METEOR: Draft Protocols on Hazard and Exposure Modelling. Report M6.3/P

UKSA IPP2 Grant Programme

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BRITISH GEOLOGICAL SURVEY

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METEOR: Draft Protocols on Hazard and Exposure Modelling. Report M6.3/P

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Glossary

BGS	British Geological Survey: The UK national geoscience focusing on public-good geoscience for government, and research to understand earth and environmental processes in the UK and internationally
DEM	Digital Elevation Model
DMD	Disaster Management Department: Prime Minister's Office of Tanzania focused on disaster risk
DRR	Disaster Risk Reduction
DRM	Disaster Risk Management
EO	Earth Observation
Fathom	Provides innovative flood modelling and analytics, based on extensive flood risk research
GCRF	Global Challenges Research Fund
GEM	Global Earthquake Model: Non-profit organisation focused on the pursuit of earthquake resilience worldwide
GIS	Geographic Information System
HOT	Humanitarian OpenStreetMap Team: A global non-profit organisation the uses collaborative technology to create OSM maps for areas affected by disasters
ImageCat	International risk management innovation company supporting global risk and catastrophe management needs of insurance industry, governments and NGOs
IPP	International Partnership Programme
METEOR	Modelling Exposure Through Earth Observation Routines
NSET	National Society for Earthquake Technology: Non-governmental organisation working on reducing earthquake risk in Nepal and abroad
ODA	Official Development Assistance
OPM	Oxford Policy Management Ltd: Organisation focused on sustainable project design and implementation for reducing social and economic disadvantage in low-income countries
OSM	OpenStreetMap
PDC	Pyroclastic Density Current
PGA	Peak Ground Acceleration
SFDRR	Sendai Framework for Disaster Risk Reduction
UKSA	United Kingdom Space Agency
VEI	Volcanic Explosivity Index
WP	Work Package

Foreword

This report is the published product of a study by the British Geological Survey (BGS) as part of the Modelling Exposure Through Earth Observation Routines (METEOR) project led by British Geological Survey (BGS).

METEOR is grant-funded by the UK Space Agency's International Partnership Programme (IPP), a >£150 million programme which is committed to using the UK's space sector research and innovation strengths to deliver sustainable economic, societal, and environmental benefit to those living in emerging and developing economies. IPP is funded from the Department for Business, Energy and Industrial Strategy's (BEIS) Global Challenges Research Fund (GCRF). This £1.5 billion Official Development Assistance (ODA) fund supports cutting-edge research and innovation on global issues affecting developing countries. ODA-funded activity focuses on outcomes that promote long-term sustainable development and growth in countries on the OECD Development Assistance Committee (DAC) list. IPP is ODA compliant, being delivered in alignment with UK Aid Strategy and the United Nations' (UN) Sustainable Development Goals (SDGs).

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Summary

This report describes a specific piece of work conducted by British Geological Survey (BGS) as part of the METEOR (Modelling Exposure Through Earth Observation Routines) project, led by British Geological Survey (BGS) with collaborative partners Oxford Policy Management Limited (OPM), SSBN Limited, The Disaster Management Department, Office of the Prime Minister – Tanzania (DMD), The Global Earthquake Model Foundation (GEM), The Humanitarian OpenStreetMap Team (HOT), ImageCat and the National Society for Earthquake Technology (NSET) – Nepal.

The 3-year project was funded by UK Space Agency through their International Partnership Programme, details of which can be located in the Foreword, and was completed in 2021.

The project aimed to provide an innovative solution to disaster risk reduction, through development of an innovative methodology of creating exposure data from Earth Observation (EO) imagery to identify development patterns throughout a country and provide detailed information when combined with population information. Level 1 exposure was developed for all 47 least developed countries on the OECD DAC list, referred to as ODA least-developed countries in the METEOR documentation, with open access to data and protocols for their development. New national detailed exposure and hazard datasets were also generated for the focus countries of Nepal and Tanzania and the impact of multiple hazards assessed for the countries. Training on product development and potential use for Disaster Risk Reduction was performed within these countries with all data made openly available on data platforms for wider use both within country and worldwide.

This report (M6.3/P) is the third report generated by BGS for the work package Multiple hazard impact (WP6) led by BGS. The other 7 METEOR work packages included, Project Management (WP1 – led by BGS), Monitoring and Evaluation (WP2 – led by OPM), EO data for exposure development (WP3 – led by ImageCat), Inputs and Validation (WP4 – led by HOT), Vulnerability and Uncertainty (WP5 - led by GEM), Knowledge sharing (WP7 – led by GEM) and Sustainability and capacity building (WP8 – led by ImageCat).

The report summarises existing modelling approaches for multihazards and outlines a proposed new hybrid approach suitable for assessing the impact of multi-hazards on exposure, with examples of applicability for METEOR data from Nepal and Tanzania.

1.METEOR Project

1.1. PROJECT SUMMARY

Project Title	Modelling Exposure Through Earth Observation Routines (METEOR): EO-based Exposure, Nepal and Tanzania
Starting Date	08/02/2018
Duration	36 months
Partners	UK Partners: The British Geological Survey (BGS) (Lead), Oxford Policy Management Limited (OPM), SSBN Limited International Partners: The Disaster Management Department, Office of the Prime Minister – Tanzania, The Global Earthquake Model (GEM) Foundation, The Humanitarian OpenStreetMap Team (HOT), ImageCat, National Society for Earthquake Technology (NSET) – Nepal
Target Countries	Nepal and Tanzania for "level 2" results and all 47 Least Developed ODA countries for "level 1" data
IPP Project	IPPC2_07_BGS_METEOR

1.2. PROJECT OVERVIEW

At present, there is a poor understanding of population exposure in some Official Development Assistance (ODA) countries, which causes major challenges when making Disaster Risk Management decisions. Modelling Exposure Through Earth Observation Routines (METEOR) takes a step-change in the application of Earth Observation exposure data by developing and delivering more accurate levels of population exposure to natural hazards. METEOR is delivering calibrated exposure data for Nepal and Tanzania, plus 'Level-1' exposure for the remaining Least developed Countries (LDCs) ODA countries. Moreover, we are: (i) developing and delivering national hazard footprints for Nepal and Tanzania; (ii) producing new vulnerability data for the impacts of hazards on exposure; and (iii) characterising how multi-hazards interact and impact upon exposure. The provision of METEOR's consistent data to governments, town planners and insurance providers will promote welfare and economic development and better enable them to respond to the hazards when they do occur.

METEOR is co-funded through the second iteration of the UK Space Agency's (UKSA) International Partnership Programme (IPP), which uses space expertise to develop and deliver innovative solutions to real world problems across the globe. The funding helps to build sustainable development while building effective partnerships that can lead to growth opportunities for British companies.

1.3. PROJECT OBJECTIVES

METEOR aims to formulate an innovative methodology of creating exposure data through the use of EO-based imagery to identify development patterns throughout a country. Stratified sampling technique harnessing traditional land use interpretation methods modified to characterise building patterns can be combined with EO and in-field building characteristics to capture the distribution of building types. These protocols and standards will be developed for broad application to ODA countries and will be tested and validated for both Nepal and Tanzania to assure they are fit-for-purpose.

Detailed building data collected on the ground for the cities of Kathmandu (Nepal) and Dar es Salaam (Tanzania) will be used to compare and validate the EO generated exposure datasets. Objectives of the project look to: deliver exposure data for 47 of the least developed ODA countries, including Nepal and Tanzania; create hazard footprints for the specific countries; create open protocol; to develop critical exposure information from EO data; and capacity-building of local decision makers to apply data and assess hazard exposure. The eight work packages (WP) that make up the METEOR project are outlined below in section 1.4.

1.4. WORK PACKAGES

Outlined below are the eight work packages that make up the METEOR project, which are led by various partners. Table 1 provides an overview of the work packages together with a brief description of what each of the work packages cover.

Work Package	Title	Lead	Overview
WP.1	Project Management	BGS	Project management, meetings with UKSA, quarterly reporting and the provision of feedback on project deliverables and direction across primary stakeholders.
WP.2	Monitoring and Evaluation	OPM	Monitoring and evaluation of the project and its impact, using a theory of change approach to assess whether the associated activities are leading to the desired outcome.
WP.3	EO Data for Exposure Development	ImageCat	EO-based data for exposure development, methods and protocols of segmenting/classifying building patterns for stratified sampling of building characteristics.
WP.4	Inputs and Validation	HOT	Collect exposure data in Kathmandu and Dar es Salaam to help validate and calibrate the data derived from the classification of building patterns from EO-based imagery.
WP.5	Vulnerability and Uncertainty	GEM	Investigate how assumptions, limitations, scale and accuracy of exposure data, as well as decisions in data development process lead to modelled uncertainty.
WP.6	Multiple Hazard Impact	BGS	Multiple hazard impacts on exposure and how they may be addressed in disaster risk management by a range of stakeholders.
WP.7	Knowledge Sharing	GEM	Disseminate to the wider space and development sectors through dedicated web-portals and use of the Challenge Fund open databases.
WP.8	Sustainability and Capacity-Building	ImageCat	Sustainability and capacity-building, with the launch of the databases for Nepal and Tanzania while working with in-country experts.

Table 1: Overview of METEOR Work Packages

1.5. MULTIPLE HAZARD IMPACT WORK PACKAGE

The multiple hazard impact work package (WP6) led by BGS includes four deliverables, which are focused on developing footprints of the hazards that have been designated as of most importance to our partner countries of Nepal (flooding, earthquake and landslide) and Tanzania (flooding, earthquake and volcanic activity) and modelling their potential impacts on exposure (Table 2). The national scale hazard footprints can be viewed in Winson, *et al.* (2019).

Deliverable	Title
M6.1	Deliver national hazard footprints for Nepal and Tanzania
M6.2	Develop models for analysing multi-hazards with exposure
M6.3	Draft protocols on hazard and exposure modelling
M6.4	Final report on multiple hazard impact

Table 2: Overview of BGS multi-hazard impact deliverables

2. Modelling approaches

The importance of multi-hazards has been long recognised, with statements about their importance appearing in both the 1992 UNEP technical report and the Sendai Framework for Disaster Risk Reduction (SFDRR). Whilst it is accepted that there is a need for multi-hazard research that is coupled with both exposure and vulnerability, this is a complex problem to address. In practice, multi-hazard assessments are complicated by factors such as: hazard processes, variations in characteristics and methods of recording them, how they relate to each other, whether they can be cumulative or cascade and how different hazards impact elements at risk differently (and occasionally in opposing ways). Most crucially perhaps, to quantify some degree of multi-hazard risk it is necessary to develop techniques to compare various kinds of hazard data. These data are likely to vary in resolution both spatially and temporally, not only between the different hazards but also in some cases for a single hazard. For example, if the baseline of the data sets are long enough that there has been significant improvement in the methods of data collection then they may no longer be internally consistent. As a consequence, other authors have developed various contrasting approaches for modelling multi-hazards. These can be broadly described as ‘qualitative’, ‘quantitative’ and ‘semi-quantitative’.

In order to create a robust model for analysing multi-hazards we reviewed c.20 different types of model. We tested some of these methods and determined that a semi-quantitative approach would be the most appropriate method for integrating these data. A brief outline of these tests can be seen in Section 2.1, with full details available in Winson & Jordan (2020). Previous multi-hazard work was predominantly focused on either small areas such as towns / catchments, at building scale resolution (e.g. Papathoma, *et al.,* 2003; Bell & Glade, 2004; Kappes, *et al.*, 2012 and others) or else regional to national scale assessments with county or national resolution (e.g. Grieving, 2006; Bartel & Muller, 2007; El Morjani, *et al.*, 2007; Carpignano, *et al.*, 2009). The aim of the multi-hazard modelling for the METEOR project is to create a nationally consistent approach to integrating hazard, exposure and vulnerability data at a resolution of c.90m (a similar resolution to studies by others focusing on the city / catchment scale assessments). This makes the approach developed for the METEOR project both novel and a significant step forward in modelling multi-hazards for the purpose of national scale policy making, Disaster Risk Reduction (DRR) planning and pre-positioning.

2.1. HYBRID MULTI-HAZARD MODEL (METEOR MODEL)

In the METEOR report on the methods for analysing multi-hazards with exposure (Winson, *et al.*, 2020) we reviewed existing multi-hazard modelling approaches and tested several of them using the draft hazard and exposure data that the METEOR project had generated for Tanzania. Outputs of these tests can be seen in Figure 1 and Figure 2.

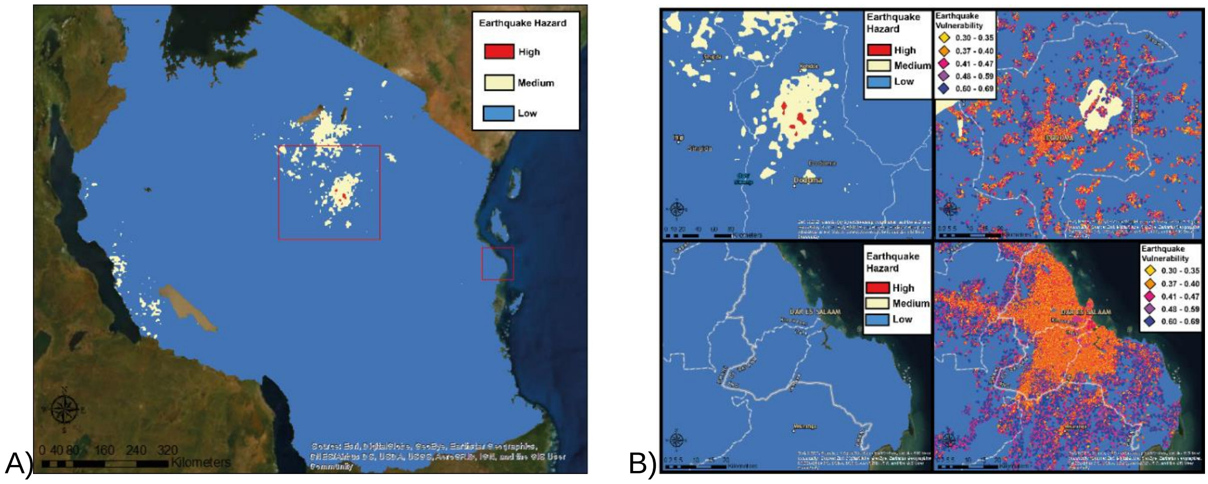

Figure 1: (A) METEOR-derived Vulnerability Indicator seismic hazard result for Tanzania. Red squares highlight regions shown in B) around Dodoma (upper) and Dar es Salaam (lower), as the national centres of government and commerce, with results of their seismic hazard (left) and vulnerability (right). Data is displayed on Esri World Imagery Basemap layer (Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community) with Esri World Reference layer (Source: Garmin, © OpenStreetMap contributors and the GIS User Community)

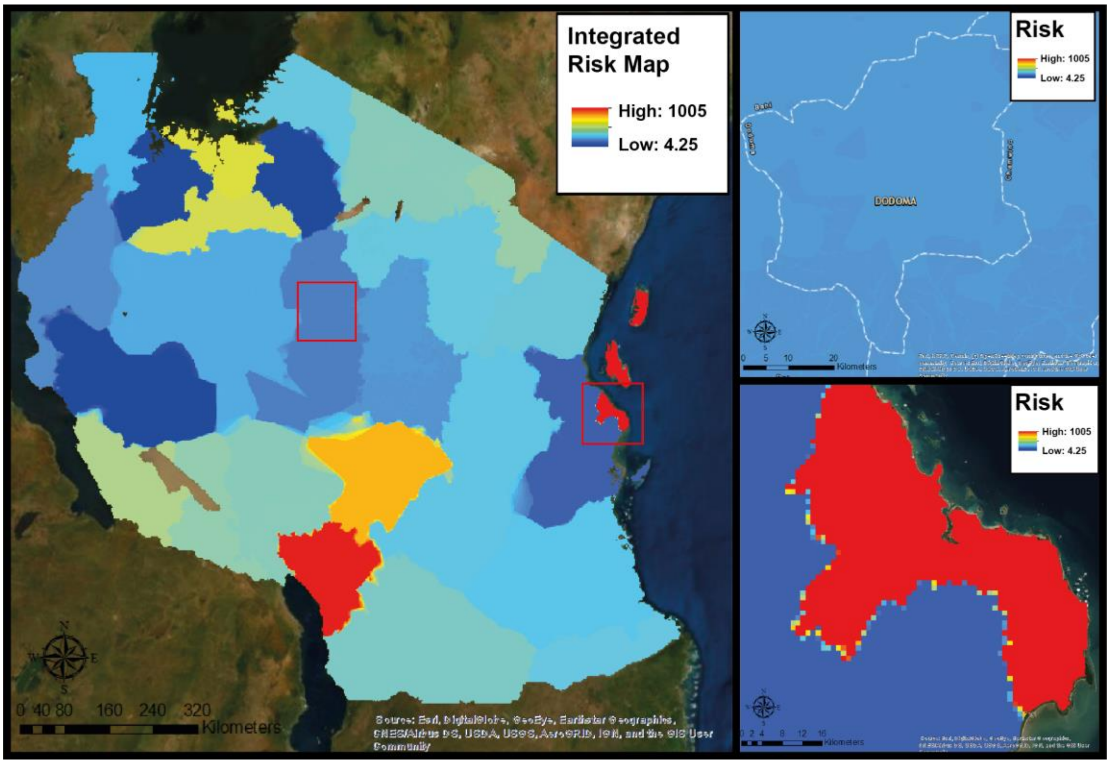

Figure 2: METEOR-derived Integrated Risk Map for Tanzania. Red squares highlight risk in Dar es Salaam (lower right) and Dodoma (upper right), Red circle marks the region of Iringa. Data is displayed on Esri World Imagery Basemap layer (Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community) with Esri World Reference layer (Source: Garmin, © OpenStreetMap contributors and the GIS User Community)

Whilst the products from both are useful in their own ways, we found that the spatial resolution of the final outputs from the Greiving model were too coarse for our purposes. Comparatively the Kappes method allowed us to retain the spatial resolution of the input data, but it produced a collection of separate hazard outputs, rather than an integrated multi-hazard product. As a consequence of this review, we proposed a model that incorporated components of both of these approaches and created a hybrid version, which retained the full resolution at a pixel scale and generated a single multi-hazard output. The framework of this model can be seen in Figure 3.

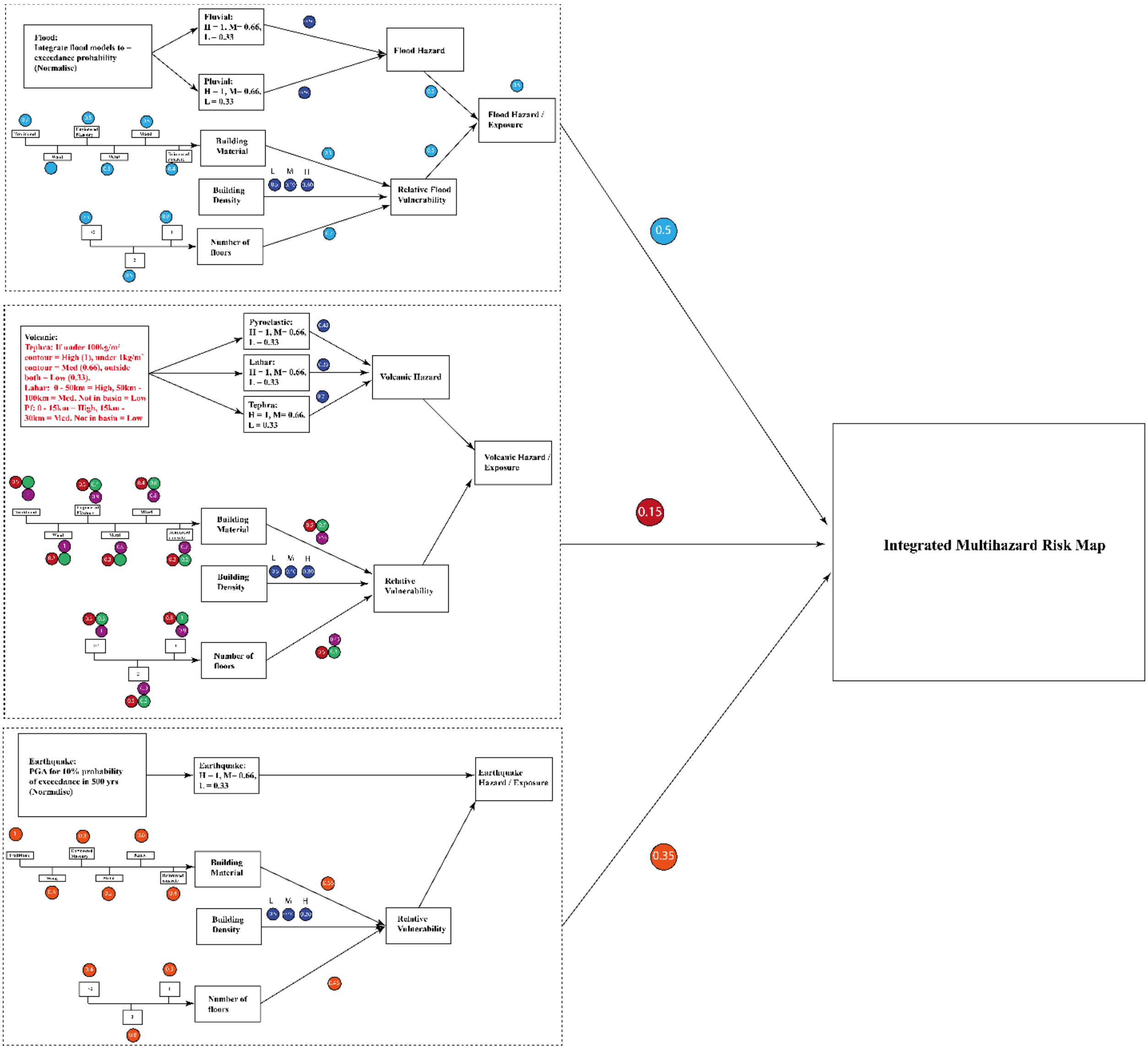

Figure 3: Proposed model framework for the METEOR multi-hazard and exposure methodology

In this report we present the protocols that we have developed to apply the METEOR to the Level 3 exposure data and the national hazard footprints for Nepal and Tanzania produced by the METEOR project.

2.2. MODELLING MULTI-HAZARDS

As discussed in Winson, *et al.* (2020), each single hazard addressed in the METEOR project has a different standardised unit of measurement for magnitude, which can create complexity when combining these data to generate a multi-hazard product. To account for this, we have created a semi-quantitative (or index-based) approach that allows for the continuous standardisation of differing and therefore not directly comparable factors, based on approaches from Kappes, *et al.* (2012) and Greiving (2006), as tested in Winson, *et al.* (2020). In this approach we have developed indices that are weighted to reflect the more likely impact of the hazard or a buildings vulnerability to the hazard.

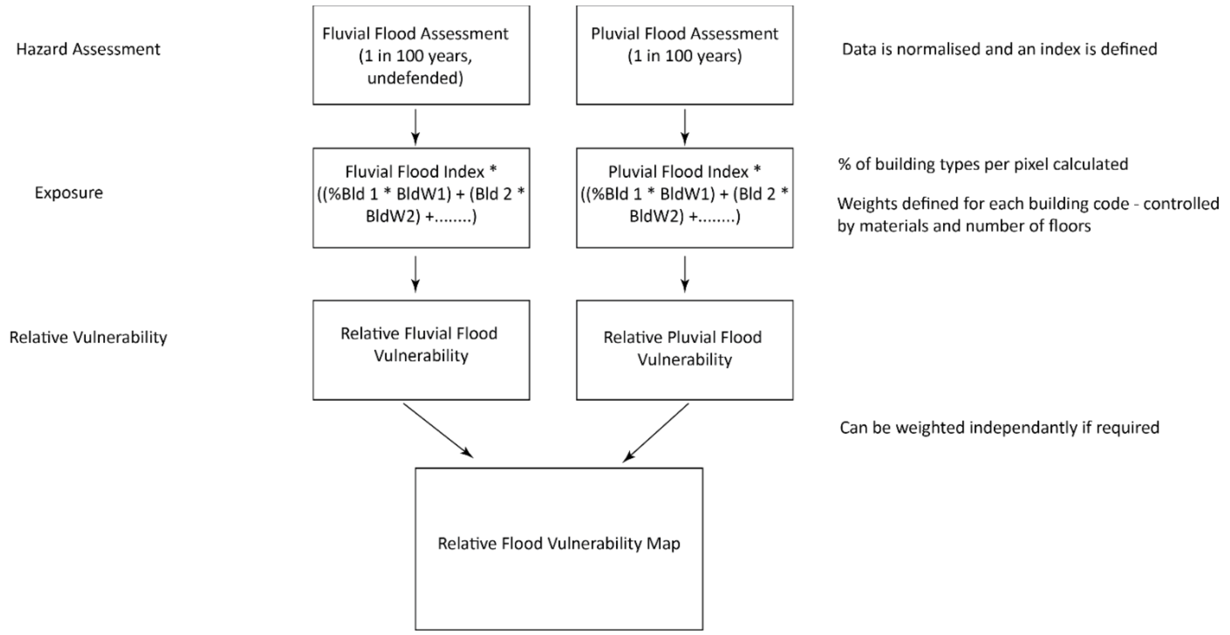

Figure 4: Schematic demonstrating the stages of the hazard component of the METEOR model. By the end of this process a 'relative' flood vulnerability map can be created.

The initial step in this model is to prepare a 'relative' hazard vulnerability map. For the purposes of this example, the steps necessary to produce a relative flood vulnerability map are shown (Figure 4). This process is broadly the same for each hazard.

Relative flood vulnerability mapping steps:

1) Each data point from the hazard assessment is normalised and then converted to a flood index value.
2) The Flood Index value per pixel is multiplied by the sum of the weighted percentage of each building type in that pixel (as a function of the total number of buildings per pixel). (Fluvial Flood Index * ((%Bld1 * BldW1) + (%Bld2* BldW2) + (%Bld3* BldW3) +…….))
3) If there is more than one output for a specific hazard (i.e. fluvial and pluvial flooding), these outputs are then weighted either through expert elicitation or, if necessary to reflect a frequency analysis of the hazard events and combined to produce a relative vulnerability map for that hazard, in this case flood.

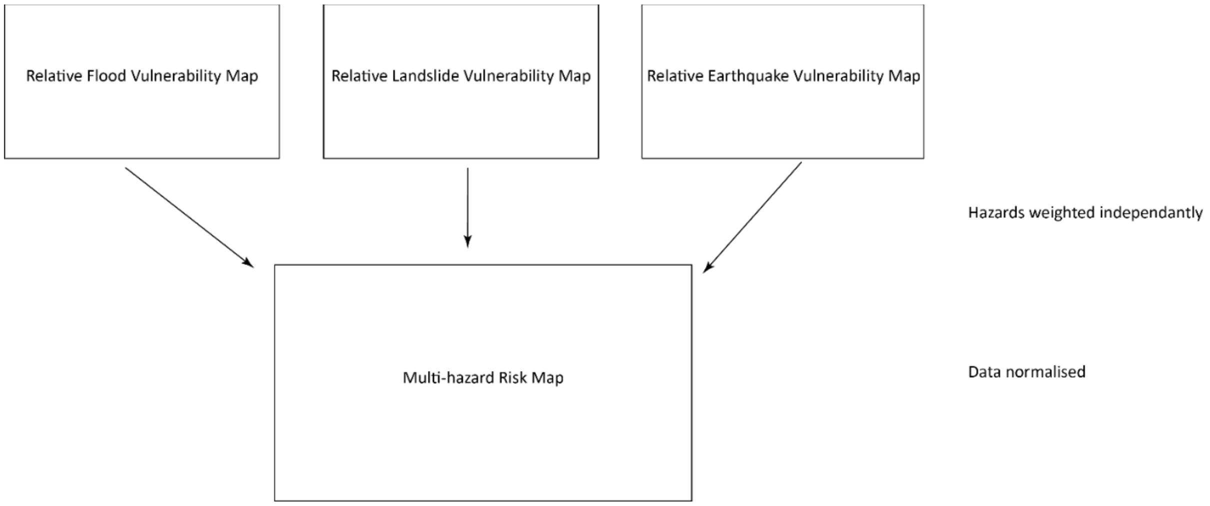

Figure 5: Schematic demonstrating combination of hazard vulnerability maps to produce multi-hazard risk map for Nepal.

Once the individual hazard vulnerability maps have been produced they can be weighted independently, combined and normalised (i.e. values are set to between 0 and 1) to create a national scale multi-hazard ‘risk’ map.

The methodology for the treatment of the hazard and exposure data is described further in sections 3 and 4.

2.3. HAZARDS

In this study every effort was made to produce the hazard assessment using a single DEM dataset with fixed grid resolution projection and origin point of the other input data. Due to the variable nature of the input data this was not always possible. In some cases it was necessary to re-project or resample data to ensure that when the layers were combined they matched exactly. The variations in this input data (Table 3) are predominantly due to cell size and spatial projection. It is likely that anyone re-producing this study for other locations will also need to align varying datasets, and so it is perhaps fortuitous that we have encountered this issue during the development of this methodology and have been able to demonstrate that incorporating data from different providers is indeed possible.

All modelling was undertaken in ArcGIS 10.3, which proved computationally intensive due to the size of the data sets (~3.5 million data points in Tanzania and ~1.5 million for Nepal). Where appropriate, models were built using the ArcGIS Model Builder tool allowing for a series of processes to be run at one time and to allow for data to be easily re-run if updated / for the different countries. The models are described in the following sections.

Country	Layer	Return Period	Type	Format	Native Spatial Reference	Units	Cell Size	Data Type
Nepal	Flooding: Pluvial	1 in 100 years	Raster	GeoTIFF	Geographic: WGS84	Decimal Degree	0.00083333333, 0.00083333333	32 Bit Floating Point
	Flooding: Fluvial Defended	1 in 100 years	Raster	GeoTIFF	Geographic: WGS84	Decimal Degree	0.00083333333, 0.00083333333	32 Bit Floating Point
	Flooding: Fluvial Undefended	1 in 100 years	Raster	GeoTIFF	Geographic: WGS84	Decimal Degree	0.00083333333, 0.00083333333	32 Bit Floating Point
	Seismic: PGA 0.1	10% probability of exceedance in 50 years	ASCII	CSV	Geographic: WGS84	Decimal Degree	n/a	n/a
	Landslide: Rainfall Triggered Hazard	n/a	Raster	FGDBR	Projected: WGS84 UTM Zone 45N	Metres	90 x 90	64-bit Double
	Landslide: Seismic Triggered Hazard	n/a	Raster	FGDBR	Projected: WGS84 UTM Zone 45N	Metres	90 x 90	64-bit Double
Tanzania	Flooding: Pluvial	1 in 100 years	Raster	GeoTIFF	Geographic: WGS84	Decimal Degree	0.00083333333, 0.00083333333	32 Bit Floating Point
	Flooding: Fluvial Defended	1 in 100 years	Raster	GeoTIFF	Geographic: WGS84	Decimal Degree	0.00083333333, 0.00083333333	32 Bit Floating Point
	Flooding: Fluvial Undefended	1 in 100 years	Raster	GeoTIFF	Geographic: WGS84	Decimal Degree	0.00083333333, 0.00083333333	32 Bit Floating Point
	Seismic: PGA 0.01	10% probability of exceedance in 50 years	Vector	Shapefile: point	Geographic: WGS84	Decimal Degree	n/a	n/a
	Seismic: PGA 0.01	10% probability of exceedance in 50 years	ASCII	CSV	Geographic: WGS84	Decimal Degree	n/a	n/a
	Volcanic: Ash fall VEI2 @ $1km^2$, $10km^2$, $100km^2$	n/a	Vector	Shapefile: point	Projected: WGS84 UTM Zone 36S	Metres	n/a	n/a
	Volcanic: Ash fall VEI4 @ $1km^2$, $10km^2$, $100km^2$	n/a	Vector	Shapefile: point	Projected: WGS84 UTM Zone 36S	Metres	n/a	n/a
	Volcanic: PDC Basins	n/a	Vector	Shapefile: polygon	Geographic: WGS84	Decimal Degree	n/a	n/a
	Volcanic: Lahar Basins	n/a	Vector	Shapefile: polygon	Geographic: WGS84	Decimal Degree	n/a	n/a

Table 3: Summary of different hazard data type, format and resolution for Nepal and Tanzania.

2.3.1. Earthquake

The seismic hazard assessment data produced by the Global Earthquake Model (GEM) was presented as a peak ground acceleration of 10% (PGA 0.1) or 2% (PGA 0.02) probability of exceedance in 50 years. For the purposes of developing this multi-hazard model, we used the PGA 0.1 layer. The model builder framework from ArcGIS can be seen in Figure 6. The first step in this model was to conduct a nearest neighbour interpolation, to convert the seismic data from point to raster data, so that it would be possible to incorporate it with the other hazard and exposure data later in the multi-hazard modelling process. After this interpolation was completed these data were normalised and reclassified to generate a seismic hazard index where: Low = 0 – 0.33, Medium = >0.33 – 0.66, High = >0.66 – 1.

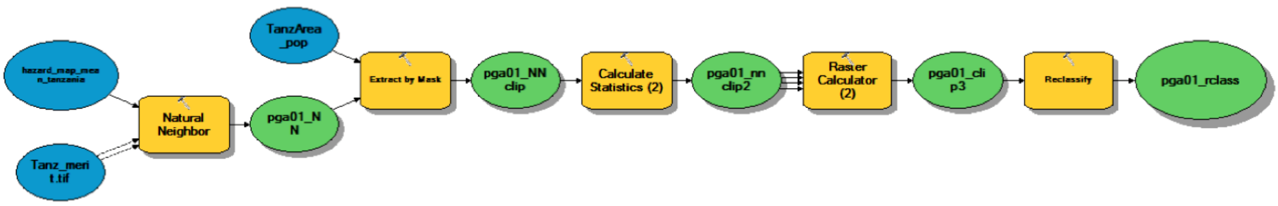

Figure 6: Schematic of the model builder tool developed to generate a seismic hazard index for Nepal and Tanzania.

2.3.2. Flood (Fluvial and Pluvial)

The data generated by Fathom for the flood hazard assessment shows the modelled depth for flood events of different return periods i.e. 1 in 5 yrs to 1 in 1000yrs, with depths shown in metres. More detail on the 48 footprints and their return periods can be found in the METEOR report on hazard footprints (Winson, *et al*., 2019). These return period simulations were prepared for fluvial and pluvial flooding. The fluvial models were generated to demonstrate the flooding potential of an event where all existing flood defences were effective (flood defended) and assuming that they all failed (flood undefended). Further details on this approach and its outputs can be found in Winson, *et al.* (2019), Sampson, *et al.* (2015), Smith, *et al.* (2015), Yamazaki, *et al.* (2017) and Yamazaki, *et al.* (2019).

For the purposes of developing the multi-hazard model we selected one each of the fluvial and pluvial outputs. After discussion we decided that the best layer to choose for this methodology testing would be the 1 in 100 year layer. This is because this return period is most commonly requested by decision makers. We also selected the flood undefended layer, as we felt that this would represent a worst-case scenario.

To begin, the flood hazard data was converted to an index so that it would be possible in later stages to compare flood data with that of other hazards. A representation of this model can be seen in Figure 7. The process first removed values associated with persistent water bodies, before the data layers were normalised. After this we assigned values as Low (0m), Medium (>0-0.5m) and High (>0.5m) reclassified as an index value between 1 (no data) and 4 (high).

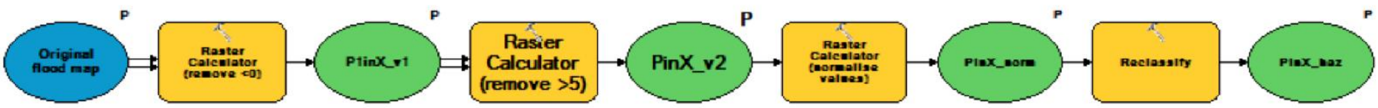

Figure 7: Schematic of the model builder tool developed to generate a flood hazard index for Nepal and Tanzania.

2.3.3. Landslide

The landslide susceptibility assessments prepared by the BGS landslide team (Winson, *et al*., 2019) were modified to include a landslide trigger, of either of rainfall or earthquake (Dashwood & Ciurean, 2020). The subsequent landslide hazard maps were used in this model. Each of these layers was normalised, then reclassified to generate a landslide hazard index where: Low = 0 – 0.33, Medium = >0.33 – 0.66, High = >0.66 – 1.

Figure 8: Schematic of the model builder tool developed to generate a landslide hazard index for Nepal.

2.3.4. Volcanic (Ash, Pyroclastic Density Currents, Lahar)

The primary volcanic hazards considered in the METEOR project are tephra fall (ash), pyroclastic density currents (PDCs) and lahars. Due to the sparsity of eruption history data available for Tanzania, it was not possible to produce tephra fall hazards for all of the volcanoes or to fully model the impact of PDC and lahars on the terrain surrounding the Tanzanian volcanoes. As a consequence of this, we have performed a tephra fall assessment for Rungwe (which has the most complete history) and a drainage basin analysis (after Aspinall, *et al.*, 2011) for all of the active volcanoes to assess potential PDC and lahar extent. More information about the approaches used by the BGS volcano group to generate this hazard assessment can be found in Winson, *et al.* (2019) and Winson, *et al.* (2020).

The model approach for incorporating the volcanic tephra data can be seen in Figure 9. Initially the tephra data were reclassified so that anything under 100kg/m^2 contour was given a value of 'High' (i.e. any point that fell between the 1kg/m^2 and the 100kg/m^2 contours), anything under the 1kg/m^2 contour was given a value of 'Medium' and everything else was valued as 'Low'.

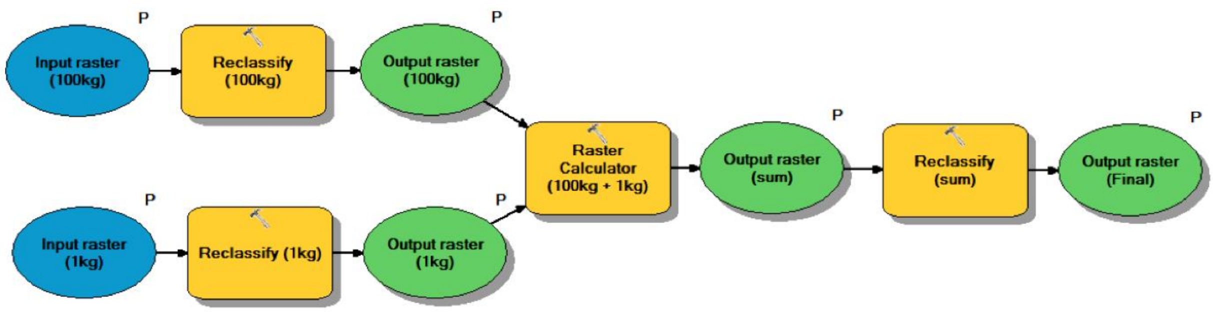

Figure 9: Schematic of the model builder tool developed to generate a tephra fall index for Tanzania.

To assess the possible hazard from PDCs and lahars we performed a drainage basin analysis which identifies regions of the DEM that are potential inundation zones for these hazards. To generate an index the model needs to identify whether a pixel falls within a PDC or lahar basin (Figure 10). If the pixel is within a PDC basin that is 0 – 15km from the summit of the volcano then it is assigned a 'High' hazard value (index value 4), if it is within a PDC basin that is 15 – 30km from the summit of the volcano then it is assigned a value of 'Medium' hazard (3). If a pixel does not fall within a PDC basin but does fall within 50km of the summit then a 'Low' (2) value is assigned. The reasoning behind these values is that, whilst PDCs can travel more than 15km from the summit of a volcano, these are generally lower frequency events than PDCs that travel shorter distances. If a pixel does not fall within a PDC basin, but does fall within a lahar basin that is 0 – 50km of the summit then it is assigned a 'High' (4) value. The 'Medium' (3) hazard pixels fall in a lahar basin 50 – 100km from the summit. If a pixel does not fall within the lahar basin but does fall within 200km of the summit it is assigned a low (2) value. Figure 11 shows how these data for PDCs and lahars are populated to their own union layers with the correct hazard descriptions and scores.

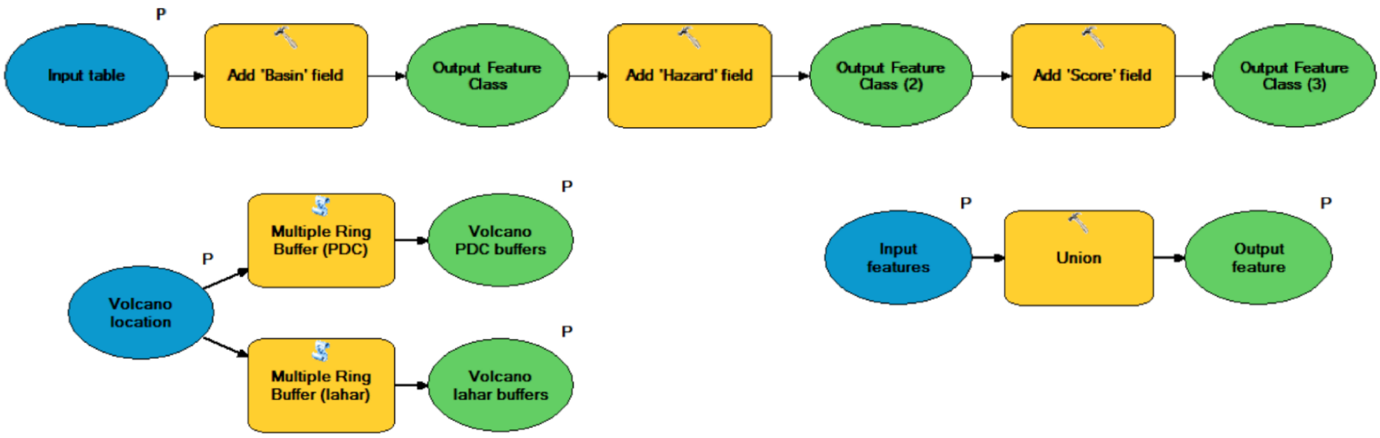

Figure 10: Model builder tool identifying volcanic flow basins.

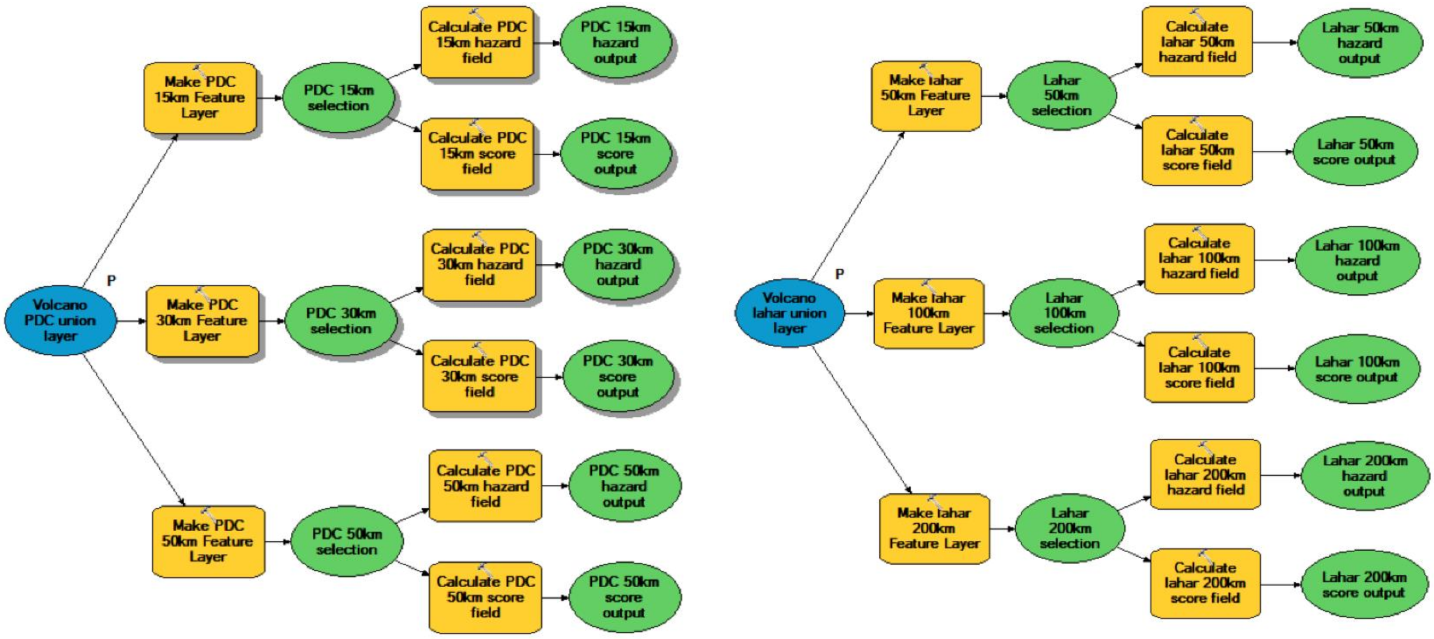

Figure 11: Schematic of model builder tools developed to generate index for PDC and Lahar hazard in Tanzania.

2.4. EXPOSURE

The exposure data for the METEOR project has been produced by ImageCat and the Humanitarian OpenStreetMap Team (HOT) as part of WP3 and WP4 respectively. The details of these data acquisition methods have been described in METEOR deliverables: M3.1/C: Classification of General Building Exposure Data[1]; M3.2/P: Exposure Data Classification, Metadata Population and Confidence Assessment (Huyck, *et al.,* 2019); M4.1/P: importing existing data into OSM (O'Hara, 2018a); M4.2/P: METEOR EO Mapping of Exposure (O'Hara, 2018b); and M4.3/P: Protocols for Crowd Sourcing Regional Exposure Data (O'Hara, 2019).

Very simply, the exposure data provided uses open source, freely available satellite data as a primary input. These data are then augmented with ground-based surveys of a sub-sample of buildings – conducted by Kathmandu Living Labs (Nepal) and Ramani Huria (Tanzania) for HOT.

These data show the total building count, the total building area and the total replacement cost value of the buildings per point. In this model the information from the total building counts has been used. For each pixel the number of different types of buildings was calculated as a percentage of the total number of buildings within that point. The way that a building responds to a specific hazard will be different, contingent on many factors. Weighting factors were defined in the model to account for this variation.

In many cases the approaches to model (multi) hazard with exposure have been developed for sub-national level at high resolution (for example studies by: Bell & Glade, 2004; Kappes, *et al.*, 2012; Papathoma, *et al.*, 2003; Papathoma-Köhle, *et al.*, 2007). Within METEOR, the inputs of the multi-hazard model are projected to a resolution of approximately 90m (or in some cases 3 arc seconds), it is therefore important to select building characteristics that can be identified at this scale and that are relevant for the hazards addressed in this study. The characteristics selected for this study were: building materials and number of floors. The ways in which these characteristics affect the vulnerability of a building will be specific to the hazard that they are subjected to, and so these must be weighted differently. For the purposes of this demonstration of the proposed methodology these weights have been taken, where possible, from existing literature or else derived by informal expert elicitation and review of the pertinent vulnerability curves (e.g. Auker, *et al.*, 2013; Blong, *et al.*, 2017; Kappes, *et al.*, 2012; Neri, *et al.*, 2000; Petrazzuoli & Zuccaro, 2004; Siebert, *et al.*, 2011; Silva & Pereira, 2014). The weights applied to the Nepal exposure data are shown in Table 4, for Tanzania see Table 5.

[1] METEOR M3.1C report is confidential

Nepal	Pluvial	Fluvial	Landslide - Rain	Landslide - Eq	Earthquake
Hazard Weight	0.165	0.165	0.165	0.165	0.33
CR/LFM/HBET:1,3 - Reinforced concrete moment frame (1-3 stories)	0.32	0.32	0.2	0.3	0.12
CR/LFM/HBET:4,7 - Reinforced concrete moment frame (4-7 stories)	0.2	0.2	0.1	0.15	0.32
CR/LFM/HBET:8,20 - Reinforced concrete moment frame (8-20 stories)	0.12	0.12	0.06	0.09	0.16
CR/LFINF+DNO/HBET:1,3 - Non-ductile reinforced concrete infilled frame (1-3 stories)	0.4	0.4	0.6	0.7	0.18
CR/LFINF+DNO/HBET:4,7 - Non-ductile reinforced concrete infilled frame (4-7 stories)	0.25	0.25	0.3	0.35	0.48
CR/LFINF+DNO/HBET:8,20 - Non-ductile reinforced concrete infilled frame (8-20 stories)	0.15	0.15	0.18	0.21	0.24
S - Steel	0.09	0.09	0.3	0.3	0.2
MUR+CB99/HBET:1,3 - Unreinforced concrete block masonry (1-3 stories)	0.4	0.4	0.4	0.5	0.09
MUR+CB99/HBET:4,7- Unreinforced concrete block masonry (4-7 stories)	0.25	0.25	0.2	0.25	0.24
W - Wood	0.8	0.8	0.3	0.3	0.09
MATO/LN - Informal constructions	0.56	0.56	0.6	0.7	0.3
MUR+ADO/HBET:1,3 - Unreinforced adobe masonry (1-3 stories)	0.56	0.56	0.6	0.7	0.3
MUR+CL99 - Unreinforced fired clay masonry	0.56	0.56	0.6	0.7	0.3
MUR+STRUB - Unreinforced rubble stone masonry	0.56	0.56	0.6	0.7	0.3
W+WWD - Wattle and Daub (Walls with bamboo/light timber log/reed mesh and post).	0.56	0.56	0.6	0.7	0.3

Table 4: Weights applied to Nepalese exposure data. These weights are calculated by considering: the type of building materials, how many floors the building has and the type of hazard.

As noted in Figure 4 the hazard index value per pixel is multiplied by the sum of the weighted percentage of each building type in that pixel to account for the differences in exposure and therefore vulnerability in each pixel. The equations to create each hazard vulnerability map output for the Nepalese data using the weights from Table 4 are shown in *Equation 1 - Equation 3*. The building codes in these equations are described in Table 4.

Equation 1: Relative earthquake vulnerability map - Nepal

Earthquake: ((%CR/LFM/HBET:1,3 * 0.12) + (%CR/LFM/HBET:4,7 *0.32) + (%CR/LFM/HBET:8,20 * 0.16) + (%CR/LFINF+DNO/HBET:1,3 * 0.18) + (%CR/LFINF+DNO/HBET:4,7 * 0.48) + (%CR/LFINF+DNO/HBET:8,20 * 0.24) + (%S*0.2) + (%MUR+CB99/HBET:1,3 * 0.09) + (%MUR+CB99/HBET:4,7 * 0.24) + (%W*0.09) + (%MATO/LN * 0.3) + (%MUR+ADO/HBET:1,3 *0.3) + (%MUR+CL99*0.3) + (%MUR+STRUB * 0.3) + (%W+WWD * 0.3))

Equation 2: Relative flood vulnerability map - Nepal

Fluvial: 0.5* ((%CR/LFM/HBET:1,3 * 0.32) + (%CR/LFM/HBET:4,7 *0.2) + (%CR/LFM/HBET:8,20 * 0.12) + (%CR/LFINF+DNO/HBET:1,3 * 0.4) + (%CR/LFINF+DNO/HBET:4,7 * 0.25) + (%CR/LFINF+DNO/HBET:8,20 * 0.15) + (%S*0.09) + (%MUR+CB99/HBET:1,3 * 0.4) + (%MUR+CB99/HBET:4,7 * 0.25) + (%W*0.8) + (%MATO/LN * 0.56) + (%MUR+ADO/HBET:1,3 *0.56) + (%MUR+CL99*0.56) + (%MUR+STRUB * 0.56) + (%W+WWD * 0.56))

+

Pluvial: 0.5*((%CR/LFM/HBET:1,3 * 0.32) + (%CR/LFM/HBET:4,7 *0.2) + (%CR/LFM/HBET:8,20 * 0.12) + (%CR/LFINF+DNO/HBET:1,3 * 0.4) + (%CR/LFINF+DNO/HBET:4,7 * 0.25) + (%CR/LFINF+DNO/HBET:8,20 * 0.15) + (%S*0.09) + (%MUR+CB99/HBET:1,3 * 0.4) + (%MUR+CB99/HBET:4,7 * 0.25) + (%W*0.8) + (%MATO/LN * 0.56) + (%MUR+ADO/HBET:1,3 *0.56) + (%MUR+CL99*0.56) + (%MUR+STRUB * 0.56) + (%W+WWD * 0.56))

Equation 3: Relative landslide vulnerability map - Nepal

Landslide - Rainfall: 0.5* ((%CR/LFM/HBET:1,3 * 0.2) + (%CR/LFM/HBET:4,7 *0.1) + (%CR/LFM/HBET:8,20 * 0.06) + (%CR/LFINF+DNO/HBET:1,3 * 0.6) + (%CR/LFINF+DNO/HBET:4,7 * 0.3) + (%CR/LFINF+DNO/HBET:8,20 * 0.18) + (%S*0.3) + (%MUR+CB99/HBET:1,3 * 0.4) + (%MUR+CB99/HBET:4,7 * 0.2) + (%W*0.3) + (%MATO/LN * 0.6) + (%MUR+ADO/HBET:1,3 *0.6) + (%MUR+CL99*0.6) + (%MUR+STRUB * 0.6) + (%W+WWD * 0.6))

+

Landslide - Eq: 0.5*((%CR/LFM/HBET:1,3 * 0.3) + (%CR/LFM/HBET:4,7 *0.15) + (%CR/LFM/HBET:8,20 * 0.09) + (%CR/LFINF+DNO/HBET:1,3 * 0.7) + (%CR/LFINF+DNO/HBET:4,7 * 0.35) + (%CR/LFINF+DNO/HBET:8,20 * 0.21) + (%S*0.3) + (%MUR+CB99/HBET:1,3 * 0.5) + (%MUR+CB99/HBET:4,7 * 0.25) + (%W*0.3) + (%MATO/LN * 0.7) + (%MUR+ADO/HBET:1,3 *0.7) + (%MUR+CL99*0.7) + (%MUR+STRUB * 0.7) + (%W+WWD * 0.7))

Tanzania	Pluvial	Fluvial	Tephra	Lahar	Pyroclastic	Earthquake
Hazard Weight	0.25	0.25	0.03	0.0525	0.0675	0.35
CR/LFM/HBET:1,3 - Reinforced concrete moment frame (1-3 stories)	0.32	0.32	0.3	0.06	0.56	0.12
CR/LFM/HBET:4,7 - Reinforced concrete moment frame (4-7 stories)	0.2	0.2	0.15	0.1	0.63	0.32
CR/LFM/HBET:8,20 - Reinforced concrete moment frame (8-20 stories)	0.12	0.12	0.09	0.06	0.7	0.16
CR/LFINF+DNO/HBET:1,3 - Non-ductile reinforced concrete infilled frame (1-3 stories)	0.4	0.4	0.4	0.6	0.64	0.18
CR/LFINF+DNO/HBET:4,7 - Non-ductile reinforced concrete infilled frame (4-7 stories)	0.25	0.25	0.2	0.3	0.72	0.48
CR/LFINF+DNO/HBET:8,20 - Non-ductile reinforced concrete infilled frame (8-20 stories)	0.15	0.15	0.12	0.18	0.8	0.24
S - Steel	0.09	0.09	0.09	0.3	0.9	0.2
MUR+CB99/HBET:1,3 - Unreinforced concrete block masonry (1-3 stories)	0.4	0.4	0.5	0.4	0.72	0.09
MUR+CB99/HBET:4,7- Unreinforced concrete block masonry (4-7 stories)	0.25	0.25	0.25	0.2	0.81	0.24
W - Wood	0.8	0.8	0.2	1	0.8	0.09
MATO/LN - Informal constructions	0.56	0.56	0.6	1	0.8	0.3
MUR+ADO/HBET:1,3 - Unreinforced adobe masonry (1-3 stories)	0.56	0.56	0.6	1	0.8	0.3
MUR+CL99 - Unreinforced fired clay masonry	0.56	0.56	0.6	1	0.8	0.3
MUR+STRUB - Unreinforced rubble stone masonry	0.56	0.56	0.6	1	0.8	0.3
W+WWD - Wattle and Daub (Walls with bamboo/light timber log/reed mesh and post).	0.56	0.56	0.6	1	0.8	0.3

Table 5: Weights applied to Tanzanian exposure data. These weights are calculated by considering: the type of building material, how many floors the building has and the type of hazard.

The equations to create each hazard vulnerability map output for Tanzania using the weights from Table 5 are shown in *Equation 4- Equation 6*. The building codes in these equations are described in Table 5.

Equation 4: Relative earthquake vulnerability map - Tanzania

((%CR/LFM/HBET:1,3 * 0.12) + (%CR/LFM/HBET:4,7 *0.32) + (%CR/LFM/HBET:8,20 * 0.16) + (%CR/LFINF+DNO/HBET:1,3 * 0.18) + (%CR/LFINF+DNO/HBET:4,7 * 0.48) + (%CR/LFINF+DNO/HBET:8,20 * 0.24) + (%S*0.2) + (%MUR+CB99/HBET:1,3 * 0.09) + (%MUR+CB99/HBET:4,7 * 0.24) + (%W*0.09) + (%MATO/LN * 0.3) + (%MUR+ADO/HBET:1,3 *0.3) + (%MUR+CL99*0.3) + (%MUR+STRUB * 0.3) + (%W+WWD * 0.3))

Equation 5: Relative flood vulnerability map - Tanzania

Fluvial: 0.5* ((%CR/LFM/HBET:1,3 * 0.32) + (%CR/LFM/HBET:4,7 *0.2) + (%CR/LFM/HBET:8,20 * 0.12) + (%CR/LFINF+DNO/HBET:1,3 * 0.4) + (%CR/LFINF+DNO/HBET:4,7 * 0.25) + (%CR/LFINF+DNO/HBET:8,20 * 0.15) + (%S*0.09) + (%MUR+CB99/HBET:1,3 * 0.4) + (%MUR+CB99/HBET:4,7 * 0.25) + (%W*0.8) + (%MATO/LN * 0.56) + (%MUR+ADO/HBET:1,3 *0.56) + (%MUR+CL99*0.56) + (%MUR+STRUB * 0.56) + (%W+WWD * 0.56))

+

Pluvial: 0.5*((%CR/LFM/HBET:1,3 * 0.32) + (%CR/LFM/HBET:4,7 *0.2) + (%CR/LFM/HBET:8,20 * 0.12) + (%CR/LFINF+DNO/HBET:1,3 * 0.4) + (%CR/LFINF+DNO/HBET:4,7 * 0.25) + (%CR/LFINF+DNO/HBET:8,20 * 0.15) + (%S*0.09) + (%MUR+CB99/HBET:1,3 * 0.4) + (%MUR+CB99/HBET:4,7 * 0.25) + (%W*0.8) + (%MATO/LN * 0.56) + (%MUR+ADO/HBET:1,3 *0.56) + (%MUR+CL99*0.56) + (%MUR+STRUB * 0.56) + (%W+WWD * 0.56))

Equation 6: Relative volcanic vulnerability map - Tanzania

Tephra: 0.2 * ((%CR/LFM/HBET:1,3 * 0.3) + (%CR/LFM/HBET:4,7 *0.15) + (%CR/LFM/HBET:8,20 * 0.09) + (%CR/LFINF+DNO/HBET:1,3 * 0.4) + (%CR/LFINF+DNO/HBET:4,7 * 0.2) + (%CR/LFINF+DNO/HBET:8,20 * 0.12) + (%S*0.09) + (%MUR+CB99/HBET:1,3 * 0.5) + (%MUR+CB99/HBET:4,7 * 0.25) + (%W*0.2) + (%MATO/LN * 0.6) + (%MUR+ADO/HBET:1,3 *0.6) + (%MUR+CL99*0.6) + (%MUR+STRUB * 0.6) + (%W+WWD * 0.6))

+

Lahar: 0.35 * ((%CR/LFM/HBET:1,3 * 0.06) + (%CR/LFM/HBET:4,7 *0.1) + (%CR/LFM/HBET:8,20 * 0.06) + (%CR/LFINF+DNO/HBET:1,3 * 0.6) + (%CR/LFINF+DNO/HBET:4,7 * 0.3) + (%CR/LFINF+DNO/HBET:8,20 * 0.18) + (%S*0.3) + (%MUR+CB99/HBET:1,3 * 0.4) + (%MUR+CB99/HBET:4,7 * 0.2) + (%W*1) + (%MATO/LN * 1) + (%MUR+ADO/HBET:1,3 *1) + (%MUR+CL99*1) + (%MUR+STRUB * 1) + (%W+WWD * 1))

+

Pf: 0.45 * ((%CR/LFM/HBET:1,3 * 0.56) + (%CR/LFM/HBET:4,7 *0.63) + (%CR/LFM/HBET:8,20 * 0.7) + (%CR/LFINF+DNO/HBET:1,3 * 0.64) + (%CR/LFINF+DNO/HBET:4,7 * 0.72) + (%CR/LFINF+DNO/HBET:8,20 * 0.8) + (%S*0.9) + (%MUR+CB99/HBET:1,3 * 0.72) + (%MUR+CB99/HBET:4,7 * 0.81) + (%W*0.08) + (%MATO/LN * 0.8) + (%MUR+ADO/HBET:1,3 *0.8) + (%MUR+CL99*0.8) + (%MUR+STRUB * 0.8) + (%W+WWD * 0.8))

3. Results

The aim of the work detailed in this report was: to test the METEOR multi-hazard methodology proposed in Winson, *et al.* (2020) using the national hazard and exposure data sets for both Nepal and Tanzania, to evaluate if it is computationally possible to run a model such as this at a resolution of c.90m, and to analyse the model results to ensure that they are consistent. The very large data sets associated with both the hazard and exposure data have made working with these data challenging. This coupled with the restrictions imposed due to remote working in light of the COVID-19 pandemic has meant that preparing and running these models has taken considerably longer than expected. The process of developing ArcGIS model builder tools also took longer than expected, this was due to an under-estimation of the required time scales when handling a data set this large, as well as the time added by conducting these processes remotely. However, it is beneficial that now that the model builder tools have been created it will be possible to use them to re-run portions of this model (if necessary) or indeed to model data from other locations more rapidly. As a consequence of these limitations, the analysis of these outputs and their sensitivity will come later and will be reported in detail in METEOR report M6.4/C.

Example data results are shown for both Nepal (Figure 12) and Tanzania (Figure 13 and Figure 14). These maps have been created from the normalised vulnerability score for multi-hazards data. However, this is just a small component of the data that has been created in the modelling process. Appendix A and Appendix B show the full metadata available from the modelling of the Nepalese and Tanzanian data, respectively. These products could be analysed in a variety of ways in the future, some of which we are proposing in Section 4 of this report, to be detailed in deliverable M6.4/C. The full data sets have been delivered in in ESRI ArcGIS format alongside this report.

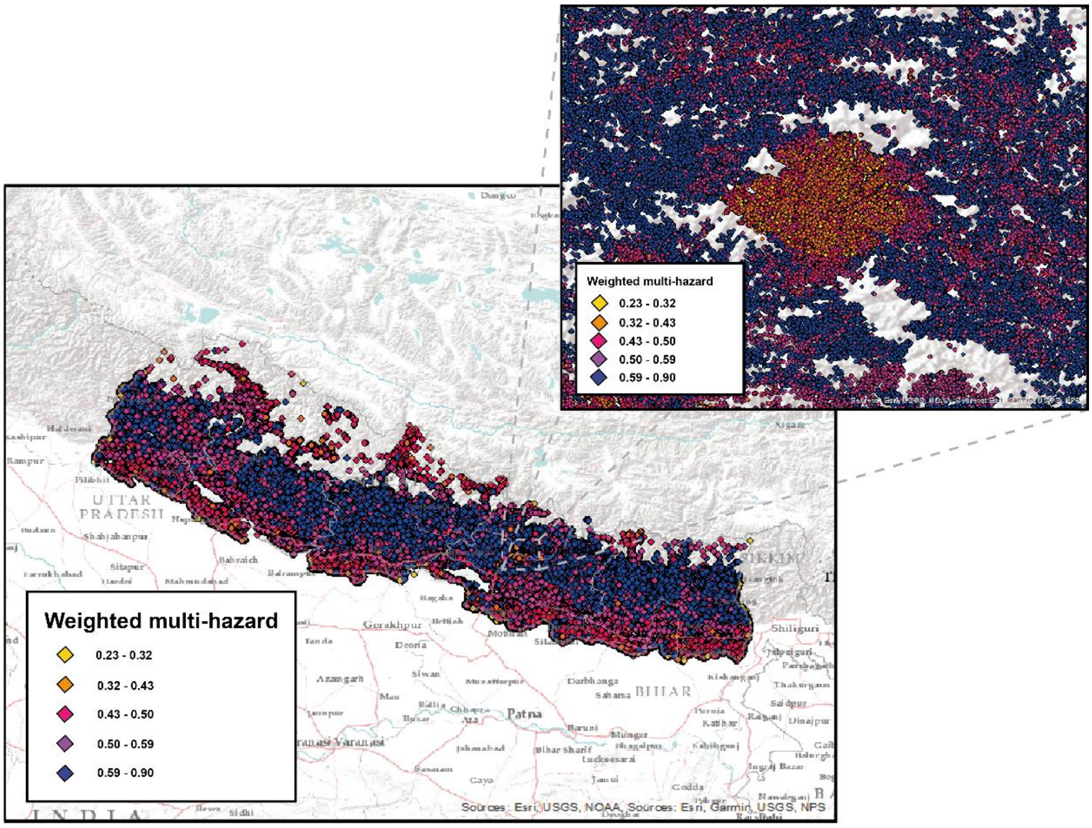

Figure 12: Weighted multi-hazard risk for Nepal. Inset box shows detail in Kathmandu. Data displayed on ESRI World Terrain Basemap layer (Source: Sources: Esri, USGS, NOAA) with Esri World Terrain Reference Layer (Sources: Esri, Garmin, USGS, NPS)

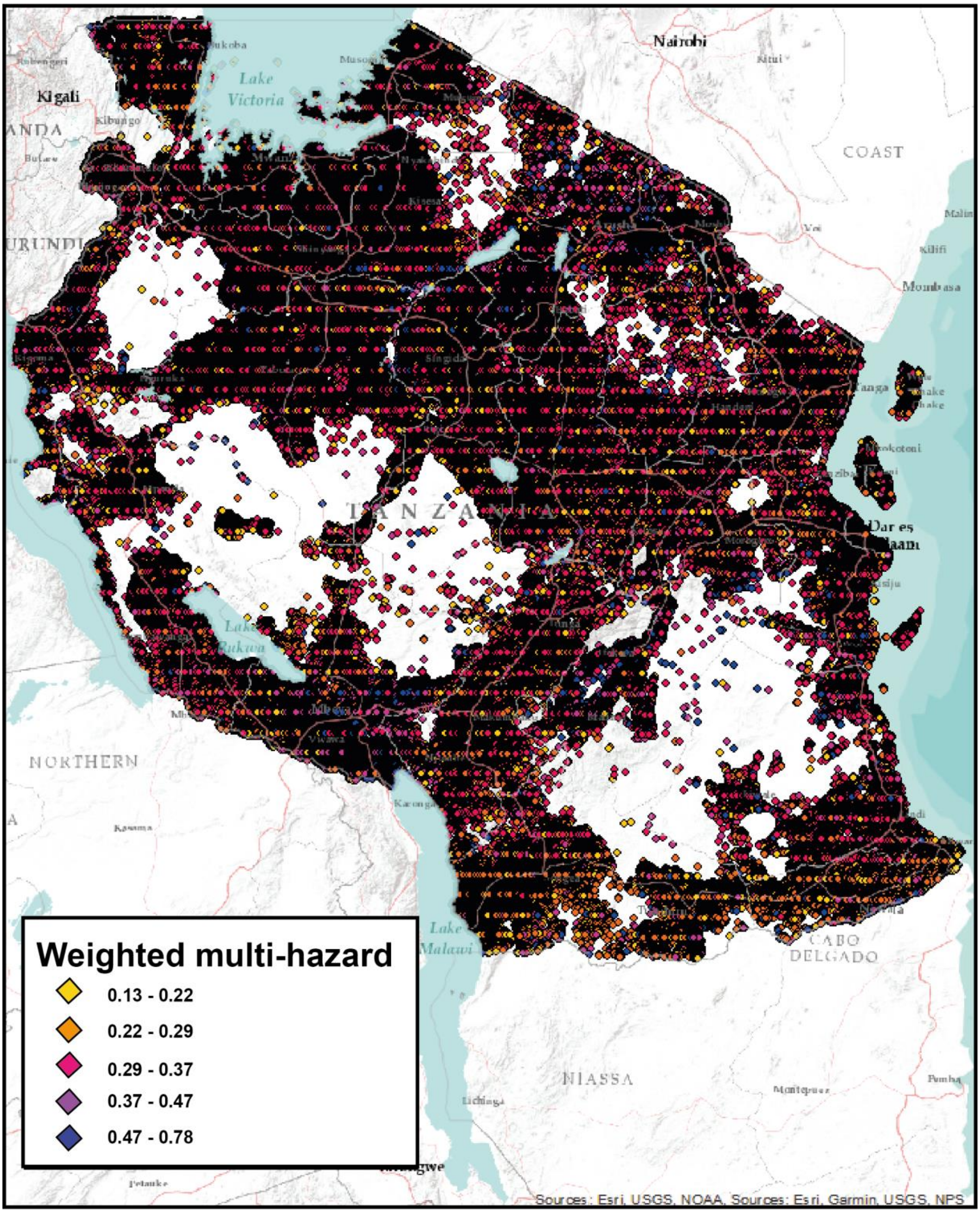

Figure 13: Weighted multi-hazard risk for Tanzania. Data displayed on ESRI World Terrain Basemap layer (Source: Sources: Esri, USGS, NOAA) with Esri World Terrain Reference Layer (Sources: Esri, Garmin, USGS, NPS)

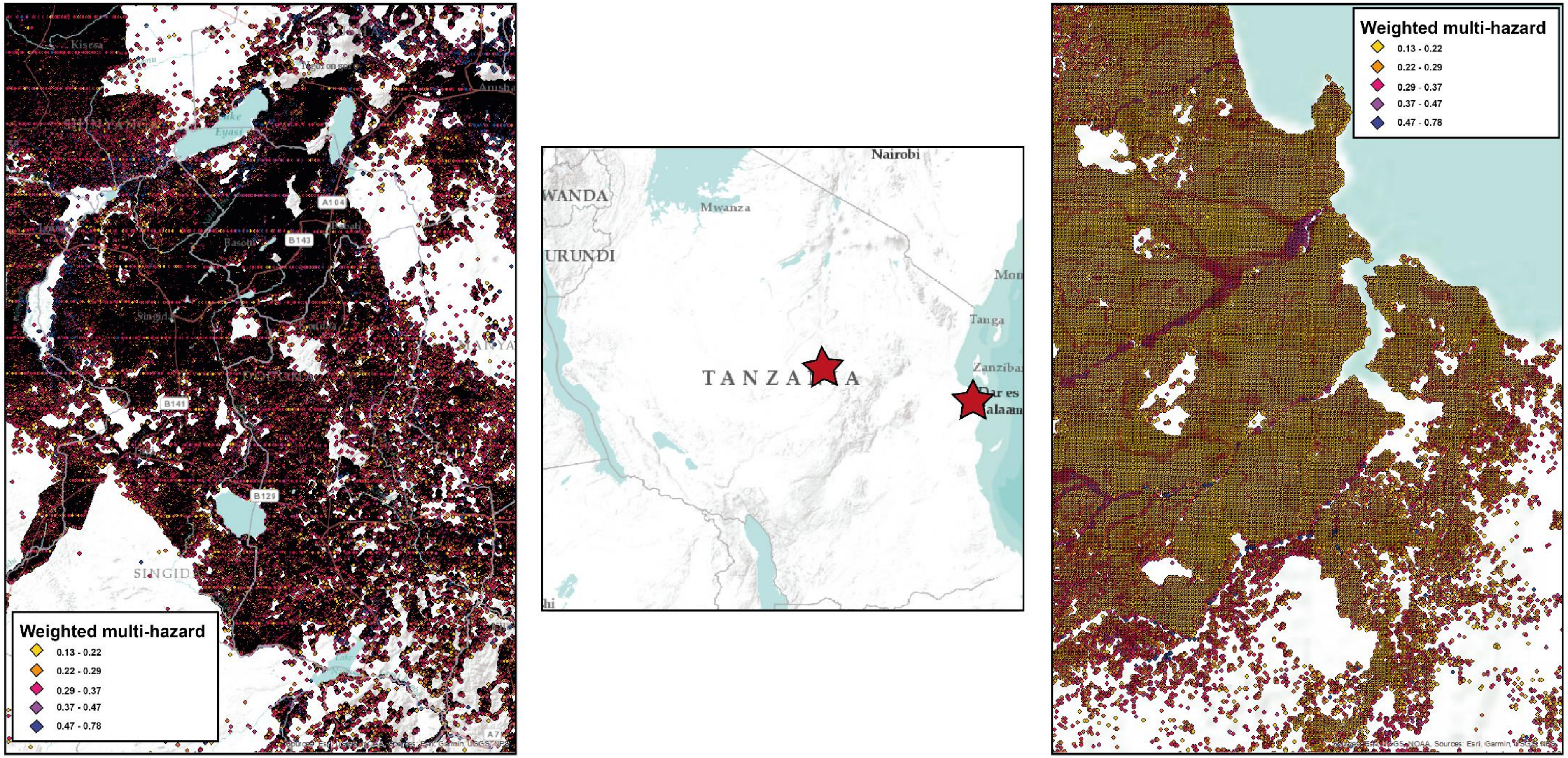

Figure 14: Weighted multi-hazard risk for Dodoma (left) and Dar es Salaam (right). Data displayed on ESRI World Terrain Basemap layer (Source: Sources: Esri, USGS, NOAA) with Esri World Terrain Reference Layer (Sources: Esri, Garmin, USGS, NPS)

4. Further Work – Work Package 6

In creating this model we aimed to develop a pragmatic approach to integrate data sets that differ widely from each other. Combining data, however, that has been generated by different processes, incorporates uncertainty into the model. As these data by their nature, are often incomplete this can mean that the uncertainty of the product is difficult to quantify. There can be several sources of uncertainty: we assume that when the hazard assessments were produced the physical processes that they represent were fully understood and free from data bias. However, we know that in reality it is very difficult to capture this in a model. We also know that some of the inventories we used to generate the hazard assessments were incomplete, this can be seen clearly in the eruption history data and is why the volcanology assessment is of a coarse resolution. Every effort has been made in this assessment to generate a model that is as accurate as the input data and the understanding of the physical systems allows, but it is likely that there is still an uncertainty in this that is so far, not quantified. It is therefore important to explore this using error analysis and determine which model parameters have the greatest influence on the modelled results by conducting a sensitivity analysis.

4.1. SENSITIVITY ANALYSIS

Initially we proposed that the best way to assess this uncertainty would be through a Monte Carlo approach, as outlined in the METEOR report on the methods for analysing multi-hazards with exposure (Winson, *et al.* 2020). As stated, a Monte Carlo method would allow us to assess how the variables such as the weighting factors control each of the final outputs by applying an algorithm that computes solutions by performing iterations with different sets of random numbers. This would also help to identify areas where an increase in baseline knowledge would have the greatest impact on the overall understanding of risk. Given the computational time needed to prepare the model thus far, it may be that a Monte Carlo approach of the entire data set may not be possible in the time available. Instead, we suggest a straight-forward sensitivity analysis, which would examine the effects of varying model parameters on the final outputs of the model. Here we would vary one model parameter at a time in a systematic way and see if a small change in a parameter resulted in a large change on the model outputs, by looking at residuals between the two final products. Assessing the difference in these outputs will allow us to infer the robustness of the current METEOR model and identify the inputs that have the greatest control on the final outputs. This approach would also allow us to explore which criteria, such as the weights assigned to the exposure data or the threshold values that were assigned when creating the index for the hazard assessment data, have a higher control on the final vulnerability.

4.2. VALIDATION OF WEIGHTING VALUES

The weighting values displayed in Table 4 and Table 5 were derived through a combination of expert elicitation, harvesting from existing literature and reviewing available vulnerability curves. They form what we propose is a best estimate of the weights that should be attached to different building criteria and different types of hazard. It is clear, however, that effort should be made to validate these figures, as they have the potential to strongly affect the outcome of the overall model.

To that end we propose the following assessment: a small area of each study country will be selected, ideally where the exposure data is augmented by the ground surveys (i.e. in Kathmandu and Dar es Salaam). In this area we will select the vulnerability curves that are most representative of the various building types in those points. These vulnerability curves will be translated into look up tables, so that when a specific hazard value (i.e. PGA) is reported it can be matched to the exact exceedance probability for that building type and this value used to weight that specific building in that specific point. Due to the way that the hazard data is generated this model approach will be taken to address the earthquake and flooding hazards. This process will be conducted for all building types in all of the points in the subset. The outputs of this approach can then be compared to the outputs from the original model format and analysed for variance. It is likely that this approach will be computationally expensive, which is why the test will be limited to a small area.

We also plan to assess the impact of varying the hazard assessments and their subsequent weights. To do this we will explore the differences in outputs when the 1 in 10 year and 1 in 1000 year flood hazard data are included (instead of the 1 in 100 year return period). This will provide a sense of what the difference between a ‘worst’ case and ‘best’ case outputs are. We could also explore the vulnerability of specific building classes to single and multi-hazards independently to try to identify the types of interventions that might have the greatest impacts in decreasing the vulnerability of certain types of buildings.

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