Annex 4:
Report of International Consultant involved with Tsunami Inundation Mapping Gap Analysis

Annex 4.1: Tsunami Inundation Mapping Gap Analysis Consultancy Report

Activity Report, Contract N°: 4500466087, Jörn Lauterjung

Workshop participation and related activities

In the following all workshops are listed which have been attended under this contract. In case of workshops which have been organized under this contract the objectives of the respective workshops are listed. Results and Recommendations are listed in a later chapter

1) First regional workshop on Tsunami Evakuation Planning (TEP)

   This workshop took place on 24. August 2022 and was of relevance for the Inundation Modeling and Mapping group because requirements and specifications of evacuation planning have a direct impact to the inundation modeling and the selection of scenarios from the PTHA.

2) First reginal workshop on Tsunami Inundation Modeling and Mapping (TIMM)

   This workshop took place virtually on 7. September 2022 and was attended by scientist from the five NWIO countries India, Iran, Pakistan, Oman and UAE and the project team. The workshop was organized under this contract and comprised following objetives:

   Through this regional workshop it is intended to kick-off a joint working process among the five partner countries and the project team to identify the requirements for tsunami inundation modelling and mapping in the region. During the workshop the following shall be achieved:

   - Providing background information on the TTF-31 project and related initiatives, such as the UN Ocean Decade Tsunami Programme and the UNESCO-IOC Tsunami Ready Recognition Programme (TRRP).
   - Getting to know each other and develop regional partnership arrangements.
   - Discuss the establishment of a Regional Working Group on Tsunami Inundation modeling and mapping (RWG-TIMMs), which is proposed as a mechanism to subsequently facilitate joint learning and national implementation of the project activities. Respective National working groups should involve not only representatives from agencies, universities and research institutions, but also the local level, preferably from the community of the Pilot Areas to be involved in order to improve cooperation between science and application in the warning process. Representatives might therefore also be drawn from Provincial Disaster Management Organisations (PDMOs) and/or Local Disaster Management Organisations (LDMOs).
   - Discussion and sharing of knowledge on principal concepts, methodologies and approaches for tsunami inundation modelling. Partner countries are invited to share their experiences and skills of tsunami inundation modeling and mapping.
   - Presentation and discussion of the approach for a gap analysis in each of the five countries and preliminary results.

   Outlook on further activities to be undertaken under the framework of the project, including next steps towards building a common understanding and joint strategy for tsunami inundation modelling in the region and nationally.

3) Workshop on Makran Subduction Zone Science Strengthening Tsunami Warning and Preparedness

   The workshop took place in Abu Dhabi, United Arab Emirates on 14 – 16 November 2022. It was attended by about 35 participants on-site and about 15 participants on-line. Participants came

from 10 countries + UN. The workshop was organized under this contract and comprised following objetives:

Through this scientific exchange workshop, it is intended to distribute, report, and discuss the recent results of an extensive PTHA for the NWIO and to discuss the utilisation of the outcomes for tsunami inundation modelling and mapping for evacuation planning and risk assessment in the region. The specific objectives of the workshop are:

- Provide background information on the TTF-31 project and related initiatives, such as the UN Ocean Decade Tsunami Programme.
- Report the outcomes and results of the Probabilistic Tsunami Hazard Assessment (PTHA) for the North-West Indian Ocean (NWIO) region under guidance of GFZ and INGV.
- Discuss future development and possible extension of the PTHA to include complex tsunami sources in the NWIO region.
- Examine potential uses of the results of the PTHA in developing community awareness and risk management.
- Discuss the utilisation of the PTHA for inundation modeling and mapping in the NWIO.
- Explore further activities to be undertaken under the framework of the project, including next steps towards a joint strategy for implementing tsunami inundation modelling in the region and nationally.
- Discuss and plan possible future realisations of inundation mapping in the region in the project Pilot Areas, as part of possible future phases of the project.

Participants of the Workshop “Makran Subduction Zone Science Strengthening Tsunami Warning and Preparedness” in Abu Dhabi

4) Special Session 11: Inundation & Evacuation Mapping in the NWIO, Friday, 25 November, held during the Indian Ocean Tsunami Ready Workshop, Bali, Indonesia, 22 – 26 November 2022.

The workshop was attended by Indian Ocean Tsunami Ready Workshop participants on site in Bali, NWIO Tsunami Inundation Modelling and Mapping (TIMM) Regional Working Group members online, NWIO Tsunami Evacuation Planning (TEP) National Working Group members

online and other online participants of the Indian Ocean Tsunami Ready Workshop. The workshop was co-organized under this contract and comprised following objetives:

- Share results to date from the work processes in the TTF project components on PTHA, inundation mapping and tsunami evacuation planning
- Discuss the connections between these components and the importance to prepare communities to be Tsunami Ready
- Sharing experiences from other Indian Ocean countries
- Development of a unified approach and method for tsunami modelling and inundation mapping for the NWIO region
- Development of national policies, standards, and approaches for tsunami evacuation planning in NWIO Member States
- Discuss the way forward (next proposed TTF project phase)

Concrete topics which have been adressed have been:

- The PTHA for the Makran region: approach, outcomes and features
- From PTHA to inundation maps: conclusions from the Abu Dhabi Workshop 14-16 Nov
- Requirements for Inundation Mapping from TEP perspective
- Results from the Gap & Capacity Analysis on TEP in the NWIO
- Experiences on TEP in other IO countries (present in the Special Session)
- The way forward: Unified approaches and Pilot Areas for Inundation Mapping and TEP in the next proposed phase of the TTF project for the NWIO

Gap analysis of each Member State's capability and capacity to undertake tsunami inundation modelling.

In preparation of the first meeting of a Regional Working Group of Tsunami Inundation Modeling and Mapping (TIMM) a questionnaire was set up to ask member states for some basic information concerning their capability for Inundation Modeling. The questionnaire was divided into 3 main categories listed below and a number of detailing questions.

Input data for modeling/mapping

Shallow Water Bathymetry

Digital Elevation Models (DEM) for coastal regions

Digital land use information, development information, zoning maps

Hazard information for pilot regions

Scenarios (available?)

Worst case scenarios (available?)

Probabilistic Hazard information (available?)

Other Information

Computational resources, please describe shortly

Software tools, software packages

Human resources

Comments

The results of the questionnaire are shown in the following table and demonstrate the heterogenities in the five countries preconditions. In the first row the type of shallow water bathymetric data and its lateral resolution are listed, row two gives information of the topographic data (Digital Elevation Model) and their horizontal resolution (SRTM = Shuttle Radar Topography Mission), row three gives information if any land use data or information is available (this might be important for evacuation planning), row four gives information on the software systems which have been used so far for inundation modeling projects and row five gives an indication what type of input scenario has been used (deterministic or probabilistic or both)

	India	Iran	Oman	Pakistan	UAE
Shallow Water Bathymetry	200 m Res. GEBCO	450 m Res. (15 arcsec GEBCO) Industry data	450 m Res. (15 arcsec GEBCO)?	Variable, 10 m in Pilot Regions	450 m Res. (15 arcsec GEBCO)
DEM	5-10m SRTM	30 m SRTM	SRTM	10 m SRTM	10 m High resolution Satellite Data
Land Use Information	Maps 1:5000	Not available	Not available	Not available	Basic map
Model Used	Tunami-N2 ADCIRC	ComMit GEOWAVE MIKE-21 Tunami-N2	COMCOT	GUITAR TOAST GeoClaw	ComMIT
Type of Studies	Deterministic	Deterministic/ Probabilistic	Deterministic/ Probabilistic	Deterministic	Deterministic

Gaps and differences in the field of input data have to be solved by the member countries themselves. The regional working group TIMM can work on recommendations what date are needed in what resolution and produce some guidelines. The usage of different software systems and tools is not seen as very critical, more important is the availability of consistent and comparable Tsunami scenario input. This is in a first step been fulfilled by the PTHA, see next chapter

Conceptual reflection for a unified approach for tsunami modelling and inundation mapping in the NWIO

An important step for a strategy to arrive at a unified approch for tsunami inundation modeling and mapping in the NWIO region is the implementation of a joint Probabilistic Tsunami Hazard Analysis in the region. In particular, a better understanding of the tsunami hazard of the Makran subduction zone has been achieved through detailed PTHA modelling. The PTHA model is the first of its kind in the region. It provides a much-needed dataset that can be utilised for modelling scenarios of local tsunami inundation that will inform community evacuation maps or Tsunami risk assessments. A detailed report/publication is in preparation.

The PTHA database must be hosted by an institution which guarantees seemless access to the data and which offers data and information following the FAIR (Findable, Accessible, Interoperable, Reusable) principles. For the NWIO Region INCOIS (India) has indicated interest to host the PTHA database and to offer modeling capacity including software tools. This is the first and very important step for an unified approach for Tsunami Inundation Modeling.

The individual choice of a software system for inundation modeling is not critical in this context, important is the availability of a common input dataset which is given by the PTHA database. Software and Softwarepackages are available as open Source products (e.g. ComMIT (https://nctr.pmel.noaa.gov/ComMIT/background.html) or GeoClaw (https://www.clawpack.org/geoclaw.html)).

As a result from the different discussions e.g. in Abu Dhabi it is clear that some activities have still to be performed. Without discussing this in depth here, following points are to be tackled in the future:

- Development of a methodology to transform waveheight data at offshore POI's to wavehights at the shore line. Usage of Green's Law? Other approaches? Role of shallow water bathymetry for this transformation.
- Translation of the spacing of POI's to finer grids used for inundation modeling. Question of interpolation. Sensitivity analysis for this step. Role of shallow water bathymetry.
- Completion of PTHA from Version 1.0 to Version 2.0 including all faults, normal faults and splay faults; see Report of the Abu Dhabi Science Workshop for more details

Efforts have to be undertaken to integrate the capacities available on national academic level (many examples of successful inundation modeling projects have been shown during the workshop of the regional workinggroup TIMM) with the capacities in the national agencies responsible for warning and mitigation. Training and eductation programs needed. Training programmes could be organized by the involvement of national academic capacities, e.g. from Pakistan. Capacities and modeling know-how are available in all countries.

It is recommended to mandate the TIMM with the discussion and preparation of such training and education programmes. Examples how such programmes can be organized and financed also with the support and help of UNESCO can be found manifold (e.g. https://www.gfz-potsdam.de/en/press/news/details/the-international-training-course-seismology-and-seismic-hazard)

Results, Achievements, Recommendations

The activities under this contract comprise two major fields:

- Establishment of a Regional Working Group for Tsunami Inundation Modeling and Mapping (TIMM) including a gap analysis of the capabilities of member countries in this field, and
- Probabilistic Tsunami Hazard Analysis (PTHA) and its implications for TIMM

The main results and discussed future activities in these fields as well as the main recommendations are listed in tabular form. The last table gives the main achievments under this contract also in tabular form.

Regional Working Group for Tsunami Inundation Modeling and Mapping (TIMM)

Results, Follow-up actions and Recommendations

As **results** of the workshop the following points can be listed:

- The regional group for Tsunami Inundation Modeling and Mapping (TIMM) has been established
- Close cooperation with the Tsunami Evacuation Planning (TEP) Group necessary
- Definition of pilot areas in the NWIO region for Tsunami Evacuation Planning (TEP) and Tsunami Inundation Modeling and Mapping (TIMM)
- First rough gap analysis through a questionnaire performed

Following **follow-up actions** have been discussed:

- Definition of the requirements to perform the respective inundation modeling in the pilot areas.
- Detailed gap analysis to be performed on the basis of the requirements.
- Discussion and definition of software tools for future harmonized and unified modeling approach
- Science Workshop with international experts and discussion of the results of the ongoing Probabilistic Tsunami Hazard Analysis (PTHA) planned for beginning of November 2022
- Discussion of strategies of inundation modeling for Tsunami Risk assessment with disaster managers and decision makers.

Recommendations

The participants of the workshop recommend that the regional working group on Tsunami Inundation Modeling and Mapping (TIMM) should be “officially” mandated by the Sub-regional Working Group for the North-West Indian Ocean of the UNESCO IOC ICG IOTWMS.

Probabilistic Tsunami Hazard Assessment (PTHA)

Conclusions

- PTHA includes sources besides the Makran subduction: all possible crustal sources along the Arabian and Red Seas and Persian Gulf (following PSHA zonation). ~ 5 000 000 sources
- Assessment along the entire coast of the Arabian and Red Sea and Persian Gulf with high density of points-of-interest
- Two alternative probabilistic models.
- Calculated hazard strongly depends on model assumptions. More alternatives should be tested to fairly estimate uncertainties
- Constraints on focal mechanism are weak (few CMT observations in many zones): may considerably over-weight physically less realistic BS scenarios

Recommendations for the development of PTHA (Version 2.0) are

1) Make various views of the probabilistic dataset including site de-aggregation for the sides planned for inundation mapping
2) Compare to recent alternative models (Salah et al.'21, Zafarani et al.'22)
3) Need of more alternative seismic models to better explore uncertainty. First of all, M_{max} and rate models
4) Consider Splay faults for higher versions of PTHA. Recent studies (Momeni et al., 2022) show the importance of splay faulting.
5) Future development from area- to fault-based PTHA.

Recommendations and plans

1) One important result of the Abu Dhabi workshop is that INCOIS (India) is ready to host the PTHA database and to offer data and information following FAIR principles.
2) Another recommendation is that the inundation modeling for evacuation planning in the already defined pilot regions shall be done in 2023 using the results of PTHA (Version 1.0). It still has to be decided if the evacuation planing shall be based on a worst case scenario or a most probable scenario. This discussion has to be done between modellers (TIMM) and the respective decision makers.

Major Achievements

Consistent PTHA database for NWIO available (Arabian and Red Sea, Persian Gulf, not yet finalized for all types of faults).

India offered to host PTHA database and propagation/inundation modeling software for NWIO countries.

Regional working group for inundation modeling established (TIMM).

Gap analysis for member countries capabilities and capacities in inundation modeling performed.

Inundation modeling in Pilot regions based on available datasets ready to go.