METEOR: Methods for Analysing Multi-Hazards with Exposure

Report Number: M6.2/P

16 January 2020

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Document Verification

Project	METEOR: Modelling Exposure Through Earth Observation Routines
Report Title	Methods for Analysing Multi-Hazards with Exposure
Related Milestone	M6.2
Reference as	Winson, A. & Jordan, C. (2020) METEOR: Methods for Analysing Multi-hazards with Exposure. Report M6.2/P
Release Type	Public / ~~Confidential~~ / ~~Confidential with Embargo Period~~

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Name:	Signature:	Date:

Date	Version	Alterations	Editor

Glossary

Term	**Descriptor**
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
DMD	Disaster Management Department: Prime Minister's Office of Tanzania focused on disaster risk
DRM	Disaster Risk Management
DTM	Digital Terrain Model
EO	Earth Observation
Fathom	Provides innovative flood modelling and analytics, based on extensive flood risk research
GCRF	Global Challenges Research Fund
GDP	Gross Domestic Product
GEM	Global Earthquake Model: Non-profit organisation focused on the pursuit of earthquake resilience worldwide
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 the global risk and catastrophe management needs of the insurance industry, governments and NGOs
IPP	International Partnership Programme
IR	Integrated Risk
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

Term	Descriptor
OPM	Oxford Policy Management : Organisation focused on sustainable project design and implementation for reducing social and economic disadvantage in low-income countries
PTVA	Papathoma Tsunami Vulnerability Assessment
RVI	Relative Vulnerability Index
SFDRR	Sendai Framework for Disaster Risk Reduction
UKSA	United Kingdom Space Agency
UNDRR	United Nations Office for Disaster Risk Reduction
UNEP	United Nations Environment Programme
VI	Vulnerability Indicator
WP	Work Package

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1. METEOR Project Introduction

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 (DMD), 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

Table 1: METEOR Project Summary

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 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. The associated 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 (Table 2). These are led by various partners, with a brief description of what each of the work packages cover provided in Table 2. BGS is leading WP.6: Multiple Hazard impact, which focuses on the multiple hazard impacts on exposure and how they may be addressed in disaster risk management by a range of stakeholders.

Table 2: Overview of METEOR Work Packages

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.

1.5. Multiple Hazard Impact

The project WP6 led by BGS is broken down into 4 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 impact on exposure (Table 3).

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

Table 3: Overview of BGS Deliverables

2. Developing models for analysing multiple hazards with exposure

Focusing on Tanzania and Nepal, METEOR has developed exposure protocols and data and hazard assessments at national scale. To support Disaster Risk Management and prepositioning decisions it is important to develop frameworks for aggregating these varied data sets, reflecting the complexities of multiple hazard exposure and their effect on vulnerability. Risk is often characterised using the equation:

Equation 1 $$E \times H \times V = Risk$$

Where E is exposure, H is hazard and V is vulnerability. METEOR is addressing the three functions in this equation. This report outlines our research into the challenge of characterising multi-hazards as well as single hazards. In this study we review existing multi-hazard methodologies and select two to test using available METEOR data. Finally, based on this assessment, we present a framework that will be used to model and analyse the hazard and exposure data produced as part of the METEOR project.

2.1. Understanding multi-hazards

The United Nations Office for Disaster Risk Reduction (UNDRR) define a hazard as the '*process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation*'. There are many models that have been developed to assess single hazards (e.g. Biass et al., 2016; Connor et al., 2017; Giardini et al., 1999; Lari et al., 2014; Sampson et al., 2015; Schilling, 1998; Sheirdan et al., 2005; Strauch et al., 2019 – and many others). These models vary, but fundamentally they make an attempt to quantify the nature, intensity and return period of specific hazards. Multi-hazards can occur simultaneously, cascadingly or cumulatively over time, and are defined as:

> "***Multi-hazard*** *means (1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects" – UNDRR (2019)*

Each single hazard has a different standardised unit of measurement for its magnitude and it is this lack of common standardisation that can make multi-hazard assessments complex (Kappes et al., 2012b). The different process characteristics and the interactions between hazards mean that methodologies for assessing multiple hazards are scarcer than those designed for assessing single hazards. As a consequence there are not, as yet, well defined standard models.

The importance of multi–hazards has been recognised for some time. In 1992, the United Nations Environment Programme (UNEP) stated that per-disaster planning should form an integral part of human settlement planning and that it should include the "*Undertaking of complete multi-hazard research into risk and vulnerability of human settlements and settlement infrastructure, including* *water and sewerage, communication and transportation networks, as one type of risk reduction may increase vulnerability to another (e.g., an earthquake-resistant house made of wood will be more vulnerable to wind storms*" (UNEP, 1992). Furthermore, the 2015-2030 Sendai Framework for Disaster Risk Reduction (SFDRR) recognises that "Disaster risk reduction practices need to be multi-hazard and multisectoral, inclusive and accessible in order to be efficient and effective". In practice multi-hazard assessments are complicated by:

1) The differences between hazard characteristics and therefore the methods used to analyse them;
2) Hazards can be related to each other, and cumulative (cascades);
3) The impacts on elements at risk can be different for differing hazards and occasionally opposing;
4) Any of the existing measures of risk quantification need to be adapted to allow for comparison of multiple risks (Kappes et al., 2012b).

These complexities have led to the development of contrasting methodologies for assessing multi-hazards. These methods can be broadly categorised as: Qualitative, Semi-Quantitative, and Quantitative. Qualitative methods are concerned with the classification of hazards and vulnerability, which can then be combined to give the resultant risk. This method creates compatibility between the hazard and vulnerability classes but also results in equivalence of all the single hazard classes, which may not reflect the frequency distribution of these hazards (Papathoma-Köhle et al., 2011). Semi–Quantitative, or index-based methods allow for the continuous standardisation of differing and therefore not directly comparable parameters (Kappes et al., 2012b). This is often achieved by developing indices that can then be uniquely weighted to reflect the more likely impact of the hazard or vulnerability class (Greiving, 2006). Quantitative methods result in the calculation of absolute values on a determined scale. These therefore provide the most statistically robust information on potential damage or losses and are therefore predominantly developed by the re-insurance industries (Kappes et al., 2012b).

Each hazard exhibits various characteristics such as: time of onset; duration; and extent. The impact of this on humans and elements at risk needs to be considered as part of a multi-hazard vulnerability assessment. In developing a methodology for METEOR it has been necessary to consider: the range of hazards in various locations across the country, hazardous events that have the potential to occur simultaneously but have entirely different causes (e.g. a volcanic eruption occurring at the same time as a drought), and cascading hazards where a primary hazard triggers a secondary hazard (e.g. a seismic event triggering landslides). In fact, multi–hazard interactions may occur spatially and/or temporarily. This means that there are at least four possible combinations for hazard interactions (Table 4).

Type	Interaction	Implications for
Only Spatial	Hazards of different sources occurring in the same location at different times.	Building codes / design of mitigation measures. It is possible that an effort to stabilize an element at risk for one hazard may destabilize it in reference to another.
Neither spatial nor temporal	Different hazards occurring in different locations at different times.	No importance to physical vulnerability but may have implications for the awareness and education of the population and their behavior.
Spatially and temporally	Hazards that occur at the same location at the same time. These may trigger each other (e.g. and earthquake causing widespread landslides) or they may simply be simultaneous.	Understanding the implications of cascading or simultaneous hazards on buildings, response, pre-positioning etc. An area defined as low hazard for a single hazard may be more exposed in the event of multiple hazards occurring at the same time, or exacerbated by each other.
Only temporally	Hazards that occur at the same time but in different locations.	Emergency planners (national / government), as they may be called upon to manage two events from separate administrative units simultaneously.

Table 4: Spatial and temporal interactions of hazards. Whether hazards interact spatially or temporarily will have implications for specific end users

2.2 Analysing vulnerability

If the aim of a multi-hazard assessment is to allow for some quantification of risk (as is the case for METEOR) then this hazard information must be coupled with exposure and vulnerability information. It is therefore necessary to have some understanding of how vulnerability is assessed. There are three major methods that are currently used for the analysis of physical vulnerability: (i) fragility curves / damage curves; (ii) damage matrices; and (iii) physical vulnerability indicators.

(i) Fragility curves / damage curves are dominantly used by engineers. They provide the conditional probability that a given building (or group of buildings) will reach or exceed a certain level of damage severity as a function of the hazard intensity (Peduto et al., 2007). From here it is possible to calculate a projected cost of repair/replacement and therefore to develop a cost benefit ratio that allows the user to decide on the practicalities of procedures such as retrofitting (Kappes et al., 2012b). The National Society for Earthquake Technology (NSET) in Nepal, for example, use these kinds of methods to advise the population on retrofitting versus demolishing and rebuilding. It is their practice to advise retrofitting if the analysis demonstrated that the cost of this will be less than 30% of the reconstruction cost. Damage curves are considered the state of the art as they make an explicit, quantitative connection between hazards, vulnerability and damage (Menoni, 2006) and are therefore extremely useful tools. The limitations of fragility / damage curves tends to be that they are generally only constructed for one characteristic, i.e. they may take into account building material but not number of floors (Kappes et al., 2012a). They are also usually only designed to address a single hazard type and a single hazard event, and so are less useful when considering either spatial or temporal (cascading) multi-hazards. These damage curves need inputs from either numerical modelling and/or the collection of information from a large number of damaged buildings. This means that it can be computationally expensive and/or time consuming to produce them. In this study we make use of the Global Earthquake Model Foundation (GEM) repository for damage curves to help inform the expert elicitation of the weighted values for both models [1].

(ii) Damage matrices are simpler than damage curves, and link observed damage to a specific level of hazards intensity and to predetermined typologies of buildings or facilities (Menoni, 2006). These matrices allow for flexibility as they can be a simple qualitative comparison of hazard and vulnerability or they can include more semi-quantitative information if and when it is available.

(iii) Physical vulnerability indicators are more qualitative tools that are often used in socio-economic assessments but have been used less widely in the physical vulnerability context (Kappes et al., 2012b). This is because the development of an overall multi-hazard model is complicated by the differences between hazards. An example of a method that considers vulnerability indicators to carry out a physical vulnerability analysis is the Papathoma Tsunami Vulnerability Assessment (PTVA), which was originally designed for tsunami prone areas (Papathoma et al., 2003). This model calculates the vulnerability of individual buildings within the inundation zone, using a multi-criteria evaluation of quantitative (e.g. population, population density, number of households), qualitative (e.g. condition, building surroundings, natural environment) and descriptive (e.g. land use) factors (Papathoma & Dominey-Howes, 2003). Building vulnerability and human vulnerability are calculated by standardising any quantitative data, ranking criteria, applying a weighting factor and then summing all components. There have been several iterations of this model, including the PTVA-2 model that was used to calculate the probable maximum losses from a 500 year tsunami inundation zone generated by a Cascadia subduction zone earthquake (Dominey-Howes et al., 2010) and the RTVA-3 model that was applied on the Aeolian Islands (Dall'Osso et al., 2010). This PTVA-2 model is what forms the basis for one of the methods tested in Section 3.2, referred to as the 'Vulnerability Indicator (VI) method' for ease.

3. Multi-hazard methodology testing

The complexities involved in considering both the spatial and temporal effects of multi-hazards has led to the development of various models, some of which are more applicable to METEOR than others. Quantifying multi-hazards is a complex challenge and so it is perhaps not unsurprising that these

[1] *NB: In some cases the terms fragility curves or damage curves are used interchangeably with the term 'vulnerability curves'. These are defined as curves that show the relationship between the mean level of damage severity in a given building and the value of hazard intensity (Peduto et al., 2007). In the METEOR project we will be using fragility / damage curves and not vulnerability curves.*

methods vary a lot from one to another. There are several very useful detailed reviews of the current state of the art in for these methods (Kappes et al., (2012b); Papathoma-Köhle et al., (2011) and Greiving et al., 2006) that detail these differences. Generally speaking these variations fall into the following categories: (i) type of hazard; (ii) scale; (iii) focus; (iv) type; (v) whether they are hazard and/or vulnerability dependant; and (vi) which end users they are focused on.

(i) Type of hazard: there are many different combinations of hazards addressed in these studies. Some of these only address natural (geological and meteorological hazards), for example the assessment by El Morjani et al., (2007) which focuses on: flood, landslide, wind speed, heat and seismic hazard. Other models include anthropogenic hazards such as the release of toxic substances (Carpignano et al., 2009).

(ii) Scale: models maybe designed to address multi-hazards at scales of local/city/catchment (Kapppes et al., 2012a), regional (King et al., 2006; Delmonaco et al., 2006), continental (Bartel and Muller, 2007; Yusuf and Francisco, 2009) and global (Peduzzi et al., 2009). Generally those that are designed for use at finer scale require a larger amount of input information than the models that have been designed for use over wider areas.

(iii) Focus: Some models are focused very heavily on buildings and require a level of information that would require building surveys, preferably by civil engineers, (Meroni, 2006), others focus heavily on socio-economic indicators (Peduzzi et al., 2009).

(iv) Type: These range from fully quantitative – usually including probabilities calculated from well characterised frequency / magnitude relationships and complete inventories of economic / social and cultural impacts from previous events (Carpignano et al.,2009) to more qualitative models, which involve the production of indices (Greiving, 2006).

(v) Models may be entirely dependent on inputs from both hazard and vulnerability data, such as the Disaster Risk Index of Peduzzi et al. (2009), which includes hazard assessments as well as an assessment of 32 socio-economic indicators. In some cases, however, the model needs neither new hazard data nor vulnerability inputs, e.g. Papathoma-Köhle et al. (2011) who use pre-existing landslide susceptibility maps and allow for vulnerability to be dynamic and change through time.

(vi) Whether these models are designed to inform: local authorities, urban planners, engineers, building owners, civil protection services, insurance companies or the public makes a difference in how they are constructed and what input parameters are included.

To explore the best ways to combine the data created by the METEOR project and to develop robust models for analysing multi-hazards with exposure, we have reviewed c.20 different models designed to address multi-hazards. Whilst some of these models focus on the frequency of events and use historical dollar losses as a proxy for infrastructure impact or exposure (Bell & Glade, 2004; Tate et al., 2010; Schmidt et al., 2011; Kappes et al., 2012b), many are concerned with producing more qualitative results (Meroni et al., 2006, Delmonaco et al., 2007). For some hazards considered in METEOR it may be possible to retrieve information that would satisfy a qualitative model e.g. the origin of an event (earthquake epicentre) and severity descriptors (maximum flood height). For others, the incomplete historic records make it difficult to estimate key factors such as historic frequency, probability of occurrence or losses. This means that developing a purely quantitative model for METEOR that allows for the determination of absolute values will not be possible. Instead, a semi-quantitative model, including the development of indicators, will limit the effect of different types of data and the inherent differences in hazard characteristics. Indices offer a continuous standardisation of differing, and therefore not directly comparable, parameters and so can be applied to the data collected in this project and allow for its integration. After reviewing the existing models, two differing methodologies have been selected for testing. These methods were chosen as they were deemed to be most compatible with the data that will be generated by the METEOR project. The first, proposed by Greiving et al (2006) is designed to be a regional assessment and the second by Kappes et al. (2012a) a more local, town / catchment scale assessment, based on the work of Papathoma and Dominey-Howes (2003). Both of these methods will therefore need to be modified to be applicable at a national scale. For the purposes of this methodology testing and development we used the hazard and exposure data for Tanzania because they were more complete than the Nepal data at the time of the analysis.

3.1. Integrated Risk Assessment for Multi-Hazards

Greiving et al. (2006) developed an 'Integrated Risk Assessment for Multi- Hazards' method, building on the work by Blaikie et al. (1994) and Hewitt (1997). They describe risk as the issue of main concern, and as being the result of 'elements of risk'. They define risk as the product of hazard and vulnerability, where vulnerability is defined as *'the degree of fragility of a system or community towards natural and technological hazards*' and is therefore place specific, integrating hazard, exposure and the coping capacity of different regions. They recognise three types of hazard exposure: 1) Economic – any factors that can affect the economy of a region that can be damaged by an extreme event; 2) Social – assess any factor that might make people more vulnerable (i.e. age, education, etc.); 3) Ecological – ecosystems and their environmental fragility.

This spatial risk assessment framework considers: multi-hazards, hazards with spatial relevance, for example river flooding and volcanic eruptions, but not hazards such as meteorite impacts or collective risks that have the potential to threaten the entire community. The method consists of four key components:

1) Generation of hazard maps: The aim of these maps is to display the location and intensity of spatially relevant hazards. Where possible this intensity should be representative of the hazards frequency and magnitude. As it is not possible to classify all hazards on the same scale, these maps are classified using an ordinal scale using five related hazard classes. This generates an index for each hazard, which means that they are compared and combined, whilst mitigating the effects of different types of data and varying levels of uncertainty. Figure 1 shows the indices developed for the relevant Tanzania hazards.
2) Production of an integrated hazard map: All hazard data are compiled into one map showing overall hazard potential. This aggregation is straight forward as all of the maps display the hazard potential as a 1 – 5 index. It is possible, however, that some hazards are considered as more important than others. In this case it is possible to weight the hazards contributions to the final aggregation. Greiving (2006) suggests using the Delphi method of expert elicitation to define these weights. In this METEOR example, the hazard potential is assigned, weighted and aggregated at the pixel scale.
3) Vulnerability Map: Any available information concerning social and economic vulnerability is combined to create a map showing the overall vulnerability of each region. In this model, the

exposure of infrastructure, buildings and production capacity are all defined by the regional GDP and the human damage potential is defined by the population density. We have not assessed the possible impacts on the ecosystem in METEOR, as it is not within the scope of this project.

4) Integrated risk map: The hazard and vulnerability maps are integrated to produce a map that shows the integrated risk each region is exposed to. This allows for the user to differentiate between areas that are simply hazardous and those areas that are risky due to a higher degree of inherent vulnerability.

This method was chosen as a test methodology for the METEOR project because it can be applied at any geographical scale and for any hazard and because it is fundamentally concerned with multi-hazards. The modelling framework, including assigned weights, can be seen in Figure 1. For ease this methodology will be referred to as the 'Integrated Risk' or IR method for the purposes of this study.

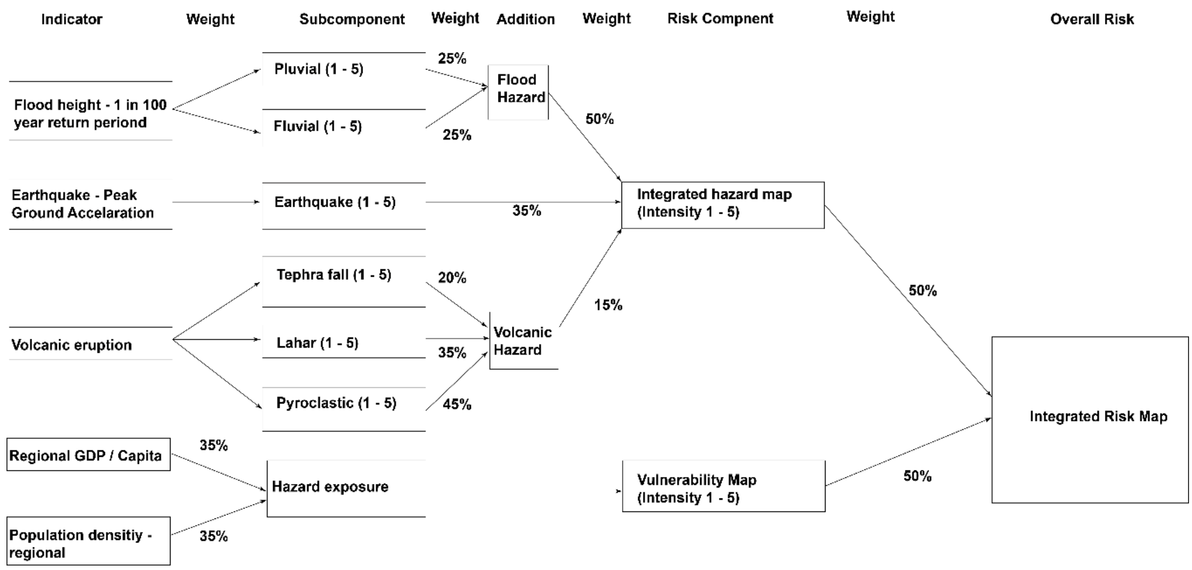

Figure 1: Schematic of the IR method for modelling integrated risk

3.2. Relative Vulnerability Index

The method designed by Kappes et al. (2012a) is an indicator–based vulnerability method that builds on the Papathoma Tsunami Vulnerability Assessment (PTVA) and adapts it for a multi-hazard context. It is a GIS-based method that assesses hazard-specific physical vulnerability, by selecting element characteristics that may be indicative of vulnerability. Vulnerability is considered as physical vulnerability of buildings, it does not take into account socio-economic indicators of vulnerability. The simplified work flow for this model can been seen in Figure 2.

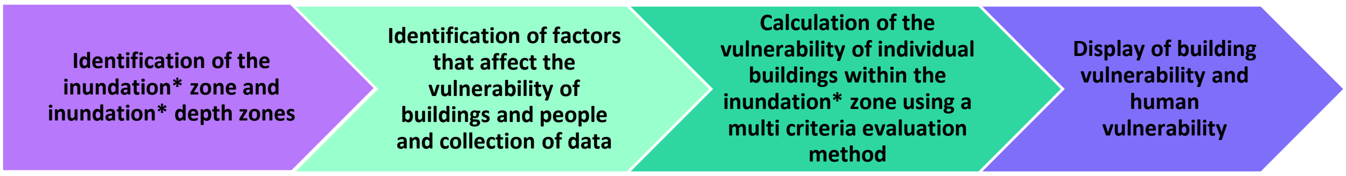

*Figure 2: Simplified workflow for the Kappes Relative Vulnerability Index model. *Note that this method was developed for tsunami and so the model refers to 'inundation zones' and 'inundation depths' - in the METEOR example we substitute these criteria for our hazard footprints and the ,measures of hazard attributed to them, be that PGA, depth or kg/m³.*

This method is similar to the IR method, in that the first step is to identify the relevant hazards for the study area and develop the relative hazard information – in this case the hazards defined by the METEOR project. The second step is the identification of factors that affect the vulnerability of people. In METEOR the factors that have been assessed are controlled by the input exposure data that has been made available by ImageCat. The factors that are available and comparable across the hazards included in the METEOR project are: the building materials, and the number of floors in each building. In the methodology defined by Kappes (2012a) the surroundings of the buildings are included in the assessment, for example the role of land cover and neighbouring buildings. As the METEOR project is producing relative vulnerability on a national scale, it has not been possible to include this component of the analysis.

The vulnerability indicators selected need to be considered for each hazard individually. This is because their impact depends on the type of hazard – for example a tall building may be more vulnerable to a large earthquake than to a flood event. For each indicator a weight is defined that reflects this. In this study these weights were defined using a combination of fragility curves (when available) and expert elicitation within the METEOR consortium. Once these weights are defined, the Kappes method follows the PTVA and applies a weighted linear combination technique. This produces a Relative Vulnerability Index (RVI) that is not dependant on the hazard intensity but instead reflects the relative vulnerability for each building for different hazards. The components and weights of the RVIs defined for the METEOR assessment can be seen in Figure 11.

Finally this method makes an assessment of the effects of hazard interactions on the overall vulnerability. As discussed in Table 4, whether hazards overlap spatially or temporarily can have very different implications for end users and for DRR practitioners. In this study the potential cumulative effects of the hazards are described in Figure 3.

Flooding (1.1)	Destabilisation of the subsurface due to increased water saturation and erosion is likely to change the response to an earthquake, increasing the potential for liquefaction. (1.2) (Alteration to the hazard / vulnerability)	No Interaction (1.3)
Cracks and damages from earthquakes may make structures more vulnerable to increased water volumes - specifically flood management infrastructure and dams. (2.1) (Alteration of vulnerability)	**Earthquake (2.2)**	(Fall) Cracks and structural damage caused by an earthquake may increase vulnerability to added pressures from ash falls (2.3a) (Alteration of vulnerability) (Flow) Cracks and structural damage may increase structures to a second impact (2.3b) (Alteration of vulnerability)
(Fall) No Interaction (3.1a) (Flow) Inundation of lahar and / or pyroclastic material may cause differences to river drainages, changing the areas of inundation from a flood event (3.1b) (Alteration of hazard)	(Fall) The addition of volcanic ash to the roofs of buildings may increase their vulnerability to shaking due to the increased weight on the structure (3.2a) (Alteration of vulnerability) (Flow) Structural damage from the impact of a volcanic flow is likely to increase a buildings vulnerabilty to further destabilisation (3.2b) (Alteration of vulnerability)	**Volcano (3.3)**

Figure 3: Cumulative hazards and their effects on vulnerability indicators (Tanzania).

This methodology was developed to be used at local / regional scales – coupled with field studies of building damage data, which may limit its applicability to national surveys. This method was chosen as the second test methodology for the METEOR project because of its capacity to develop relative hazard vulnerability in a semi-quantitative manner at a variety of scales.

3.3. Expert weightings

To produce an integrated hazard index (including all relevant outputs) there must be an understanding of how these hazard indicators interact with each other and what their relative weights are in the subsequent index. A summation of indicator scores per pixel would allow for a straightforward analysis, but it seems a more appropriate method would allow for these different components to be weighted differently, reflecting their relative severities or their frequency relative to each other. These weights can be determined either using expert elicitation (the Delphi method as used in IR method) or statistically by weighted linear combination models (WLC) – or a combination of both.

Both of the methods tested in this analysis require some component of expert elicitation (Aspinall et al., 2013). This allows for the users to define the rankings of hazards relative to each other and therefore their subsequent weighting in the resulting index. Where possible these have been underpinned by tools such as fragility curves and inventories of data. However, not all of the hazards considered in this analysis have complete historic inventories, making constructing frequency / magnitude distributions complicated. Expert elicitation allows for users to draw on experience from other locations and make a best estimate of the likely relationships between hazards and vulnerability indicators. The weights defined in Table 5 have been solicited from experts in the METEOR consortium. These weights are used in both the IR and VI methodologies discussed in sections 3.1 and 3.2.

Hazard	Pluvial	Fluvial	Tephra	Lahar	Pyroclastic	Earthquake
	0.25	0.25	0.03	0.0525	0.0675	0.35
Indicator - Material	0.2	0.2	0.5	0.7	0.55	0.55
Reinforced Concrete	0.4	0.4	0.3	0.2	0.7	0.4
Mixed	0.5	0.5	0.4	0.6	0.8	0.6
Metal	0.3	0.3	0.3	1	0.9	0.5
Masonry	0.5	0.5	0.5	0.4	0.9	0.3
Wood	1	1	0.2	1	1	0.3
Traditional	0.7	0.7	0.6	1	1	1
Indicator – No of floors	0.7	0.7	0.5	0.3	0.45	0.45
1	0.8	0.8	1	1	0.8	0.3
2	0.5	0.5	0.5	0.5	0.9	0.8
>2	0.3	0.3	0.3	0.3	1	0.4

Table 5: Indicator weights derived by expert elicitation.

4. Hazard assessment

Both of the methodologies tested in this exercise require, as their starting point, an assessment of hazard. The hazard assessments discussed here were delivered as part of METEOR deliverable M6.1 'Hazard footprints for Nepal and Tanzania'. The METEOR project addresses: flood, earthquake, landslide and volcanic hazard. The hazards addressed in Tanzania are flood (pluvial and fluvial), seismic and volcanic. Landslide hazard is not a component of the hazards addressed in M6.2 (this report) because they are not one of the hazards addressed in Tanzania, they are however a key hazard in Nepal. The models used to model flood and seismic hazard generate outputs which are broadly comparable (see sections 4.1 and 4.2), whereas the methods used to assess the volcanic (in Tanzania) and landslide (in Nepal) hazards are not as statistically robust and are therefore not directly comparable. They are however, quite similar to each other. This means that whilst this report will not include data from Nepal, the methods used to integrate the volcanic hazard into the Tanzania multi-hazards framework will be the same as that used to include the landslide data into the Nepal framework.

4.1. Flood Hazard

In the METEOR project pluvial and fluvial flood hazard has been modelled using varying water depth for flood events of different return periods (1 in 5 yrs., 1 in 10 yrs., 1 in 20 yrs., 1 in 50 yrs., 1 in 75 yrs., 1 in 100 yrs., 1 in 200 yrs., 1 in 250 yrs., 1 in 500 yrs. and 1 in 1000 yrs.). The data has been produced using the Fathom global flood hazard modelling framework (a development of Sampson et al., 2015 and Smith et al., 2015). The model uses the MERIT global DEM and hydrography for elevation and river network data sources respectively (Yamazaki et al., 2017; Yamazaki et al., 2019). The framework automatically constructs flood models across a specified region, using the two-dimensional shallow water equations to simulate the behaviour of floodwaters during the modelled flood events. The framework produces maps of flood depths at 3 arc second (~90m) spatial resolution for a specified range of return periods.

Modelling a range of return periods expresses the probability of experiencing a given water depth within a single year; i.e. depths shown by the '1-in-100 year' layer have a 1-in-100 (or 1%) chance of occurrence in any given year (see Figure 4).

Given that the modelling framework used to create this data is semi-autonomous and uses data available at the regional to global scale, its accuracy is limited by the quality of this input data and the simplified range of processes it can represent. While the data is suitable for providing guidance at the regional scale, it is not recommended to use the data for local scale assessments or engineering purposes. Further details on the Fathom methodology for the production of these hazard footprints can be found in the METEOR: Draft Training Protocols (Report number: M8.7/CIC) and the following publications: Sampson et al., 2015; Smith et al., 2015; Yamazaki et al., 2017 and Yamazaki et al., 2019.

For the purposes of this report the multi-hazard modelling was completed using the 1 in 100 year (flood defended) model (Figure 4A and B).

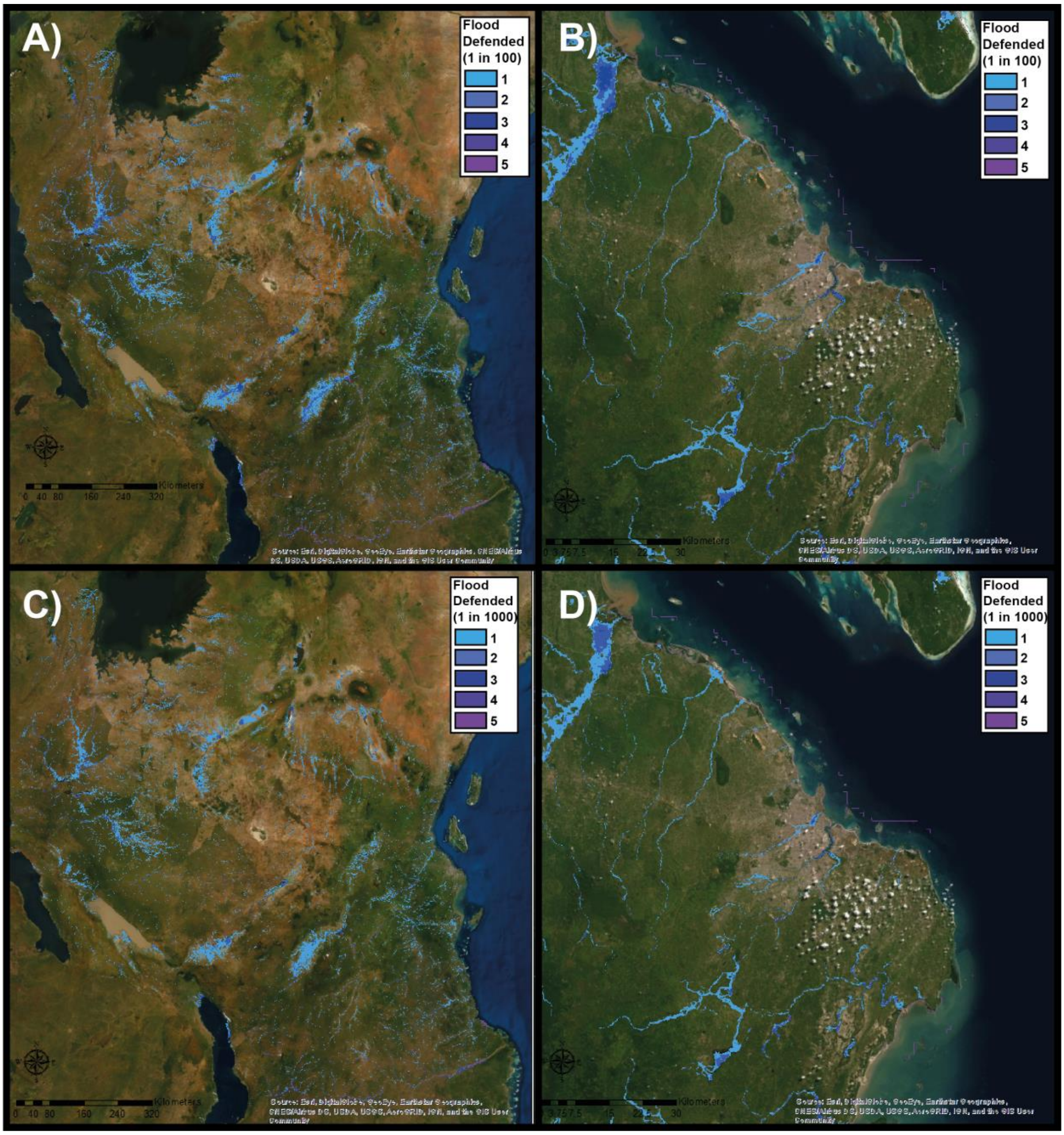

Figure 4: National flood hazard footprints for Tanzania. These footprints show a 1 in 100 year (A, B) and 1 in 1000 year (C, D) fluvial flood event in Tanzania (A, C) and the region around Dar es Salaam (B, D). The complete set of flood hazard footprints for fluvial and pluvial flooding in Tanzania and Nepal are available from deliverable M6.1C.

4.2. Seismic Hazard

The seismic hazard models were produced by GEM using the OpenQuake Engine and the SSA model (further details can be found here: https://hazard.openquake.org/gem/models/SSA/). These models have a resolution of 3 arc seconds. The hazard map produced relates to a 10% probability of exceedance in 50 years of a specific peak ground acceleration (PGA) (Figure 5) (Poggi et al., 2017).

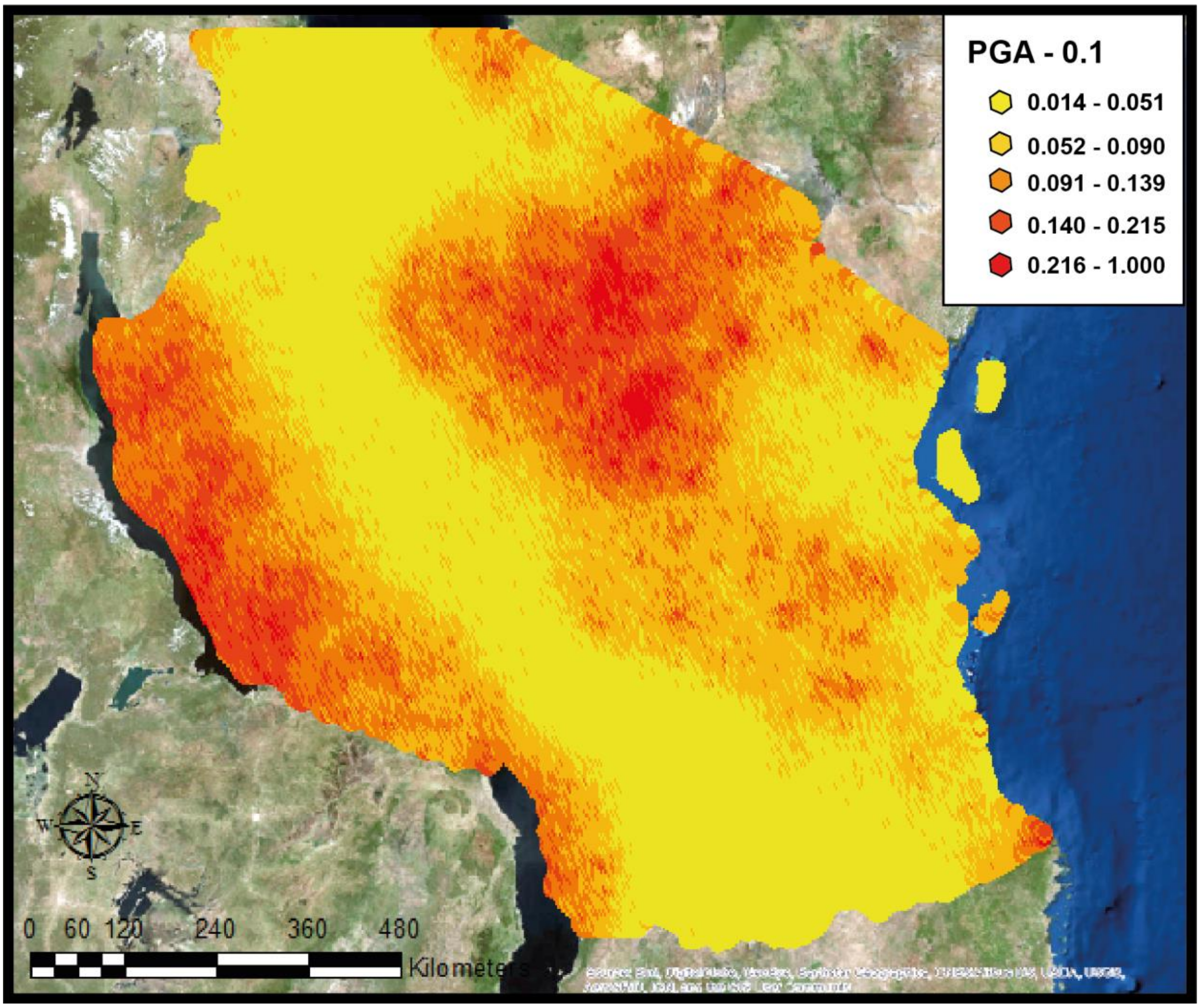

Figure 5: National seismic hazard footprint (Peak Ground Acceleration) for a 10% in 50 year probability of exceedance (PGA 0.1) (1 in 475 year return period).

4.3. Volcanic

Volcanoes themselves can be considered as multi-hazard phenomena. In this project the primary hazards considered are: tephra fall (ash), pyroclastic density currents (PDCs) and lahars. The volcanoes included in this study have all been active in the Holocene and are: Ol Doniyo Lengai, Meru, Igwisi Hills, Ngozi, Kyejo and Rungwe[2]. The known eruption history of Tanzanian volcanoes is incomplete and as a consequence, it has not been possible to compile robust frequency / magnitude distributions for them.

The tephra fall hazard footprints in this study have therefore only been produced for Rungwe volcano, where the eruption history is the most complete. Tephra fall hazard footprints were generated using *TephraProb*, a freely available *Matlab* package developed to produce probabilistic hazard assessments for tephra fallout (Biass et al., 2016). The outputs of these models can be seen in Figure 6. The events simulated were: (i) a relatively small VEI 2 eruption; and (ii) a larger, more explosive VEI 4 eruption. The size of these events was picked based on the work of Fontijn et al. (2010) who described the deposits and geomorphology of this volcano. If the necessarily geological data could be collected for the remaining 5 volcanoes then the same methodology could be used to model the potential tephra fall from appropriately sized eruptions.

[2] General information concerning Tanzanian volcanoes and their eruptions histories can be found at the Global Volcanism Program website (https://volcano.si.edu/).

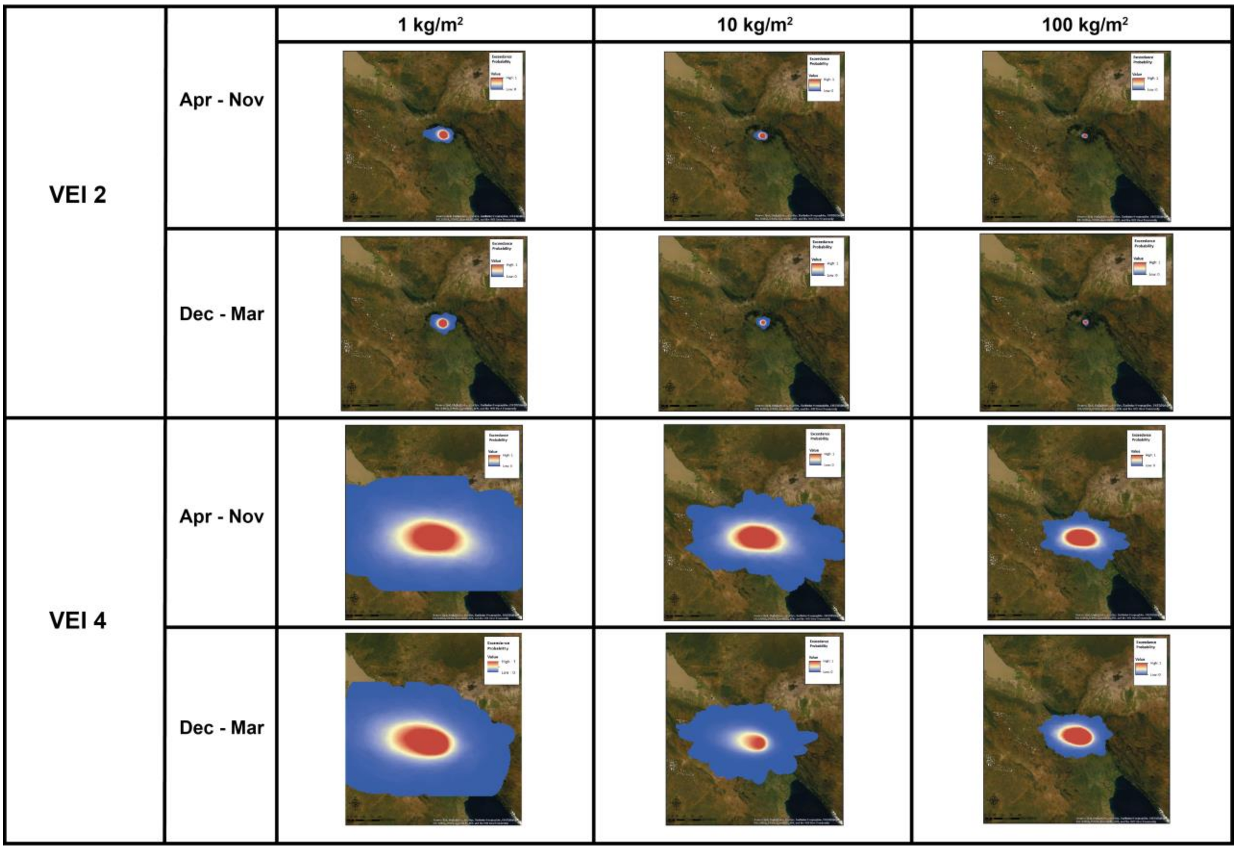

Figure 6: Tephra fall exceedance probability footprints for VEI 2 and VEI 4 eruptions from Rungwe volcano. These footprints show the probability of tephra fall around the volcano exceeding a thickness of 1kg/m^3, 10kg/m^3 and 100kg/m^3. The predominant wind direction in this area of Tanzania are easterlies and south easterlies and show some marked seasonal variation. The simulations are therefore spilt between April – November and December – March to account for the wet and dry season respectively.

Due to the sparsity of eruption history data for the Tanzanian volcanoes it was also not possible to model specific eruption scenarios for pyroclastic flows or lahars. Instead the areas that are potentially at risk from pyroclastic flows and lahars have been assessed using a drainage basin analysis methodology based on Earth Observation (EO) data. Once again if the relevant geological data could be collected then it would be possible to further model these phenomena for all volcanoes in Tanzania using freely available programs such as Titan2D (Sheridan et al., 2005) and LaharZ (Schilling, 1998). A simplified workflow for this analysis can be seen in Figure 8. Drainage channels that intersect with these buffers are assumed to be areas of potential PDC and lahar activity. This does not mean that these hazards will occur over this entire region but that drainage channels and areas around them in this location *could be* impacted by volcanic flows. Figure 7 shows an example of basin analysis for PDC and lahar hazards at Ngozi, Rungwe and Kyejo volcanoes.

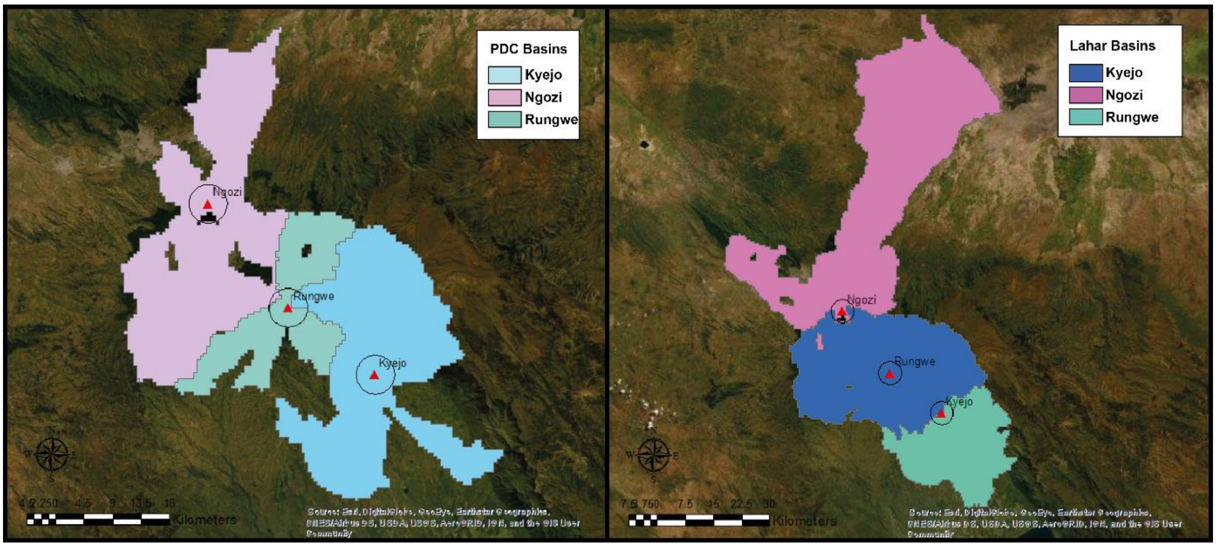

Figure 7: Pyroclastic and lahar basins for Kyejo, Ngozi and Rungwe volcanoes in southern Tanzania.

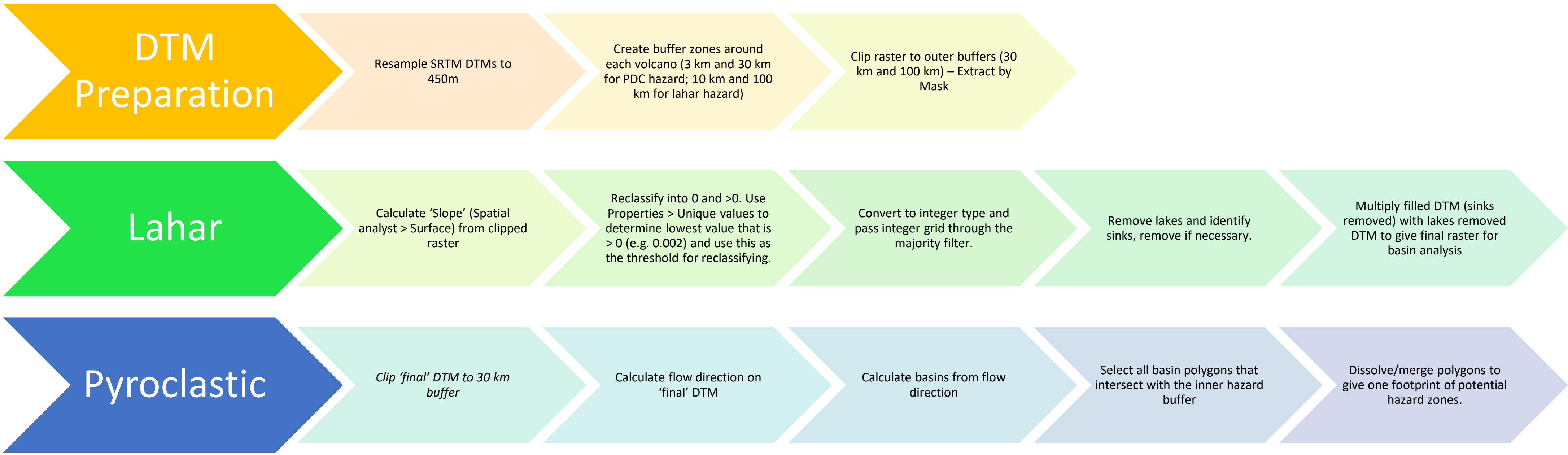

Figure 8: Simplified GIS workflow for assessing volcanic basins.

5. Understanding Exposure and Vulnerability

The exposure data for the METEOR project has been produced by ImageCat and Humanitarian OpenStreetMap Team as part of WP3 and WP4 respectively. The details of the data acquisition methods have been described in these specific METEOR deliverables: M3.1C: Classification of General Building Exposure Data; M3.2: Exposure Data Classification, Metadata Population and Confidence Assessment; M4.1: importing existing data into OSM; M4.2: METEOR EO Mapping of Exposure and M4.3: Protocols for Crowd Sourcing Regional Exposure Data.

Very simply, the exposure data provided by ImageCat uses open source, freely available satellite data sources as a primary input. These data are then augmented with ground based surveys of a random sub-sample of buildings – conducted by Kathmandu Living Labs (Nepal) and Ramani Huria (Tanzania) for Humanitarian OpenStreetMap Team. A simplified work flow can be seen in Figure 9.

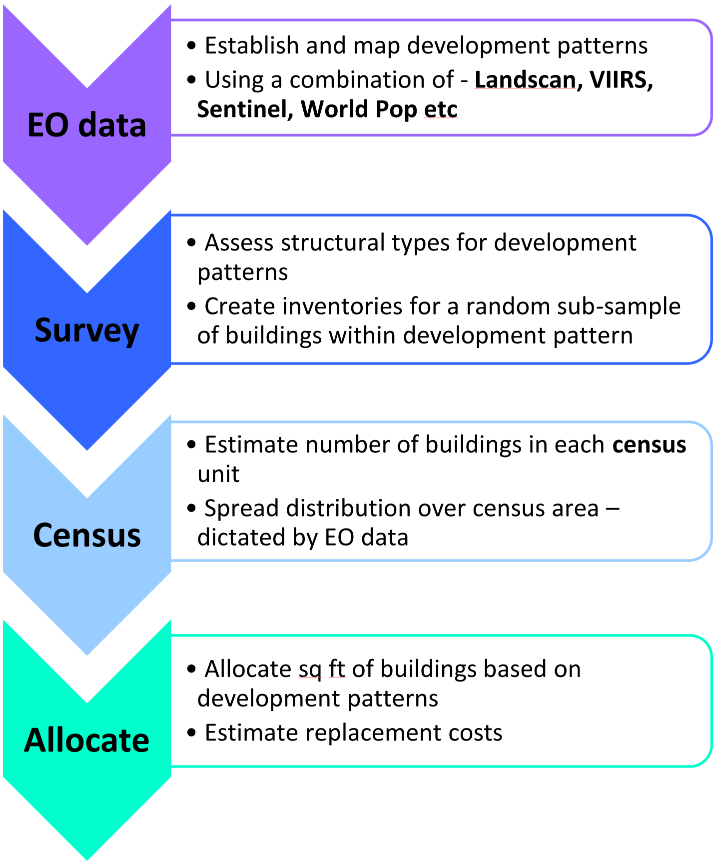

Figure 9: Simplified work flow for the production of exposure data, further details can be found in assorted METEOR milestone documentation (listed above).

National exposure data for Tanzania was compiled using an EO analysis of various satellite outputs; the product has a 90m resolution. The main sources of uncertainty in this analysis are: 1) the census data used as an input - Dar es Salaam is one of the fastest growing metropolitan areas east Africa, with a population of 5 million and projected growth of 85% by 2025, and as such older census data may therefore limit the accuracy of the exposure data collected; 2) average number of people per building – this is a key parameter for estimating the number of buildings per census unit, and 3) the replacement costs.

Both the IR and VI methods require an assessment of vulnerability, which is tied to the exposure of people, buildings and infrastructure. The different methods that these methodologies employ are described in section 3.1 and 3.2. An example of the data generated as part of the METEOR project by ImageCat can be seen in Figure 10. For each 90 m pixel, the exposure dataset details information such as the proportion of building types and the expected replacement costs.

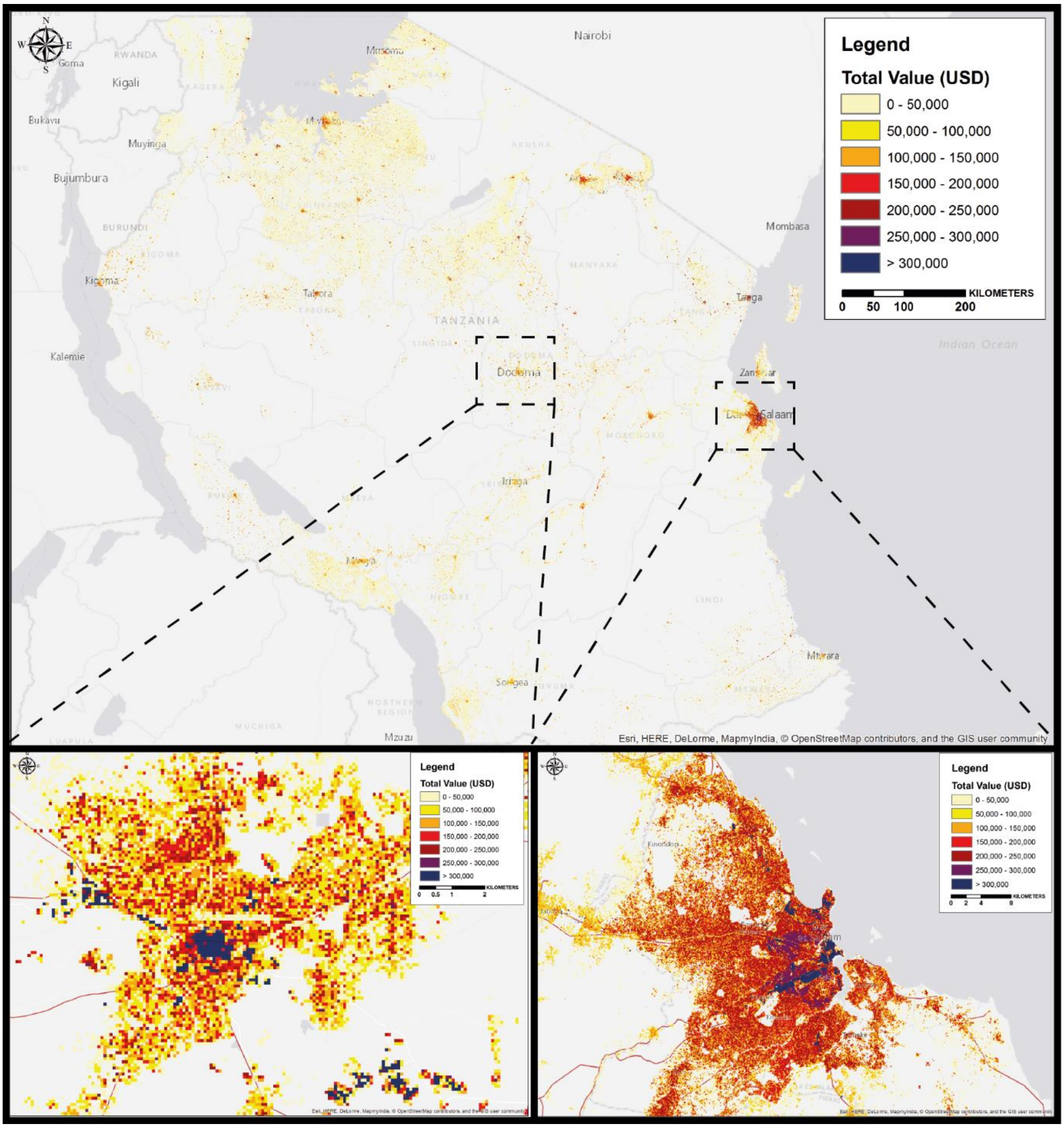

Figure 10: Total value of building stock derived from the ImageCat data collection. Highlighted regions show values in Dodoma (left) and Dar es Salaam (right).

5.1. Vulnerability Map

The two multi-hazard modelling methods treat vulnerability slightly differently, which is why they were chosen as test cases for the METEOR project. The IR method addresses vulnerability by selecting key indicators at a regional resolution, whereas the VI method assesses criteria that need to be applied on a building by building scale.

In the IR method, the regional GDP per capita is an indicator to represent the hazard exposure of the region, defined as exposure to: infrastructure, industrial facilities, production capacity and residential buildings. The human damage potential is represented by the area's population density. Greiving (2006) makes an assessment of the fragmentation of natural areas as an indicator for the possible impacts on the ecosystem. The METEOR project is not considering ecological exposure to hazards and so we have not included this criteria in this analysis.

The data used to create the vulnerability map is taken from the Bureau of National Statistics census website (http://www.tsed.go.tz/CensusInfoTanzania/libraries/aspx/Home.aspx) and can be seen in Table 6.

Region	Regional GDP per captia (USD)*	Population density
Dodoma	397.55	50.4
Arusha	752.06	45.1
Kilimanjaro	739.76	123.8
Tanga	613.46	76.7
Morogoro	588.51	31.4
Pwani	222.63	68.1
Dar es Salaam	1036.85	3133.2
Lindi	583.43	13.1
Mtwara	556.34	76.1
Ruvuma	739.89	21.6
Iringa	1490.33	26.3
Mbeya	723.21	75.3
Singida	374.12	27.8
Tabora	460.72	30.1
Rukwa	909.87	44.1
Kigoma	363.77	57.4
Shinyanga	1047.03	81.2
Kagera	428.05	97.3
Mwanza	881.80	292.9
Mara	565.45	80.1
Manyara	626.61	32.1
Songwe	799.51	36.1

Table 6: Population and GDP data for Tanzanian regions. This data is from 2012. *TShs to USD exchange rate on the 03/10/2019 ($1 = 2298.7TShs)

5.2 Development of vulnerability indicators

The building classes defined in the exposure analysis performed by ImageCat allow us to infer the likely building material and number of floors in buildings of specific types. This information is tied to fragility curves and expert elicitation that are hazard specific and therefore allow for these different criteria to be weighted in the Kappes et al. (2009a) method to provide a Relative Vulnerability Indicator (see Figure 11). This allows for a vulnerability indicator to be applied to each pixel in a GIS-based analysis, a much higher resolution representation of vulnerability than the IR method.

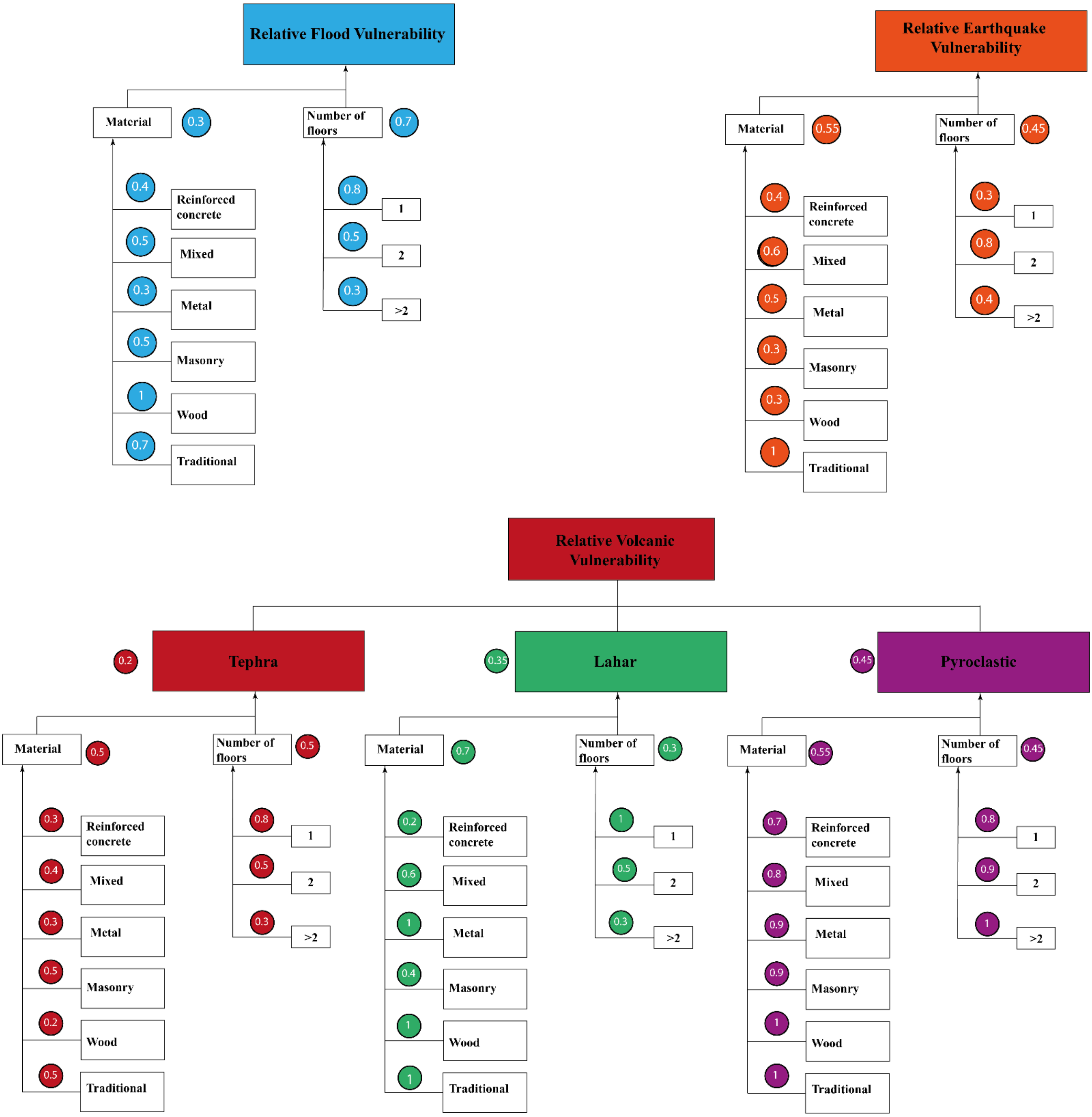

Figure 11: Method for deriving Relative Vulnerability Indicators, after Kappes et al., 2012a.

6. Results

The two methodologies used in this study allow for aggregation of the hazard assessment and exposure data. In the IR method the separate hazards are combined with the exposure data to produce a single national integrated risk map. The VI method, however, produces a separate relative vulnerability map for each individual hazard (in Tanzania - volcanic, flood, earthquake). The results of these two aggregation methods are shown in the following sections.

6.1. Integrated Risk results

The IR methodology identifies the highest risk regions in Tanzania as: Dar es Salaam, Iringa, Mwanza, Njombe, and Shinyanga (Figure 12). These are not regions associated with particularly high hazard for any of the multi-hazards addressed in this study (see Section 4). These regions do however, have some of the highest Regional GDP per capita in the country (Iringa, Shinyanga and Dar es Salaam being the top 3) (Table 6). This suggests that the factor controlling the risk in this analysis is the financial exposure component of this analysis. Whilst this is perhaps not surprising, it is potentially misleading.

The region around Dar es Salaam is, unsurprisingly classified as high risk. As the previous capital of Tanzania and current economic centre this region has a high GDP and this is therefore reflected in the higher risk result. Comparatively the area around Dodoma (highlighted in Figure 12) is relatively low risk, despite the seismic hazard being significantly higher in this region. Now that the government is transitioning to Dodoma this is a region whose risk is likely to increase, in line with an increase in the financial investment and industry. Iringa (also highlighted in Figure 12), is a highly productive agricultural region and this industry accounts for 85% of its GDP (National Bureau of Statistics). This means that there are fewer people and buildings exposed to hazards than in the densely populated areas like Dar es Salaam, and yet the region is still comparatively high risk. For hazards such as flooding, which may ruin crops this may be an accurate reflection of the economic risk in this region but it may overestimate the impact of an earthquake in this region (especially because this region is relatively low in seismic hazard). This is difficult to assess in the IR method as it is not possible to disaggregate and visualise this information.

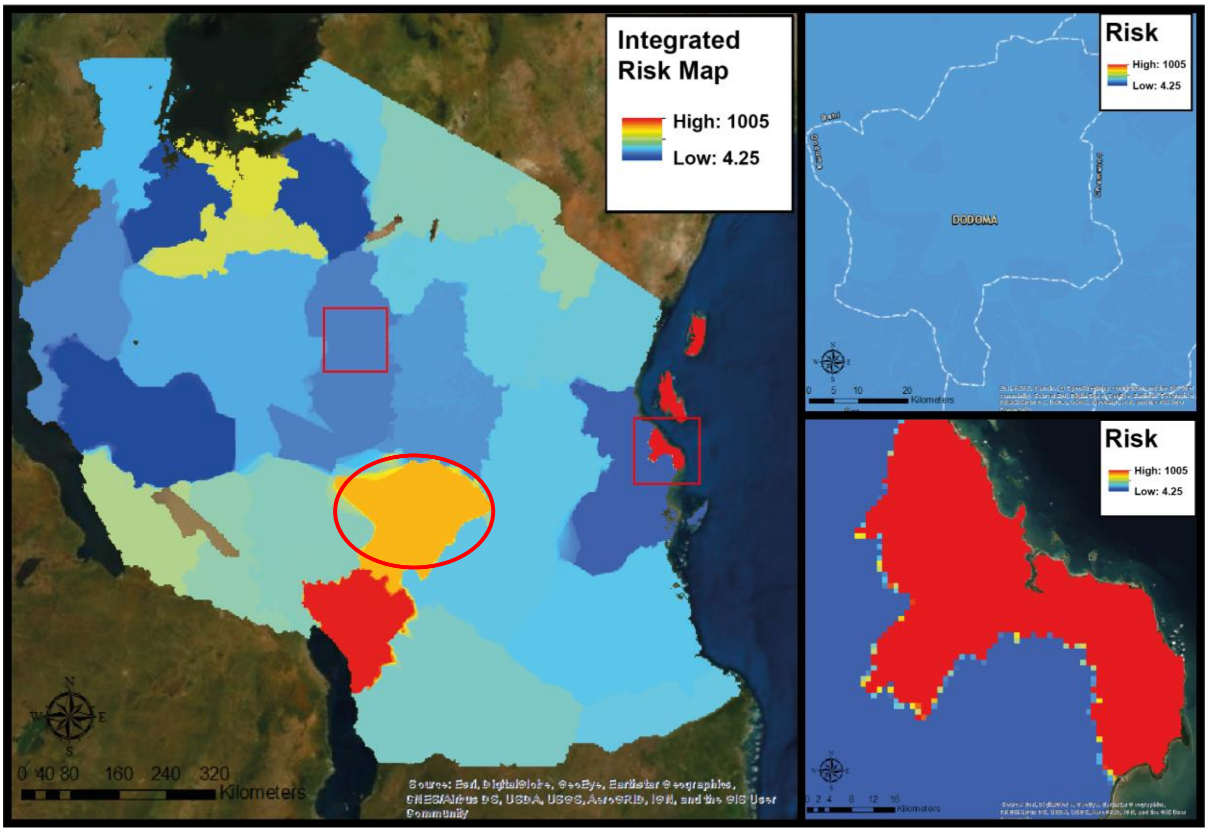

Figure 12: Integrated Risk Map following the Greiving et al. (2006) methodology. Red square highlights risk in Dar es Salaam and Dodoma. Red circle marks the region of Iringa.

6.2. Vulnerability Indicators results

The VI methodology produces a separate output for each hazard at compatible scales. The highest earthquake hazard areas in this analysis highlight the East African Rift valley. This means that Dar es Salaam is categorised as low risk but areas of Dodoma, where the capital has moved to, is medium to high risk. When we assess the vulnerability of buildings in Dar es Salaam to seismic hazard, it appears that areas on the edges of the city have higher vulnerability. Similarly in Dodoma, buildings on the periphery of the main urban areas have higher vulnerability (Figure 13). On reviewing the building information in this location, it appears that these regions have a higher proportion of traditional, unreinforced and wooden buildings than some of the areas closer to the city centre. It therefore follows that this analysis is correctly identifying areas where property is less likely to have been designed or retrofitted to withstand earthquakes.

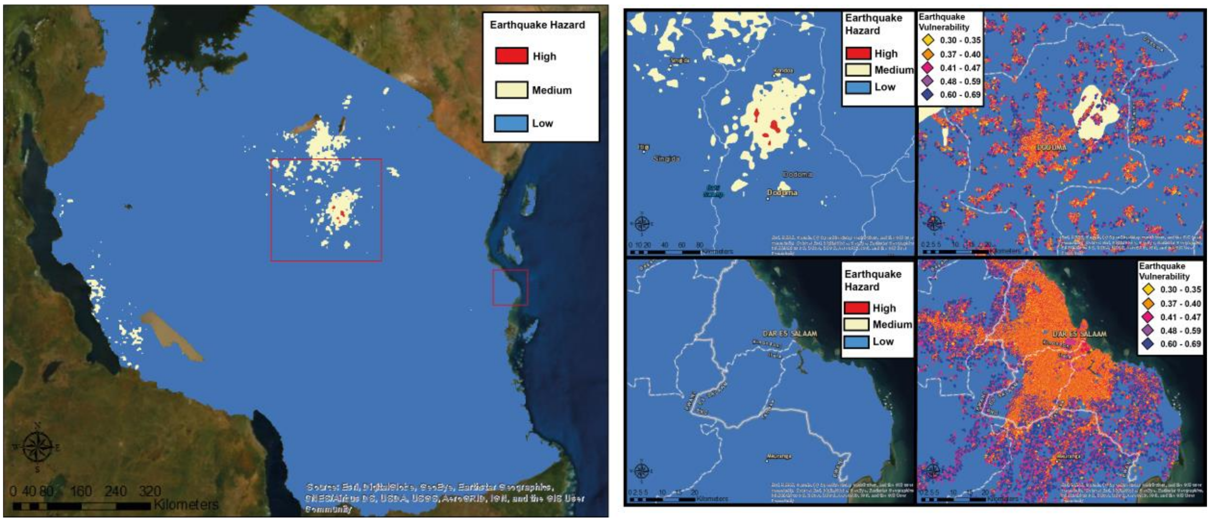

Figure 13: Seismic hazard and vulnerability following the VI method by Kappes et al., 2012a. The regions around Dodoma and Dar es Salaam are highlighted as they are national centres of government and commerce.

Flooding in Tanzania is a persistent hazard with large events occurring frequently. When assessing the building stock vulnerability to flooding in Tanzania we see high vulnerability in many regions including: Geita, Shinyanga, Iringa, Dar es Salaam, Rukwa and others. This suggests that for larger events much of the country could be considered vulnerable. Whilst GDP per capita is not included in this analysis, it is important to note that some of these regions do have high economic output tied to industries that are vulnerable to flood events. Iringa, for example, has a strong agricultural industry that could be heavily impacted by flooding (Figure 14).

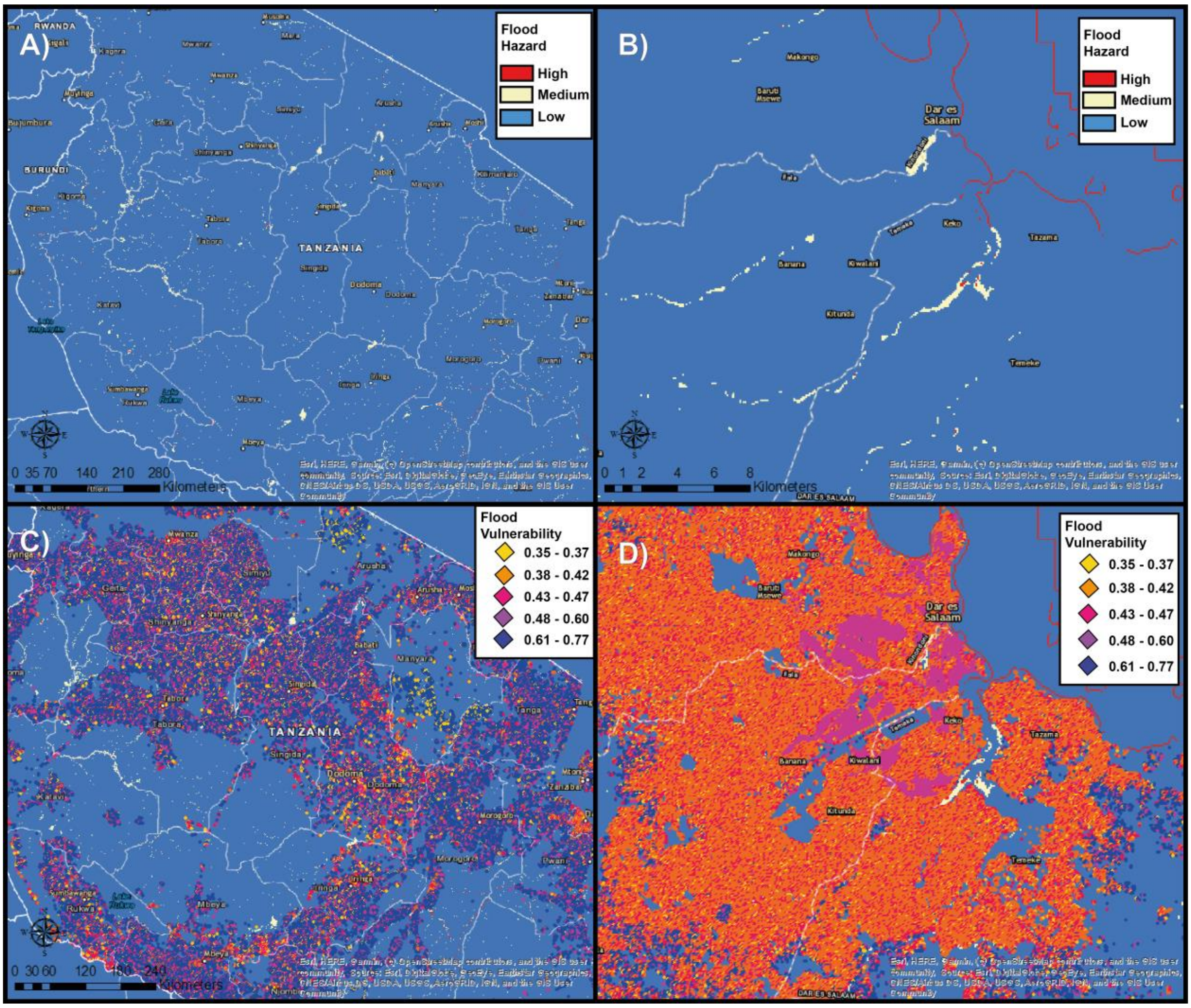

Figure 14: Flood hazard (A) and vulnerability (C) for Tazania following the VI method by Kappes et al., 2012a. The hazard (B) and vulnerability (D) for Dar es Salaam is highlighted.

There are 6 volcanoes included in this study, due to the incomplete history the available data regarding Tanzanian volcanoes it was only possible to assess the pyroclastic and lahar basins of the volcanoes in this methodology. The ash fall data was only produced for Rungwe and so only this data has been included in the analysis. This means that ash hazard may seem artificially low around the other five volcanoes.

The high hazard zones in this analysis can be assumed to be areas where there could be impact from pyroclastic flows and lahars whereas the medium hazard zones are areas that could only be impacted by lahars. These flow phenomena are highly destructive and as a consequence the vulnerability of buildings in these areas is generally high (Figure 15).

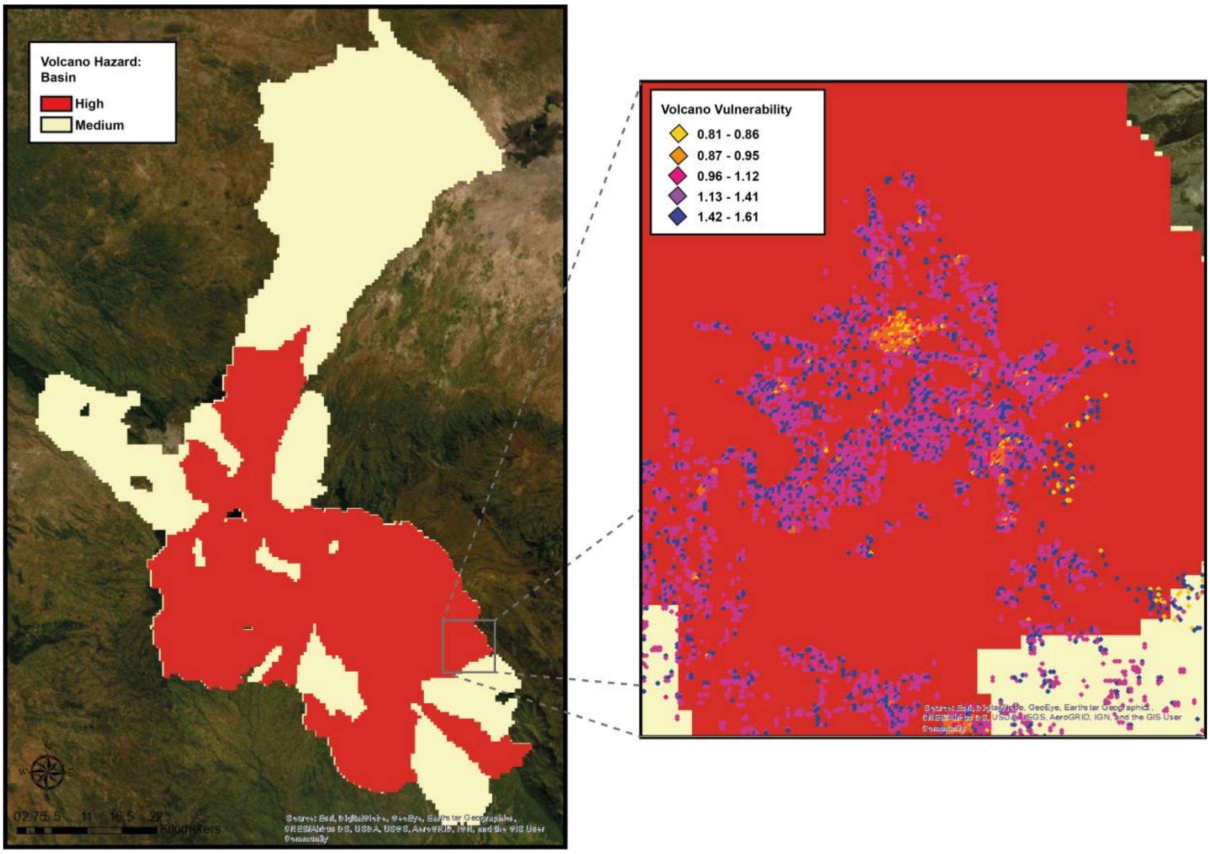

Figure 15: Volcanic hazard and vulnerability following the VI method by Kappes et al., 2012a for Kyejo, Ngozi and Rungwe.

7. Next Steps

7.1. METEOR multi-hazard framework

In this study we have used two different methodologies to assess multi-hazards and exposure in Tanzania. The IR method is based on producing standardised hazard indices that are then weighted and aggregated into an integrated hazard map. In this methodology, exposure is represented by factors such as regional GDP per capita and regional population density. These factors are also represented as indices in a vulnerability map. The standardisation of both the hazard and exposure data allows for these components to be compiled into an Integrated Risk Map. Whilst this method allows us to assess the national scale integrated risk, the finest resolution of the final product is only regional. The VI methodology, by comparison, allows for the retention of the resolution of the original data and therefore produces greater detail for assessing exposure. It also includes an assessment of the building materials and how these may respond differently to interactions with different hazards. As these are generated as unique outputs for each hazard, however, it is not possible to assess the integrated multi-hazard risk. As a consequence, neither the IR nor the VI methods in isolation fully address the needs of the METEOR project. We therefore propose a methodology which is a hybrid of these two models and will allow for an aggregated spatial multi-risk assessment at a resolution of 90m (Figure 16, for more detailed figure content see Annex A).

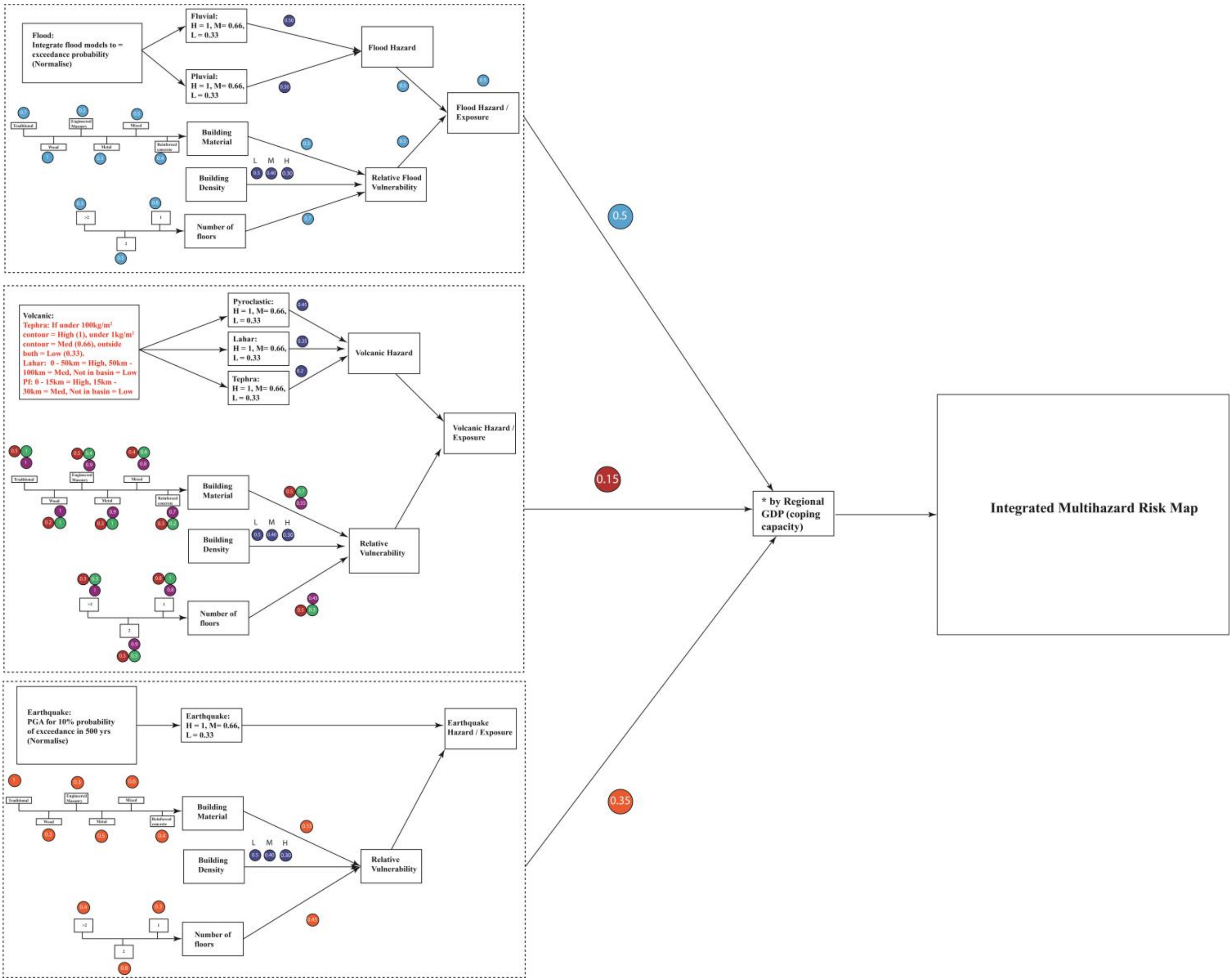

Figure 16: Proposed model framework for the METEOR Multi-hazard and exposure methodology.

This new METEOR methodology is a GIS-based model that uses the project hazard footprints and exposure data as its primary inputs. Where possible, the hazard data will be converted to an exceedance probability (flood, seismic and volcanic ash). This data will then be converted to indices, the criteria of which will be user defined. If there is more than one component to the hazard (i.e. flood hazard is a compilation of the fluvial and pluvial hazard) then these inputs will be weighted and aggregated to produce a representative hazard map. Where it is not possible to produce exceedance probabilities for the hazards (e.g. volcanic basins in Tanzania and landslides in Nepal) then the indices will be constructed with the aid of expert elicitation of the experts involved in the production of the original hazard footprints. For this study, high, medium and low values were assigned based on whether or not the pixel fell within a volcanic basin and then based on how far from the volcano that pixel was. For example, for pyroclastic flow hazard, if a pixel was located in a pyroclastic flow basin that was 0 – 15km from the summit of the volcano then it was assigned a 'high' hazard value. The same methodology (of constructing indices based on expert elicitation) will be employed in the Nepal case study for landslide hazard. The landslide hazard footprints produced in M6.1 represent landslide hazard as a susceptibility value – rather than an exceedance probability. This will therefore need to be converted to a normalised (1 – 5) scale. The landslide susceptibility score could be used as an index itself, or it could be modified to reflect the expert's judgement on the appropriate definition of thresholds.

The Relative Vulnerability Indicator map will be produced in much the same way as the RVI's were produced in the VI method, with the weights of each indicator reflecting a combination of expert elicitation and the available fragility curves (provided by the Global Earthquake Model in METEOR deliverable M5.2C). We will explore adding other vulnerability indices, if the information is available in the updated exposure data collected by ImageCat and Humanitarian OpenStreetMap Team. Specifically it would be beneficial to add criteria that reflect roof type and pitch, if possible. Once again, the weights assigned to these parameters will be informed by any available fragility / damage curves and expert elicitation.

Once the RVI maps for each hazard have been produced they will be combined by assigning weights to each hazard. These will once again be defined by expert elicitation, but should take into account relative return periods and intensities where possible. The IR method highlighted the impact of regional GDP on the final integrated risk map, this parameter will be preserved in our hybrid model and will be applied to the combined hazard and vulnerability outputs to generate an integrated hazard map.

The METEOR hybrid method is designed to be flexible to allow for the aggregation of different types of input data and to mitigate the impact of incomplete data sets. For example, if we do not have access to a damage curve for a specific parameter then a value can still be assigned by expert elicitation. We propose that this flexible model will enable the METEOR project to make the best use of the available data and demonstrate the possibilities of assessing multi-hazard risk at a national scale even in the context of data scarcity.

7.2. Uncertainty and Sensitivity Testing

Whilst our proposed hybrid methodology is designed to be flexible, it is important to recognise that the input data sets have a degree of uncertainty associated with them already and that this model could potentially amplify these. The Global Earthquake Model will be delivering an assessment of the uncertainty of the vulnerability and exposure data in METEOR deliverable M5.3 but this will not address the uncertainty propagated through the model (Figure 16). It is essential to the goal of providing a robust, evidence-based analysis of the multi-hazard potential in Nepal and Tanzania for DRM that we are able to speak to the uncertainty associated with the data we deliver. As such we will be addressing the uncertainty of this method in two ways:

1) As this model will be GIS based we will be able to conduct a Monte Carlo assessment to test its sensitivity to variations in all parameters and inputs, including the weights of the indices. The Monte Carlo method applies an algorithm that computes solutions to problems that

contain a large number of variables by performing iterations with different sets of random numbers. This will allow us to assess how much control each parameter has on the final output. It will also help to identify areas where an increase in baseline knowledge would have the greatest impact on the overall understanding of risk. This will provide avenues for the most impactful investigations going forward.

2) We have purposefully not included loss in this model. This is because the loss data that exists for Tanzania and Nepal is quite patchy and certainly not consistent between countries and different hazards (see METEOR deliverable M5.2). This being said, there are several hazard events for which we do have robust data. We therefore plan to make use of this data by determining whether it is possible to recreate the loss from a specific event using a branch of the model that we have developed. This assessment would be limited to either a previous flood or earthquake event, as these are the hazards where we are able to attribute an exceedance probability and have more complete frequency / magnitude histories than the other hazards.

7.3. Cascading hazards

The model outlined in Figure 16 will provide an understanding of multi-hazard and exposure in a spatial context but it does not specifically address the temporal component of multi-hazards (i.e. cascading hazards). There are multiple ways that the four hazards addressed in the METEOR project could interact with each other in a cascading fashion. The matrix demonstrating these relationships can be seen in Figure 17.

The framework outlined in Figure 16 is underpinned by the fragility curves that are available for assessing the impact of a hazards on specific building types. When considering the implications of cascading hazards and how they act together to impact on exposure, it is necessary to assess how these fragility curves may be modified by a preceding hazard, and therefore how a single element maybe damaged as a consequence. For example, if a building has already been covered in a metre of ash and is subsequently subjected to an earthquake – how will this change the response of the structure? Likewise if a building is subject to a large earthquake, followed by a series of aftershock events, how would each subsequent event change the original fragility curve?

Flooding (1.1)	Flooding can increase erosion in river valleys and increase slope instability (1.2) (Siwauli landslide - Dadu River)	No Interaction (1.3)	No Interaction (1.4)
Landslides can cut of the natural flow of rivers, causing damming of water courses and consequential rapid outburst (2.1) (Usoi Dam)	Landslide (2.2)	No Interaction (2.3)	Sector collapse can cause unroofing of magmatic bodies (cryptodomes), leading to rapid destabilisation and eruption. (2.4) (Mt St Helens)
Seismic activity can offset rivers causing flooding (3.1) (Hawkes Bay - Tutaekuri River)	Seismic motion can cause landslides (3.2)(Gorkha earthquake)	Earthquake (3.3)	In some rare cases regional seismictiy can trigger volcanic eruptions (3.4) (Cordon Caulle, Mt Fuji)
Crater lakes can be disrupted in eruptions, leading to wide spread flooding (4.1) (Tarawera - OVC)	Increased volcanic activity can destabilise the volcanic edific and lead to sector collapse / mass movements (4.2) (Krakatau)	Volcanic unrest periods can cause distal and promixal earthquakes (4.3) (Santa Maria (?), Pinatubo)	Volcano (4.4)

Figure 17: Cascading hazard interaction matrix for the METEOR project. Relationships between hazards can be assessed by cross-referencing between cells. Examples of other locations where these interactions have been observed in the past are also provided.

Currently the fragility curves for this type of analysis are not available from METEOR deliverable M5.2, as there are few examples where this data has been collected. Therefore, to explore the impact of multiple events on exposure in this study we propose conducting some tests of the model for a limited area and for a specific sequence of hazards. In Tanzania, this is likely to be an investigation of the potential impacts of a shock / aftershock sequence in the region surrounding Dodoma. This area was shown in the VI method to be of higher seismic hazard than much of the rest of the country (Figure 13) and is now the official capital. We will investigate the compound fragility of several earthquake events by testing the model using the Monte Carlo method discussed in Section 7.2 and in partnership with GEM.

For Nepal, this case study will be decided after the initial analysis of the data has been completed but is expected to address links between earthquake and landslide, informed by the Gorkha earthquake event (2015). These studies will test the hypotheses outlined in Figure 3 and Figure 18.

Flooding (1.1)	Destabilisation of the subsurface due to increased water saturation and erosion is likely to change the response to an earthquake, increasing the potential for liquefaction. (1.2) (Alteration to the hazard / vulnerability)	Destabilisation of the subsurface due to increased water saturation and erosion will change the potential for landslides. (1.3) (Alteration to the hazard)
Cracks and damage from earthquakes may make structures more vulnerable to increased water volumes - specifically flood management infrastructure and dams. (2.1) (Alteration of vulnerability)	**Earthquake (2.2)**	Structural damage caused by an earthquake may increase vulnerabilty to added pressures from landslides. (2.3) (Alteration of vulnerability)
Displacement and destabilisation of surface may distrupt river draingages and therefore increase the flood potential. (3.1) (Alteration of hazard)	Material destabilized by mass movements may be more susceptible to the effects of shaking. Sturctures that have already been affected by a landslide are likely to be more susceptible to earthquake hazard (3.2) (Alteration of vulnerability)	**Landslides (3.3)**

Figure 18: Cumulative hazards and their effects on vulnerability indicators (Nepal).

8. Conclusions

In this study we reviewed the current status of multi-hazard modelling and tested two methodologies that were developed for this purpose, using the hazard and exposure data generated for Tanzania by the METEOR project. We found that whilst these models were both useful, they did not fully reflect the aims of the METEOR project. As such we have proposed a hybrid framework that we will use to develop the multi-risk assessment for both Nepal and Tanzania. We intend to use sensitivity testing such as the Monte Carlo method to understand the uncertainty of the data produced by this model. We also plan to develop, with The Global Earthquake Model and other partners, a detailed case study to address cascading hazards.

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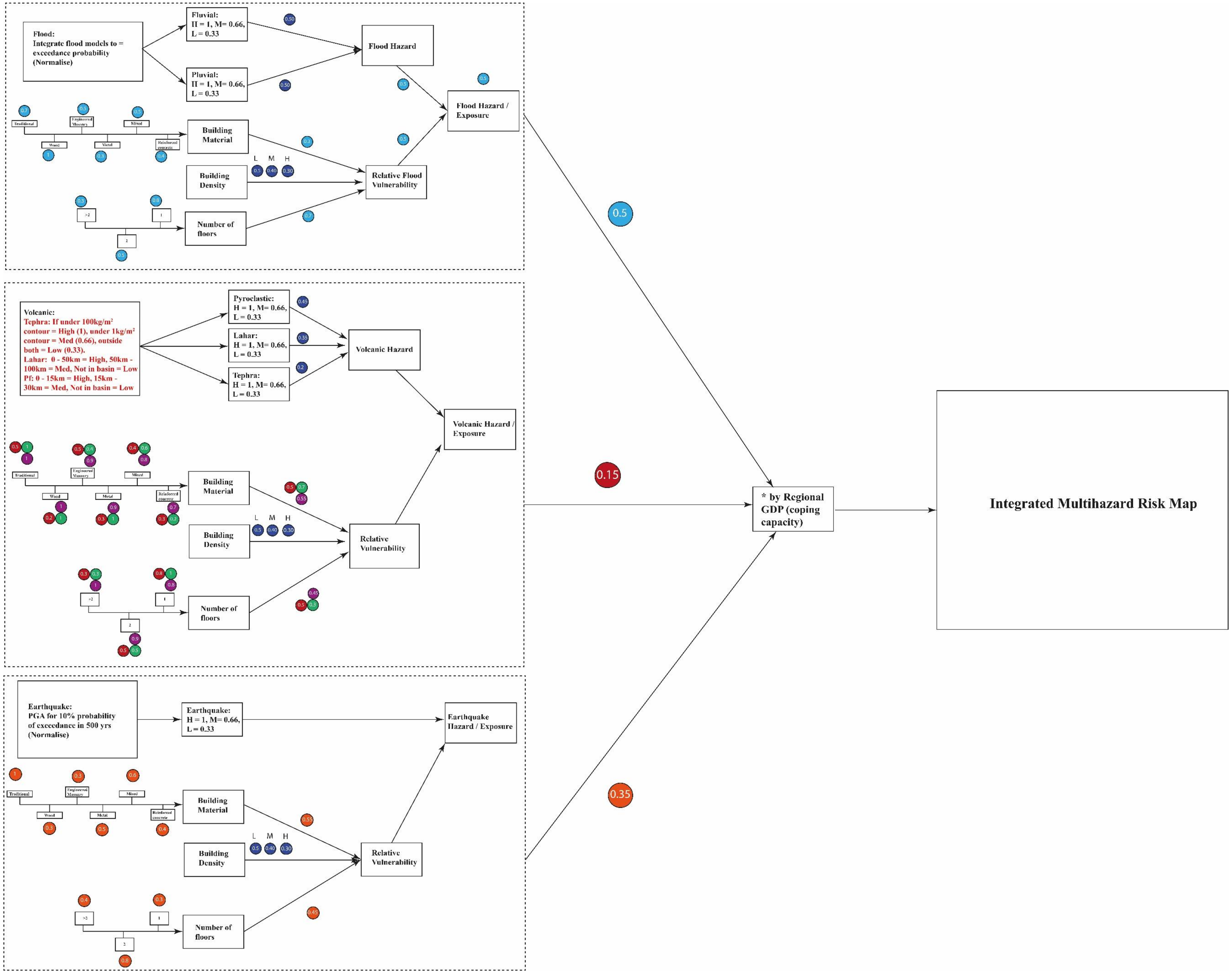
Annex A


Flood:
Integrate flood models to = exceedance probability (Normalise)
Fluvial:
H = 1, M= 0.66, L = 0.33
Pluvial:
H = 1, M= 0.66, L = 0.33
Flood Hazard
Flood Hazard / Exposure
Building Material
Building Density
Number of floors
Relative Flood Vulnerability
L M H
Volcanic:
Tephra: If under 100kg/m² contour = High (1), under 1kg/m² contour = Med (0.66), outside both = Low (0.33).
Lahar: 0 - 50km = High, 50km - 100km = Med, Not in basin = Low
Pf: 0 - 15km = High, 15km - 30km = Med, Not in basin = Low
Pyroclastic:
H = 1, M= 0.66, L = 0.33
Lahar:
H = 1, M= 0.66, L = 0.33
Tephra:
H = 1, M= 0.66, L = 0.33
Volcanic Hazard
Volcanic Hazard / Exposure
Building Material
Building Density
Number of floors
Relative Vulnerability
Earthquake:
PGA for 10% probability of exceedance in 500 yrs (Normalise)
Earthquake:
H = 1, M= 0.66, L = 0.33
Earthquake Hazard / Exposure
Building Material
Building Density
Number of floors
Relative Vulnerability
0.5
0.15
0.35
* by Regional GDP (coping capacity)
Integrated Multihazard Risk Map