Edaga Barai. The waves swept over a causeway and ships in the harbor were seen swaying violently. Multiple flooding events from the sea left dead fish onshore (Ambraseys et al., 1994).

Indian Ocean/Arabian Sea

325 B.C. – Port of Alexander (Near present-day Karachi, Pakistan). Some reports have dated this event to 326 B.C., but 325 B.C. may be more accurate. A large wave believed to be a tsunami, damaged the Macedonian fleet of Alexander the Great while at anchor east of the present-day Karachi. The damaging waves probably originated in the same source region as the destructive 1945 Makran tsunami. Its effects on the Arabian Peninsula would likely have been similar to those in the 1945 event. The description of Diodorus Siculus (c. 90 BC - c. 30 BC) of a tsunami that struck the Macedonian Fleet has been credited by some to be describing this event (Oldfather, 1989), but is more likely describing an event that occurred elsewhere in Alexander's Empire (
http://www.drgeorgepc.com/Tsunami325BCIndiaAlexander.html).

1524 - Dabul, India. In 1524, the arrival of Vasco de Gama's fleet on the western coast of India coincided with a large "sea quake" and tsunami (Bendick and Bilham, 1999; PMD, 2005). It is not known if this event occurred locally or regionally. Since an earthquake was not reported onshore, this may indicate that the tsunami was generated at a more distant location. The Makran region of Pakistan has been suggested as a possible source (Bilham, 2004). If that is the case, then the eastern coasts of the Arabian Peninsula would have been impacted by the tsunami as well.

***1819 – Rann of Kachchh, India*.** A large (7-8 Ms) earthquake occurred on 16 June 1819 in the Kutch region on the western coast of India. It has been suggested that the quake was caused by a near-surface reverse fault (Bilham, 1999). It is estimated that 7-9 m of crustal displacement occurred (Quittmeyer and Jacob, 1979), which generated a destructive tsunami. The Indian town of Sindri was submerged by an inrushing flood that occurred as the coastal land sank an estimated 4-5 m (Berninghausen, 1966; Quittmeyer and Jacob, 1979; Bilham, 1999). In addition, a dam was formed, backing up a tributary of the Indus River (Bilham, 1999). Just as with the previous event, the most likely area of the Arabian Peninsula that would have been impacted by this tsunami would have been the southern and eastern coasts.
The tsunami travel time would have been approximately 4 hours (Bhaskaran et al., 2005).

***1845 – Kutch, India*.** Following an earthquake, eyewitnesses described a large wave from the sea that caused the mouth of the Indus River to flood the surrounding land. Unfortunately, other than the general region of the Indus, other geographical names used in the description cannot be located (Berninghausen, 1966). In the event that this was a true tsunami, it is highly unlikely that it had any significant effect on the Arabian Peninsula.

***1851 – Makran, Pakistan*.** The Makran coast of Pakistan lies on the southern edge of the country, to the northeast of Oman. Okal et al. (2006) mention a seismic event that may have occurred in 1851 off Makran, west of the 1945 tsunamigenic earthquake. Given the proximity of this event to the 1945 tsunami source, it is possible that a tsunami was generated and that the region has the potential to generate tsunamis that could impact the Arabian Peninsula.

***1883 – Krakatau, Indonesia*.** The eruption of the Krakatau Volcano near the Sunda Strait of Indonesia on 28 August 1883 produced a destructive tsunami that devastated villages and towns and killed nearly 36,000 people in the immediate area. Sea level oscillations were observed worldwide and recorded by tide gauges at distant locations. The tsunami was generated by a combination of caldera and slope collapse, pyroclastic flows, subsidence and final explosion and collapse (Berninghausen, 1966; Pararas-Carayannis, 2003; Winchester, S., 2003). Once outside the Sunda Strait, the waves attenuated quickly in height. In Karachi, Pakistan, the maximum wave was measured at 37 cm in height. It took an estimated 12 hours travel time for the wave to reach the Gulf of Aden on the southern end of the Arabian Peninsula, where the tide gauge registered a tsunami wave that was 13 cm in height (Berninghausen, 1966; Pararas-Carayannis, 2003). The eastern portion of the peninsula would have felt the effects of the wave in about 9.5 hours (Bhaskaran et al., 2005) with somewhat greater wave-heights, but no other Arabian records could be found for the event.

***1945 – Makran, Pakistan*.** At 03:26 IST (Indian Standard Time) on 28 November 1945 an 8.1 magnitude earthquake was generated in the northern Arabian Sea off the Makran coast (Berninghausen, 1966; Quittmeyer and Jacob, 1979; Ambraseys and Melville, 1982). The earthquake was felt in Karachi, Pakistan where ground motions lasted approximately 30 seconds, stopping the clock in the Karachi Municipality Building and interrupting the communication cable link between Karachi and Muscat, Oman (Omar, 2005). Ground motions were felt as far away as Calcutta, on the eastern side of the Indian subcontinent (Ambraseys and Melville, 1982; Byrne et al., 1992; Pacheco and Sykes, 1992; Pararas-Carayannis, 2006; Omar, 2005).

The epicenter is estimated to have been at 24.20 N, 62.60 E, about 408 km SSW of Karachi and 465 km NNE of Muscat, Oman. The quake caused extensive damage throughout the region. Subsequent eruptions of mud volcanoes in the Baluchistan region of Pakistan formed four small islands. The damage from the earthquake was great, but the greatest destruction to the region was caused by the tsunami that was generated. Tsunami waves "swept the whole of the Arabian Sea coast" (Berninghausen, 1966, p. 73). It is estimated that 4,000 people were killed. The fishing village of Khudi, Pakistan and its entire population, 48 km west of Karachi, was swept away. The trading towns of Pasni and Ormara, Pakistan, located 100 km away from the epicenter, were flooded by a ~15 m high wall of water (Murty and Bapat, 1999; PTI, 2004; Omar, 2005). At least three waves (05:30, 07:00, 08:15 IST), over 2 m high, reached Karachi 408 km away, as well as Bombay, which was 1,200 km away (Ambraseys and Melville, 1982; Omar, 2005). In Karachi the waves persisted for so long that significant harbor damage and loss of life occurred. During the strong drawdown of the water preceding the tsunami in Keti Bandar of the Indus Delta "low-lying hills collapsed and spread out, totally destroying a number of fishing villages" (Ambraseys and Melville, 1982, p. 90). This tsunami reached eastward as far as Karwar, India, 1,600 km away (IST, 2004).

The tsunami was recorded along the coasts of Iran and in Muscat, Oman, which is 580 km from the source, and where there was considerable damage and loss of life (ASC, 2003; Pararas-Carayannis, 2006). In addition, a boat traveling from Muscat to Karachi was lost (Ambraseys and Melville, 1982, p. 90, 193). The tsunami travel time to the Arabian Peninsula would have been less than an hour (Bhaskaran et al., 2005). It is assumed that if the tsunami affected Muscat as well as coastal cities in Iran, more than likely it affected the United Arab Emirates (UAE) and Indian Ocean coastal communities, such as Khorfakkan and Fujeirah. Persistent seismic activity in the Northern Arabian Sea since 1945, implies that the potential for other large earthquakes may exist for this region (Quittmeyer, 1979).
Although there are no direct records of this tsunami in the Arabian Gulf, at Julfar, the forerunner of Ras al-Khaimah, UAE, there was a large sandbar that ships had to transport goods over. It was noted that sometime before 1964 this bar was breached by a "tidal wave", which formed a direct channel from the open sea to the harbor. Ambraseys and Melville (1982, p. 193) have suggested that this wave was associated with the 1945 Makran tsunami.

1983 – Chagos Archipelago**.** On 30 November 1983, the Chagos Archipelago and the island of Diego Garcia were struck by a 6.6 M earthquake. The epicenter was at 6.85 S, 72.11 E. Locally, the quake produced a tsunami with maximum height of 1.5 m. By the time this tsunami reached Seychelles to the west, 1,700 km away, it had attenuated to 40 cm in height (USGS, 2002). Although this tsunami had no obvious impact on the Arabian Peninsula, the location of the Chagos Archipelago in the middle of the Indian Ocean indicates that a larger earthquake from this region has the potential to produce a tsunami that can adversely impact other Indian Ocean coasts, including those of the Arabian Peninsula.

2004 – Aceh, Indonesia**.** As mentioned previously, the 26 December 2004 earthquake generated a large tsunami that affected the entire Indian Ocean basin (Fig. 2). It did not greatly impact the Arabian Peninsula, but small waves ranging from 3 to 30 cm in height occurred along the northern Arabian Peninsula coasts, adjacent to the Gulf of Oman (Kowalik et al., 2005). However, further south, from Shannah, Oman to Dhalkut, Oman, the wave runup heights varied between 0.8 m to 3.3 m (Okal et al, 2006). At the port of Salalah, large eddies formed. One freighter actually broke loose from its mooring and drifted for several hours (Okal et al. 2006). Local fisherman in Rakhyut (just north of Dhalkut), near the Oman-Yemen border, where the tsunami runup was 2.6 m (Okal et al., 2006), noticed a discoloration of the water and unusual surface wave behavior (Jordan, 2008).

Table 6-1: Summary of Tsunamis related to the Arabian Peninsula (Jordan, 2008)

Date	Source Location	Description
Persian Gulf		
A.D. 978, 17 June	Siraf, Iran	Large earthquake, but not followed by a tsunami.
A.D. 1008, Spring	Siraf, Iran	Large earthquake with reports of ships sinking, but ships likely sank due to a concurrent storm, not tsunami.
Red Sea		
A.D. 1879, 11 July	Tor (present-day El Tor), Egypt	Moderate earthquakes were felt in upper Egypt, village of Tor inundated by tsunami.
A.D. 1884, 20 July	Massawa (present-day Mitsiwa), Eritrea	Offshore earthquake occurred, sea waves built up in harbor and swept over causeway.
Indian Ocean/Arabian Sea		
326 B.C., November	Southern Pakistan	Tsunami sank Macedonian ships - this event probably did not occur.
A.D. 1524	Dabul, India	Tsunami occurred, but no earthquake was felt – this event was probably local and did not affect Arabia.
A.D. 1819, 16 June	Gujarat, India	Large earthquake in western India generated a large tsunami - the wave would have arrived in Arabia in about 4 hours, but there is no record of affects in the Arabian Peninsula.
A.D. 1845	Kutch, India	An earthquake was followed by a small tsunami – this event was probably too small to have affected the Arabian Peninsula.
A.D. 1851	Makran, Pakistan	An earthquake occurred off of the Makran coast with an epicenter west of the better known 1945 earthquake epicenter and tsunami.
A.D. 1883, 8 August	Krakatau, Indonesia	The eruption of Krakatau volcano generated a large tsunami, which was measured worldwide. A station located in the Gulf of Aden measured a small tsunami 13 cm in height. No other records are apparent for Arabia.
A.D. 1945, 28 November	Makran, Pakistan	A large earthquake off of the southern coast of Pakistan generated a large tsunami that devastated the region, killing more than 4,000 people. This wave may have also swept into the

Date	Source Location	Description
		Persian Gulf and washed out a large sandbar at Ras al-Khaimah, UAE.
A.D. 1983, 30 November	Chagos Archipelago	An earthquake at the Island of Diego Garcia produced a small tsunami (1.5 m high) - its small size did not produce any recordable impacts on the Arabian Peninsula, but future events from the same location could.
A.D. 2004, 26 December	Aceh, Indonesia	An extremely large earthquake generated a 10-15 m high tsunami that killed over 225,000 people. It had minor impacts along the southern Arabian coast.

The 26 December tsunami wave and subsequent sea surges hit the coast of Yemen between 11.40 a.m. and 8.30 pm., causing damage to Yemen's mainland and associated islands facing the Indian Ocean. Local observations indicate that water started to rise at about 11:00 a.m. local time on 26 December 2004. The water level receded in some locations (such as Muhaifif in Al Mahara), exposing about two kilometers of the sub-tidal flats before flooding in. The tsunami severely affected Yemen's Socotra Island with a death at a distance of 4,600 km from the epicenter of the Magnitude 9.0 earthquake.

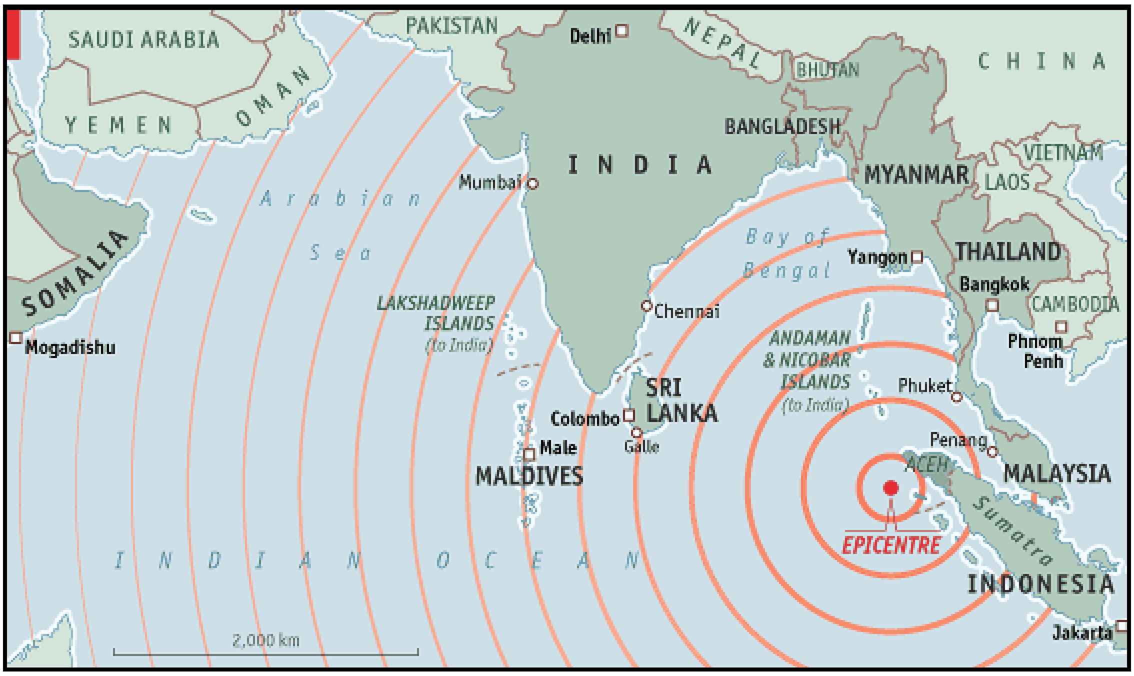


Figure 6-2: Indian Ocean Earthquake/Tsunami Disaster Area (Source: Economist 2005)

As is apparent from Figure 6-2 above, relative to the countries of Southeast Asia, damage in Yemen was much less, mainly because of its distance from the epicenter of the earthquake, and the protection it receives from the Indian Peninsula and Horn of Africa. Nevertheless, the impacts on the livelihoods of local people, especially fishermen, were significant, as many of them lost their main form of income. The two main areas identified as the most affected include Socotra Island and the coastline of Al Mahara Governorate, especially the area extending from Saihut to Wadi Hauf (Ministry of Agriculture and Irrigation, 2004). Figure 6-3 depicts the destruction due to the 2004 tsunami at Dabut in Hadramout.

Figure 6-3: Dabut, Yemen (28 December 2004)

The main direct impact of the tsunami in Yemen was on the fishing sector. However, in Al Mahara some other sectors were affected to some extent. In Al Mahara the coastal area between Saihut and Hauf near the Omani boarder (particularly the fishing villages of Muhayfif (Figure 6-4), Yeroub and Nashtoun) experienced a strong tsunami wave (a 6 m high wave penetrated 400–500 m inland at Muhayfif), which destroyed houses and other facilities on the beaches, destroyed and lifted boats several hundred meters inland and destroyed fishing gear. As far as is known at present, in Socotra primarily the coast between Omouk, Mahferhin and Matyif in the southeast of the island was affected. Floods also covered agricultural land near the coast, destroying fences and crops, and depositing salt on the soil.

Figure 6-4: Muhayfif, Yemen (28 December 2004). Tsunami debris outside the offices of the Al Mahara Fisheries Association

The damage to human economic activities, including the fisheries sector, as reported by the Ministry of Agriculture and Irrigation, 2004 is highlighted in Table 6-2:

Table 6-2: Summary of damage to fisheries and other sectors

	Al Mahara	Socotra
Fishing nets and	500 nets	174 nets long lines 37 hook lines
Fishing traps	9,500	486
Fishing boats	33 (totally destroyed)	16 boats 108 (partly destroyed) 143 ropes, 260 anchors, buoys and other equipment
Outboard engines	33 (totally destroyed)	36 engines, 106 (partly destroyed), 10 fuel tanks
Fisheries facilities	Fish market stands and a 146 m long wall, ice plant, , Fisheries Cooperative, storage area	23 petrol drums, 45 sacks of salt
Other buildings	Mosque, gas station	
Vehicles	5 cars, motorcycles	

6.2 Other Tsunami Data

Modeling of tsunami propagation and associated inundation requires accurate bathymetry over the ocean and high-resolution offshore topography near the coast. The National Geophysical Data Center (NGDC) recently published the 1-min global relief model ETOPO1, which covers the entire layer-1 grid. In addition, the SRTM data set interpolated at 30 m resolution provides high-resolution topography.

7 Historical Storm-surge Hazard Data Review, Analysis and Quality Assessment

7.1 Introduction

North Indian Ocean is one of the regions in the world, which is frequently affected by storm surges associated with tropical cyclones. Statistics show that about 15% of the global tropical cyclones form over the North Indian Ocean (Gray 1975). On an average, about 5-6 tropical cyclones form over the Bay of Bengal and the Arabian Sea every year, out of which 2 to 3 are generally severe. Moreover, it has been observed that annual frequency of cyclones in the Bay of Bengal is much higher than in the Arabian Sea, in the ratio of 4:1. May, June, October and November are the stormiest months of the year. In the post-monsoon period, the peak in the storm activity is reached in the second half of October and in the first half of November. Compared to the pre-monsoon season; the months of October and November are known for severe cyclonic storms.

Storm surges are produced when these tropical cyclones pass over the continental shelf. Winds associated with tropical cyclones are the main driving force for accumulation of the water on the shoreline, which in turn, results in a sudden and substantial rise in sea level. This abnormal rise in sea level above the astronomical tide, which reaches a maximum on the coast, normally at the time of the landfall of the cyclone, is called storm surge. Storm surges are atmospherically forced oscillations of the water level in a coastal or inland water body, in the period range of a few hours to a few days, depending upon the speed of the cyclone. These come under the classification of long gravity waves, which are often 100 km wide with amplitude at times higher than 5m. The intensity of the cyclone determines the power of the storm surges, the more intense the storm, the stronger the waves. If the occurrence of storm surge coincides with normal astronomical tide, the total rise in the water level may be spectacular. Storm surges cause heavy loss of life and property, damage coastal structures, harbors, oilrigs and other residential complexes close to the coast. Most of the world's greatest human disasters associated with tropical cyclones have been directly attributed to the coastal flooding associated with storm surges. The destruction caused by storm surges may be serious cause of concern along the coastal regions of the countries around the North Indian Ocean. These storm surges inundate vast stretches of coastal areas, killing people and livestock, and damage the property. Therefore, development of numerical storm surge prediction system is important for the counties around North Indian Ocean.

There can be little doubt that the number of casualties would be considerably lower if the surges could be predicted say 24 hours in advance, thus allowing effective warnings in the threatened areas. The prediction must, of course, be accurate enough so that one can distinguish between dangerous surges and surges that cause little harm, as people cannot be evacuated from exposed areas for every approaching storm. Various techniques such as empirical, statistical, analytical and numerical are employed for the prediction of storm surges around the world. In general, empirical and statistical methods require several years of observations on vast shelf areas, which are difficult to obtain. Consequently, one of the possibilities to study storm surges is through hydrodynamic modeling, and in recent years numerical methods have been used effectively to predict storm surges. This can be achieved by solving the governing equations to determine the response of the sea to a cyclone moving over its surface. Numerical prediction of storm surges in real time has become easier due to the availability of high-speed computers and advances in satellite technology.

7.2 Tropical cyclone

Tropical cyclones are large atmospheric vortices, which form over the tropical warm oceans. A severe cyclone can extend horizontally from 150 km to 1,200 km with fierce winds spiraling around a central low-pressure area. In the northern hemisphere, the air rotates around the cyclone in an anti-clockwise direction and in the southern hemisphere in a clockwise direction. The cyclones strike certain exposed coastal regions around the world every year, causing heavy loss of life and property. The intensity of a cyclonic disturbance is measured by the strength of the associated winds. The maximum wind speeds associated with a mature cyclone could be as high as 150 to 250 km per hour. The strongest winds are often observed to the right of the cyclone's track in the northern hemisphere. The total radial dimensions of a mature cyclone vary from a 50-100 km diameter in very narrow ones, to diameters as large as 2,000 km in large ones. Over the Indian seas, the size is usually between 600 to 1,200 km (for nearly 70% of the cyclones) in the post monsoon season (October-December). It is slightly less in the pre-monsoon period (April-June), the diameter being about 400 to 800 km for 70 % of the cyclones.

Tropical cyclones generally form between the latitudes 5°N and 15°N, over the Indian seas, during the pre-monsoon (April-June) and post-monsoon (October to December) seasons. They usually form out of weak low-pressure systems and gather strength sometimes very rapidly as they travel over the warm seas. The large quantity of moisture picked up from the ocean is the chief source of energy for the storm that is why tropical cyclones never form over the land. They also weaken off rapidly after crossing the coast and moving inland. The cyclone covers roughly a distance of 300 km to 500 km per day. The average life of a cyclone in the Indian seas is six days from the time they form until they dissipate. Some storms last only for a few hours while others as long as two weeks. The evolution of the average storm from its formation to decay has been given in detail by Riehl (1979).

7.3 Storm surges and their effect on coastal zone

The most destructive component of a tropical cyclone is the storm surge that sometimes inundates vast stretches of highly populated coastal region and cause heavy damage to the life and property. A surge is caused by the interactions of Air, Sea, and land. The cyclone provides the driving force in the form of a very high horizontal atmospheric pressure gradient and very strong winds. As a result, the sea level rises and continues to rise as the cyclone approaches the shallow water, and reaches a maximum on the coast near the point of landfall. Surge waves inundate vast stretches of coastal area and wash away all that comes in their way. A usual fall in the sea level in coastal areas is sometimes called a negative surge. Such falls may be created by the backwash in advance of a storm surge or they may be a result of a recession of the sea at the coast under the influence of strong winds having an offshore component.

The storm surge at any place may be divided into three stages: forerunner, the main surge, and resurgence. A forerunner is the gradual rise of sea level preceding the storm; even when the cyclone is far from the coast, some broad scale disturbances seem to produce variations of coastal sea level. Thus, a forerunner can be used as an indicator of the arrival of a cyclone. The main surge follows after the storm surge rises to its peak, the period of the main surge at a place varies from a few hours to more than two or three days, depending on the speed of the cyclone. Resurgence follows the main surge. The sea level gradually tends to return to the normal state in this stage. It includes, however, various kinds of oscillations due to topographic and other effects. The resurgence may sometimes continue for two or three days. Resurgences are also hazardous, particularly for marine and inland shipping.

7.4 Historical Cyclone Data Review

Traditionally, areas of tropical cyclone formation are divided into seven basins. Yemen and the rest of the Arabian Peninsula are located in the North Indian Ocean basin. This basin is divided into two areas: the Bay of Bengal and the Arabian Sea, with the Bay of Bengal dominating (5 to 6 times more activity). Still, this basin is the most inactive worldwide, with only 4 to 6 storms per year. This basin's season has a double peak: one in April and May, before the onset of the monsoon, and another in October and November (JTWC 2004).

Figure 7-1 depicts the cyclone tracks that originated in the North Indian Ocean during the period 1970-2005.

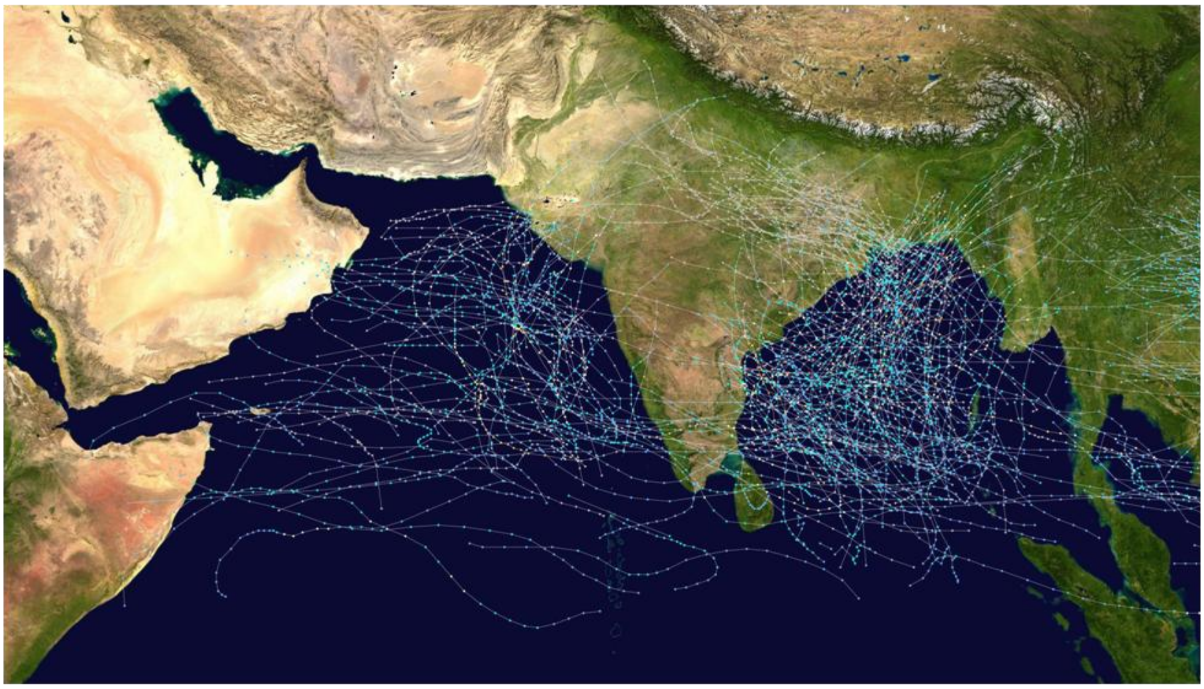


Figure 7-1: Cumulative track map of North Indian Ocean cyclones (1970-2005)

Although it is an inactive basin, the deadliest tropical cyclones in the world have formed here, including the 1970 Bhola cyclone, which killed 500,000 people. Countries affected include India, Bangladesh, Sri Lanka, Thailand, Myanmar, and Pakistan. Recently, the Nargis cyclone of May 2008 killed about 140,000 people in Myanmar as well as caused enormous property damage. Rarely do tropical cyclones that form in this basin affect the Arabian Peninsula or Somalia; however, cyclone Gonu caused heavy damage in Oman on the peninsula in 2007. On 24 October 2008 a tropical storm 03B struck south-eastern coast of Yemen and caused the severe flooding, in the two governorates of Hadramout and Al Mahara leaving about 184 dead and caused estimated losses of YER 327,551 million (USD 1,638 million), or 6 percent of Yemen's Gross Domestic Product (DLNA Storm 03-B, 2009)http://en.wikipedia.org/wiki/Yemen.http://en.wikipedia.org/wiki/Yemen The 2002 01A cyclone was an uncommon tropical cyclone that struck the Dhofar region of Oman in May 2002. The storm was rare, in that it was one of only eleven tropical cyclones on record to approach the Arabian Peninsula in the month of May. The storm brought the heaviest rainfall totals to Dhofar in 30 years, causing severe flooding. Several people drowned after their vehicles were swept away by the flooding. The storm caused locally heavy damage totaling USD 25 million (2002 USD, USD 30 million 2008 USD).

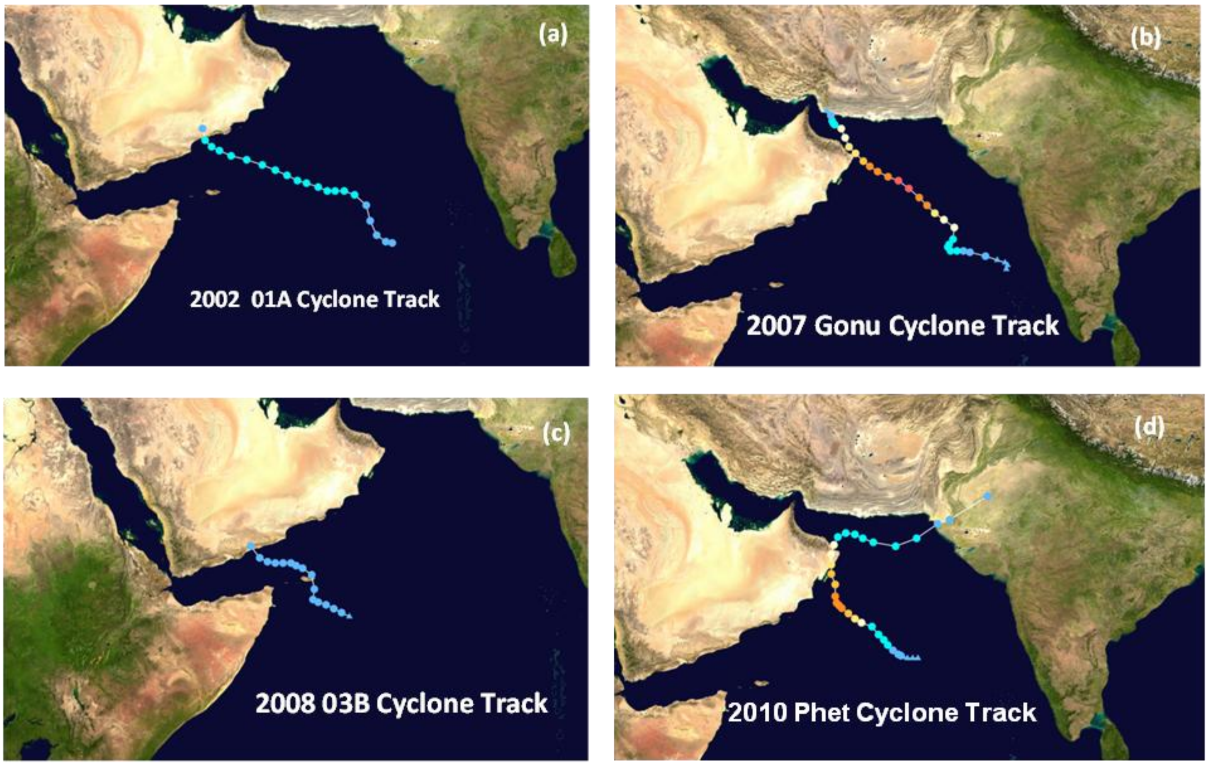


Figure 7-2 (a-d): Cyclonic tracks over the Arabian Peninsula

There are few documented accounts of tropical cyclones hitting the Arabian Peninsula and the devastation caused by the associated surges. Major storms that occurred in the Arabian Sea in the past are very less. The historical records of cyclones and associated storm surges were collected for the period 1945-2010 for the western sector of the Arabian Sea from various sources viz., the internet, the Unisys Hurricane Database, and several research publications. Detailed information for a few events over the Arabian Peninsula in the last several years is given below:

- 19-26 October, 1948 - Tropical Cyclone struck Salalah in Oman.
- 18-24 May, 1959 - Tropical Cyclone struck Salalah in Oman.
- 9-13 June, 1977 - tropical cyclone struck the Masirah and Dhofar in Oman, people killed 105, displaced 5,048.
- 16-25 September, 1979 - tropical cyclone struck Salalah in Oman
- 9-10 August, 1983 - Tropical Storm Aurora struck Oman.
- 23-28, May, 1984 - Tropical Storm 01-A transited the Gulf of Aden and made landfall in northwest Somalia, the first tropical cyclone on record to do so.
- 27 Nov-08 December, 1984 - Tropical storm 4B developed over western Bay of Bengal and hit southeastern India, while moving the system again redeveloped over the Arabian Sea and turned towards southwest to hit Somalia.
- 29 Sept-04 October, 1992 - Tropical Storm 06-A struck Oman.
- 18-24 December, 1992 - Tropical Storm 12-A struck Somalia.
- 05-09 June, 1994 - Tropical Storm ARB-02 struck Oman.
- 29 Sept-04 October, 1994 - Tropical Storm ARA-04 struck Somalia.

- 09-12 June, 1996 - Tropical Storm 02-A struck Oman.
- 11-17 December, 1998 – Tropical storm ARA-06 struck Duqm, Oman.
- 05-10 May, 2002 - Tropical Storm ARB-01 struck Salalah in Oman. Seven deaths occurred and the cyclone displaced 83 people. It caused estimated damages to the tune of USD 50 million.
- 02-07 June, 2007 – Super cyclonic storm Gonu struck Ash Sharqiyah in Oman, causing catastrophic damage. Fifty deaths occurred, around 20,000 peoples were affected, and damage in the country was estimated at around USD 4.2 billion (2007 USD). In Iran, the cyclone caused 28 deaths and estimated economic damages stood at USD 216 million.
- 20-23 October, 2008 – Tropical cyclone ARB-01 struck south-eastern coast of Yemen. Overall, this weak storm killed at least 184 people in Yemen. Damage is estimated at about USD 1 billion.
- 31 May-06 June, 2010– Cyclonic storm Phet struck Oman. It caused 44 deaths and economic damages estimated at about USD 780 million.

Historical data shows that only a few cyclones that develop in the Arabian Sea in the month of May could track westwards up to the Arabian Coast. This has happened in the years 1886, 1889, 1911, 1916, 1919, 1927, 1959, 1960, 1963, and 1970.

7.5 Cyclones over the Arabian Peninsula in the present decade

Four severe cyclonic storms struck the Arabian Peninsula during the present decade, the super cyclonic storm Gonu of June 2007 being the most intense. The tracks of these events are shown in Figure 7-2 (a-d).

7.5.1 Cyclonic storm 01A over the Arabian Sea (06-10 May, 2002)

A depression developed over southeast Arabian Sea on May 6. 2002. Moving northwest, it intensified into a deep depression on the morning of May 7. Thereafter, it moved in a westerly direction until the evening of May 8. Moving in a west-northwesterly direction, it intensified into a cyclonic storm by the noon of May 9. Continuing to move in a west-north-westerly direction, it crossed the Arabian coast close to and south of Salalah Port (Sultanate of Oman) around noon of May 10. The storm brought the heaviest rainfall totals to Dhofar in 30 years, causing severe flooding. Several people drowned after their vehicles were swept away by the flooding. The storm caused locally heavy damage, totaling USD 25 million.

7.5.2 Super cyclonic storm Gonu over the Arabian Sea (02-07 June, 2007)

Super Cyclonic Storm Gonu (JTWC designation: 02A)) was the strongest tropical cyclone on record in the Arabian Sea, and tied for the strongest tropical cyclone on record in the northern Indian Ocean and was the strongest named cyclone in this basin. The second named tropical cyclone of the 2007 North Indian Ocean cyclone season, Gonu developed from a persistent area of convection in the eastern Arabian Sea on June 1. With a favorable upper-level environment and warm sea surface temperatures, it rapidly intensified to attain peak winds of 240 km/h (150 mph) on June 3, according to the India Meteorological Department. Gonu weakened after encountering dry air and cooler waters, and later on June 5 it made landfall on the eastern-most tip of Oman with winds of 150 km/h (90 mph), becoming the strongest tropical cyclone to hit the Arabian Peninsula. It then turned northward into the Gulf of Oman, and dissipated after moving ashore along southern Iran on June 7.

Intense cyclones like Gonu have been extremely rare over the Arabian Sea, as most storms in this area tend to be small and dissipate quickly. The cyclone caused about USD 4 billion in damage (2007 USD) and nearly 50 deaths in Oman, where the cyclone was considered the nation's worst natural disaster. Gonu dropped heavy rainfall near the eastern coastline, reaching up to 610 mm (24 inches), which caused flooding and heavy damage. In Iran, the cyclone caused 23 deaths and USD 215 million in damage (2007 USD).

7.5.3 Cyclonic storm 03B over the Arabian Sea (20-23 October, 2008)

On October 19, the IMD noted that an area of low pressure, which located to the south east of Salalah, Oman had intensified into a tropical depression and assigned it the number ARB 02. IMD updated the system on October 21, to a Deep Depression while it lay 700 km south of Salalah, Oman near the east coast of Somalia. It lost its strength while crossing the Gulf of Aden due to entry of dry air and land interaction as it passed close to the northeastern coast of Somalia. It later was downgraded to a Depression, named TC 03B by the JTWC. On October 24, it made landfall on the southeastern coast of Yemen, leaving at least 26 civilians and six soldiers dead while trapping hundreds of people due to flooding and torrential rainfall. The casualties indicated 180 persons dead and 100 others missing, mostly from the region of Hadramout, where the storm made landfall. Seven hundred and thirty three houses were destroyed in the governorates of Hadramout and Al-Mahara, while 22,000 people were displaced. Overall, this weak storm killed at least 180 people in Yemen. The estimated damage is YER 327,551 million (USD 1,638 million), or 6 percent of Yemen’s GDP (DLNA Storm 03B, 2009).

7.5.4 Cyclonic storm Phet over the Arabian Sea (31 May-06 June, 2010)

Cyclone Phet (RSMC/IMD Designation: ARB 02, JTWC designation: 03A) was the third named cyclone of the 2010 North Indian Ocean cyclone season. The low pressure area in the Arabian Sea was converted into a tropical cyclone on May 31. It initially moved to the northwest direction near Oman but later turned more towards the North before reaching the Arabian Peninsula and later to a northeastern track onto Pakistan. Cyclone Phet made landfall at Thatta about 50 km south from Karachi, Pakistan on June 6, 2010 at about 16:30 GMT. "Phet" is a Thai word, meaning diamond. Damage from the storm in Oman was estimated to have exceeded USD 780 million.

7.4 Data Requirement

Modeling of storm surges and associated inundation requires the following data input:

- High resolution cyclonic winds
- Bathymetry, particularly in the continental shelf
- Detailed coastal geometry
- Land topography both horizontal and vertical

The National Geophysical Data Center (NGDC) recently published the 1-min global relief model ETOPO1, which covers the entire layer-1 grid. In addition, the 30 m interpolated SRTM data set provides higher resolution topography.

8 Conclusions on Data Quality Assessment

Catastrophe modeling results are largely ineffective without quality data collection. For decision makers the key risk is that poor data quality could lead to a misunderstanding regarding distribution of hazard to the potential catastrophic events. This in turn will have an impact on decision-making and management, possibly leading to unwanted exposure distribution and unexpected losses. The subsequent sections discuss data quality assessment for each hazard.

8.1 Earthquake

A typical earthquake hazard model requires, at a minimum, the following three sets of data.

(a) Earthquake catalogue - Distribution of earthquake in space, time and size to estimate regional seismicity
(b) local soil conditions (loose or hard rock beneath the location) for estimation of amplification/ de-amplification of seismic signals
(c) The attenuation of seismic waves at increasing distances from the location of the earthquake

For developing an earthquake hazard model, the critical input data such as event catalog, historical records of earthquake events are available online and in published reports and research papers. The quality of such data is fairly good. The other critical information is the local site conditions. The 35 sheets of detailed geological maps on 1:250k scales are digitized and interpreted to prepare soil index map. The quality of geological maps is very good. Events records for developing Yemen specific attenuation functions are not available. In absence of these, global or other similar region specific attenuation functions will be used in the model. Additional required data are a) Seismic fault map b) Seismicity rate of known faults. Fault specific data is not available in Yemen. In absence of this, seismicity of Yemen will be modeled as area source, instead of fault line source.

8.2 Volcanic Hazard

In assessing volcanic hazard for a region, the historical record of activity is relevant, as is the record of activity in the Quaternary, which is the comparatively recent geological past. In the region of Yemen, Quaternary activity has been experienced as small-scale basaltic eruptions from rift-induced fissures scattered across a broad zone (Hughes and Collings, 2000). Rather than causing dangerous explosions, these eruptions generate flows of lava, which can incinerate and entomb property along their paths. A stark example of the destructive power of lava is the obliteration of an important temple by a 3rd century eruption on Jabal Zabib.

Yemen is exposed to a moderate degree of volcano hazard. There is no known major eruption with Volcano Explosivity Index (VEI) 4 or more, so the explosion risk from tephra fall is very low beyond the immediate region of a volcano. Consequently, the economic risk is predominantly from lava flow, which essentially destroys everything in its path.

The available volcanic database in Yemen is sufficient for the basic catastrophe modeling approach, which requires stochastic event set frequencies and loss consequences.

8.3 Landslide

Following is the list of data and its quality assessment.

Item		Data Quality		
	Details of Available data	**Completeness of data**	**Missing information**	**Overall Quality of data**
Landslide Inventory				
Landslide Inventory data	Landslide inventory data from 1982 to 2009 91 landslides consist of information of location, province, causalities and cause	Data seems to be complete with respect to major landslides in Yemen	Specific location of event, size of event, area affected is not known	Data quality is not good for developing landslide probabilistic model
Landslide/Rockslide monitoring	Survey data from Litho Cover Hazard Mapping Project (LCHMP) program of YGSMRB	So far only few areas of Yemen are covered.	Only ten parameters are described in detail	Data is not complete to provide estimates of landslide recurrences
Environmental factors				
Geology	Detailed geological maps, covering in 35 sheets of scale 1:250k.	Good		Good
Morphometric parameters	Slope angle, aspects, internal relief and flow accumulation are being developed using SRTM 90m interpolated to 30m DEM for Yemen.	Good		Good
Lithology and Structures	Lithological units are captured from geological maps of scale 1:250k. There are 35 sheets covering the extent of geological formations, age, and lithological composition.	Good		Good
Geological Structures	Geological structure of Yemen derived from geological maps	Average	Not detailed to capture local landslides	Average
Soil types	Soil maps are not available. Soils maps are inferred from geological maps on 1:250K scale.	Average	Soil types are converted to NEHRP classes	Average

Item		Data Quality		
	Details of Available data	**Completeness of data**	**Missing information**	**Overall Quality of data**
Triggering factors				
Rainfall:	TRMM data and flood model results	good		good
Earthquake	Earthquake model data and results	good		good

Considering the paucity of historical loss information required for landslide modeling and calibration, the available information of past historical events are not enough to develop a landslide probabilistic risk model. Instead, RMSI team is preparing landslide susceptibility maps and deterministic landslide hazard maps

8.4 Flood Hazard

The following data sets have been collected for flood risk model development.

- SRTM Digital Elevation Model (DEM), soil characteristics, and land use
- Rainfall data
- Exposure - population and household
- Flood extent footprints from DLNA report
- Loss reports from EMDAT

Besides the above-mentioned datasets, flow and flood level data are essential is any flood risk modeling task.

SRTM elevation data is available for the entire country. In absence of elevation data sets from national agencies, the SRTM DEM can be adopted for national level studies.

The meteorological, particularly rainfall, data is insufficient which is being augmented from global sources of rainfall such TRMM and Santa Clara university.

Observed discharge and flow level are not available for the study. In the absence of observed flow records, the RMSI team is planning to use published reports and information from the local people for recent flood events for validation of model results.

Historical flood footprints are available for the recent Storm 03B event that affected the Hadramout valley. The absence of flood prints in other region will have some limitation on the simulated flood extent. However, loss information in terms of affected population and damages are available for the major events from 1981-2008 at a country level from EMDAT. This loss information will be used for validation of modeled losses.

With this information, national level flood risk assessment study can be carried out. There is further scope of improving the model with the detailed data in terms of rainfall, runoff, elevation, and flood levels.

8.5 Tsunami Hazard

The development of Tsunami model can be divided into three stages:

Generation

This includes formation of an initial disturbance at the ocean surface due to the earthquake-triggered deformation at the sea floor. The basic parameters required for these models include the fault area (length and width), angle of strike, dip, slip, depth of fracture, dislocation and moment magnitude of the earthquake. The waveform generated varies with these source parameters and, hence, the information on above parameters is essential.

Propagation

In Tsunamis, the wave disturbance extends through the entire water column from sea surface to the ocean bottom. Tsunamis travel outward in all directions from the generating area, with the direction of the main energy propagation generally being orthogonal to the direction of the earthquake fracture. Tsunami propagation variation is largely depends on (i) orientation or dimensions of the generating area, (ii) regional bathymetric and topographic features and (iii) rate of advance.

Inundation

The propagating Tsunami wave from the deep water undergoes a change, causing increase in the wave height at the coast due to the near shore bathymetry and coastal morphology such as inlets, sand dunes, water bodies etc. This requires high quality fine resolution bathymetry / topographic data.

Keeping in view the above, data collected for developing the Tsunami hazard model is sufficient for a scenario-based model to identify Tsunami sources or for the waves offshore to determine the corresponding impact on the nearby coast. Models can also be initialized with smaller sources to understand the severity of the hazard for the less extreme but more frequent events. The Tsunami evacuation maps and procedures can be created with the help of available inputs on detailed bathymetry and topographic data for the area being modeled.

8.6 Storm-surge

The output quality of storm surge models is highly dependent on the following factors:

(a) Meteorological parameters such as Intensity of storm, atmospheric pressure, track of storm, forward speed, radius of maximum winds.

(b) Physical characteristics of the basin such as slope of the coast, roughness of coast, coastal geometry and natural or manmade barriers

As cyclones are rare in the region, it is difficult to get large number of actual storm events with well-documented meteorology and storm surge histories. It is even rarer to find adequate, reliable measurement of storm surge elevations. The accuracy and reliability of historical wind record has serious implications for long-term trend analysis, and the frequency and intensity of tropical cyclones.

Challenges lie on recovering reliable wind estimates and other related information from the historical records, especially for highly dynamic and short-lived extreme events. The cyclonic events may be determined by threshold wind speeds based on Saffir-Simpson hurricane categories. The uncertainties in data can be minimized using standard statistical tools and models. It may be noted that the inherently lower-quality components of the records should be used with caution.

Appendix A: Details of Important Previous Seismic Studies

Seismicity of Yemen. 1999. By Alsinawi, S. A. and Aydrus, A. Al, Faculty of Science, University of Sana'a

Note: This is one of the most informative books on seismicity in Yemen

Highlights: *Geology and Tectonics, Macroseismicity of Yemen, Seismotectonics and Seismological Engineering, Volcanocity in Yemen*

The book primarily focuses on the seismic hazards associated with Yemen and adjacent areas. It describes the regional geology including the evolution of the Arabian Shield and Afar Triple Junction as well as major tectonic features.

Figure 2-3: The main geologic units of Yemen, after Yemen Geological Bulletin, No 6 (1995)

It also shows macroseismicity in Yemen with considerable details and presents a historical earthquake catalog. Analysis of Dhamar earthquake is significant.

Table 3-1: Catalog of Historical Earthquakes of Yemen

It also emphasizes on earthquake data evaluation for the period 1900 – 1994. The nature of Arabian Plate motion is also important in the context of seismicity in Yemen.

Figure 5-5: The Seismotectonic map of Yemen

The book also presents an earthquake-engineering assessment of the Dhamar earthquake with focus to reduction of earthquake losses. The volcanic activity in the Arabian sub-continent is described with respect to various volcanic fields and the eruption history of the area.

The Seismicity of Egypt, Arabia and the Red Sea - a historical review. 1994, Ambraseys, N. N., Melville, C. P. and Adams, Cambridge University Press

Note: This is one of the most important and analytical books on seismicity in Yemen.

Highlights: *Macroseismic information and related data assessment, Earthquake catalog Completeness of historical earthquake catalog and regional distribution of seismicity.*

This is a unique book on historical seismicity in Yemen and its surrounding areas. The authors collected all possible details of past earthquake from Arabic sources, travel literature and all other possible sources. It presents a descriptive earthquake catalog starting from 184 BC to 1992 for Yemen. The book also describes spurious events, catalog completeness and regional distribution of seismicity.

Evaluation of Seismic Ground Motion for Sana'a Region. January 1997, Razaq, N. A. A., Al-Mukhadri, N. M. and Ahmed, A. A., Ministry of Oil and Mineral Resources, Republic of Yemen

Highlights: *Historical and recent seismicity, seismic hazard considerations*

The report presents tectonic and volcanic hazards in Yemen. It also emphasizes on earthquake engineering design criteria and the role of soil properties at the site.

Figure 1: Structural Map shows the main Geological Structures around Sana'a region

Figure 2: Epicentral distribution map of Yemen and adjacent areas

Seismic and Volcanic Risks in the Yemen Arab Republic. August 1976. By UNDRO, Geneva

Highlights: *The report analyzed the Seismic hazards in Yemen, Physiography and tectonics, Seismic activity and risk, volcanic and landslide risks.*

The report describes and analyzes the seismic and volcanic hazards associated with Yemen. It represents the physical features, geology and earthquake catalog showing macro seismicity.

Table 1: Available recording of earthquake shocks having occurred in or near the Yemen Arab Republic (10° to 20°N; 40° to 50°E) for the period – January 1953 – December 1975

The volcanic risk includes the study of past eruptions, recent volcanism as well as future risk associated with volcanic eruptions.

Figure 8: The Sana'a – Amran volcanic field (after Grolier and Overstreet, 1975 and LandSat-1 imagery)

It describes various volcanic fields of Yemen and analyzes the periodicity, possible future eruption and disaster risks associated with them. The report also highlights the landslide risks in the country.

Survey of Damages during the Dhamar Earthquake of 13 December 1982 in the Yemen Arab Republic. Bulletin of the Seismological Society of America, Vol. 75, No. 2, pp. 597-610, April 1985, Arya, A. S., Srivastava, L. S., and Gupta, S. P.

Note: This report critically analyzes the 13 December 1982 Dhamar earthquake and its impact on structures.

The report presents the area damaged and population affected from the Dhamar earthquake. It shows the seismotectonics setup of the area around north Yemen.

Figure 2: Seismotectonics map of the area around North Yemen

Figure 3: Isoseismal map for 13 December 1982, the Dhamar earthquake, the Yemen Arab Republic.

The report critically analyzes the ground fractures with intensity of earthquakes and ground motion. The type of construction practiced in the area and the effect of ground motion on them is very significant. It shows the extent of damage associated with various building types and the mechanism of failures for them.

A Basis for Evaluation of Seismic Hazard and Design Criteria for Saudi Arabia. Earthquake Spectra, Vol. 10, No. 2, 1994. By Haddad, M. et al.

Highlights: *Seismotectonics and seismic source regionalization, seismic hazard analysis, seismic source modeling and attenuation relationship*

The study represents the first regionally consistent and systematic collection and critical treatment of the limited historical and instrumental data on earthquakes and seismotectonics of the region and development of seismic design criteria. Yemen and Kingdom of Saudi Arabia are divided into seismotectonic regions based on different source parameters.

Table 1: Sources of Saudi Arabian Earthquake data file

Fig 1: Tectonic boundary of Arabian Peninsula

In the next step, the seismic source regions have been numbered and assigned maximum credible magnitude.

Fig 3: Seismic Source Regionalization Map of Arabian Peninsula and its vicinity

Table 4: Seismic Source Regions and their maximum credible magnitudes

Seismic hazard analysis for these areas was performed particularly with reference to missing magnitudes, incompleteness followed by analysis of maximum magnitude, source seismicity and recurrence forecasting. The study presents an iso-acceleration map for 10 percent probability of exceedance in 50 years.

Surface Effects and Tectonic Setting of the 13 December 1982 North Yemen Earthquake . Bulletin of the Seismological Society of America, Vol. 77, No. 6, pp. 2018-2037, December 1987, by Plafker, G. et al.

Highlights: *Spatial distribution of surface damage, geologic foundations and surface tectonics*

The study describes and analyzes the surface effects and tectonics of the 13 December 1982 earthquake in Dhamar, Yemen. It also describes the geological setting of the region emphasizing the evolution of the region. The length, width and other characteristics of the surface cracks were studied and relationships of cracks to seismicity were calculated. An Isoseismal map for the area has been prepared based on the damage to structures and surficial geologic effects.

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Appendix B: Details of Important Previous Volcanic Studies

Seismicity of Yemen. 1999. By Alsinawi, S. A. and Aydrus, A. Al, Faculty of Science, University of Sana'a

Note: This is one of the most informative books on seismicity and volcanocity in Yemen.

Highlights: *History of volcanism in Arabian sub-continent/ Yemen, Major volcanic fields, Volcanism, tectonism and seismicity, Thermal springs*

The book primarily focuses on the seismic hazards and volcanocity associated with Yemen and adjacent areas. It describes the regional geology including the evolution of Arabian Shield and Afar Triple Junction as well as major tectonic features.

Figure 7-2: Chronology of known recent volcanic activity in Yemen, after NPR (1992).

The book describes Quaternary volcanic activity with description of various volcanic fields in Yemen. It also analyzes the relationship of volcanocity with tectonism and seismicity.

Fig 7-4: Location map of major thermal springs in Yemen

It shows the location of thermal water springs, a consequence of volcanic activity and represents a volcano-seismicity model for the Dhamar earthquake region.

Fig 7-5: Crustal section along E-W line through Sana'a Marib showing relation between seismicity and volcanism, after Plafker et al (1987) (no vertical exaggeration)

Younger Volcanic Fields of Yemen with Focus on Jabal At-Tair active Volcano., 2007, Mattash, A. M., Ministry of Oil and Minerals, Geological Survey and Minerals Resources Board, Republic of Yemen.

Note: Younger volcanic fields of Yemen, history of past eruption, recent volcanism in the Red Sea

The study describes the different trap series with composition of volcanic rocks. It analyzes the volcanic activity in the context of structural geology of Yemen. Yemeni volcanic series is divided into – coastal plains of the Gulf of Aden, west of Aden volcanic fields, central volcanoes, east of Aden and intraplate volcanic fields and intraplate Quaternary volcanic fields.

Table 1: Schematic mineral composition, to briefly show phenocrysts mineralogy and geochemistry for alkali olivine basalts, olivine transitional basalts, and rhyolites from the Yemen Volcanic Series

It describes the recent volcanism in the Red Sea with their eruption history. The most recent eruption of Jabel at Tair (2007) is studied well and presented with details of lava flow, type and extent of eruption, chemical composition of rocks and other features.

The Western Part of the Shuqra Volcanic Filed, South Yemen. 1977, Cox, K. G., Gass, I. G. and Mallick, D. I. J., Lithos 10, 185-191, Oslo

Note: General geology, past volcanic activity, chemical composition of volcanic rocks

This report shows a detailed study of Shuqra volcanic field in south Yemen, which erupted basaltic lavas in recent past. This volcanic field has numerous cinder cones covering an area of approximately 4000 km². It describes the general geology of that area with pre-volcanic topography, current structural geology and type of intrusions.

Figure 2: Geological map of the Shuqra area

The volcanic rocks of Shuqra have been studied and their petrography and chemistry has been discussed. Detailed chemical, microprobe, and isotopic studies are in progress for the area.

Jabal An Nar: An Upper Miocene Volcanic Centre Near Al Mukha (Yemen Arab Republic). August 1986, Capaldi et al. Journal of Volcanology and Geothermal Research, 31 (1987) pp. 345-351

Jabal an Nar near Al Mukha is considered among the active volcanoes of Yemen (Padang, 1963). In this paper, geochronological, chemical and petrological data on selected samples from Jabal an Nar are reported, in order to discuss the relationship of this centre with the Aden Volcanic Series (A.V.S.) volcanic activity. It describes the geology of the region and shows the result of the chemical analysis performed on volcanic rock samples.

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