A Multiscale Exposure Model for Seismic Risk Assessment in Central Asia

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INTRODUCTION

Seismic risk assessment is carried out combining hazard, exposure, and vulnerability models (United Nations Disaster Relief Organization [UNDRO], 1979). Exposure in this context refers to the elements at risk, which can be buildings, population, lifeline systems, or socioeconomic activities. Exposure data may vary depending on the scale of analysis, going from detailed descriptions of characteristics and locations of structural elements to composite models aggregated to larger geographical entities, such as administrative units, cities, or countries. When significant structural characteristics like the construction type or the building height are available, the vulnerability of structures here referred to as physical vulnerability, can be assessed by expert judgment, analytical modeling, or empirical analysis. A detailed overview of different methods for vulnerability assessment of structures is given in Calvi et al. (2006). The recently published Organization for Economic Cooperation and Development (OECD) Global Science Forum report on Global Modeling of Natural Hazard Risks 2012 (OECD, 2012) concludes, from the analysis of risk assessment practices worldwide, that exposure and vulnerability are critical elements for effective risk assessment and suggests that more efforts should be undertaken to identify and develop proxy measures to reduce uncertainties in these models and to consider their time dependency to improve assessments. Moreover, the report highlights that commonly used methods and data for risk assessments are strongly heterogeneous in format and quality, making it difficult to compare results between different methods, analysis scales, or across national borders.

Despite its importance in risk assessment and its relative independence on the underlying hazard type, reliable information on exposed assets is frequently missing, incomplete, out-dated, or strongly aggregated. This is especially the case in developing countries where commonly used exposure data capturing procedures can often not adequately cope with the rapid urban growth and increasingly high spatiotemporal variability in urban areas. Global exposure databases that specifically include physical exposure information are for example the Prompt Assessment of Global Earthquakes for Response (PAGER; http://earthquake.usgs.gov/earthquakes/pager, last accessed May 2014; Wald et al., 2008), the Global Exposure Database for GAR13 (GED-13; De Bono, 2013), and the Global Exposure Database for GEM (GED4GEM; Dell'Acqua et al., 2013). All the global exposure models face the problem of unevenly distributed data availability, where some regions of the world clearly show a lack of information about the exposed building stock and its population. Central Asia is one of these regions where crucial information about predominant building types, their composition, spatial distribution, and structural characteristics are largely missing and are, therefore, often inferred from neighboring regions, which introduces a large degree of uncertainty into any loss estimations of the region.

In this regard, the Earthquake Model Central Asia (EMCA; http://www.emca-gem.org, last accessed May 2014), as the regional initiative for Central Asia to the Global Earthquake Model (GEM; http://www.globalquakemodel.org, last accessed May 2014), develops in close collaboration with local institutes a comprehensive exposure model for the data-poor countries of Central Asia (Kyrgyzstan, Kazakhstan, Tajikistan, Turkmenistan, and Uzbekistan). The main aim of EMCA is to provide up-to-date cross-border seismic risk assessments (Pittore et al., 2011). This includes also the development of a revised seismic-hazard model for the region and microzonation studies of the most important urban settlements. Having a good understanding of exposure and vulnerability in the region, however, is of utmost importance for seismic risk assessments, especially on the background that Central Asia is one of the seismically most hazardous areas in the world (Bindi et al., 2012) and that it shows an increasing urbanization trend and a potentially high vulnerability of the building stock.

The objective of this study is to describe the development of the EMCA exposure model. Particular focus points within the exposure modeling include the collection and harmonization of available data and the development of tools and methods to continuously update the exposure model at multiple scales.

STUDY AREA

Central Asia, covering the countries of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (Fig. 1) with a combined population of about 60 million people, is located in the collision zone between the Eurasian and Indo-Australian lithosphere plates. As shown by its historical seismicity, the region is prone to large earthquakes, where between the end of the 19th century and the beginning of the 20th, several destructive earthquakes struck Central Asian cities. Examples include the Belovodsk earthquake that hit the city of Kara-Balta, just west of Bishkek in Kyrgyzstan, on 3 August 1885 with a maximum intensity of IX, the **M** 7.8 Kemin (Kyrgyzstan) earthquake of
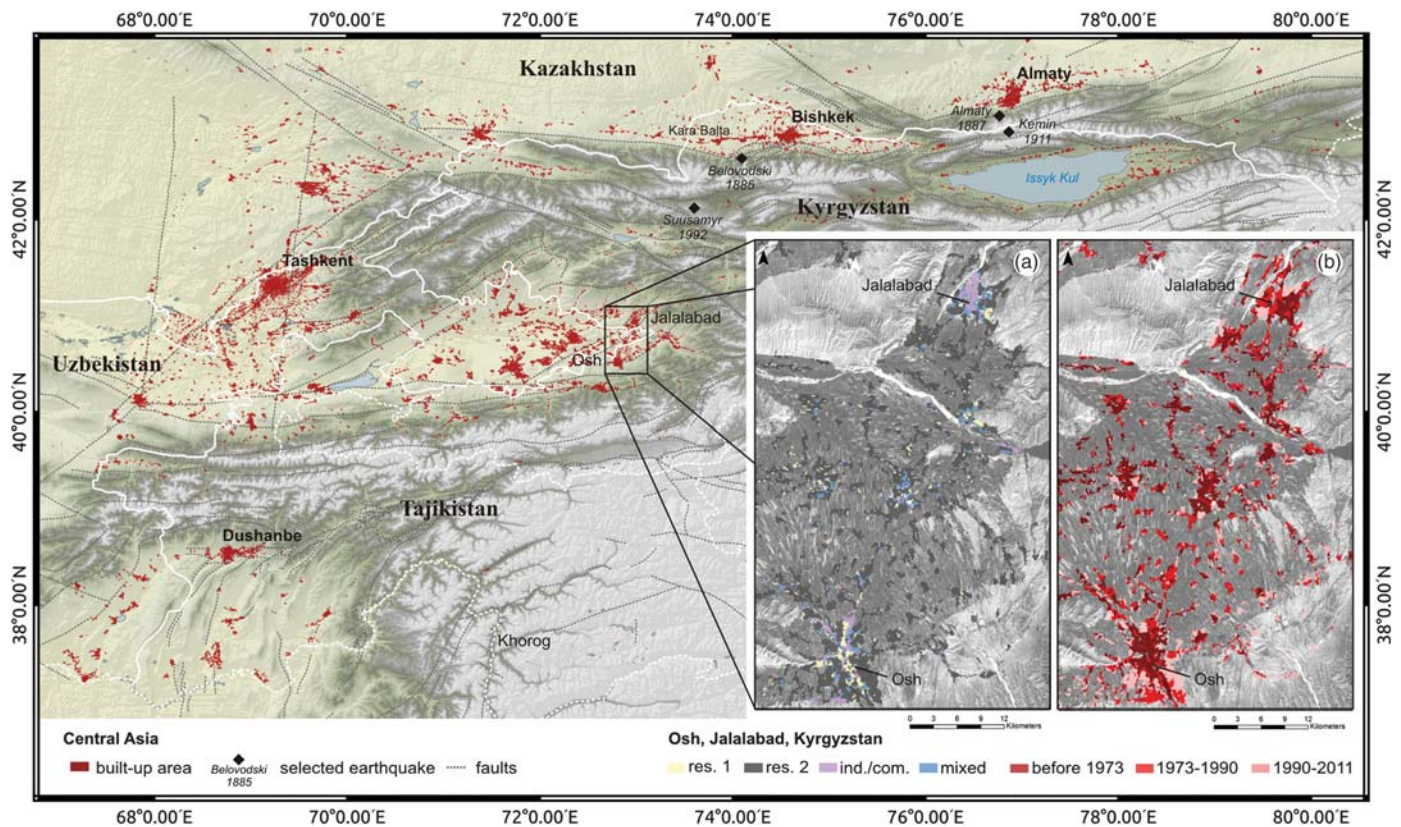
▲ **Figure 1.** Overview of the study area with built-up area mask and the tier 2 exposure zonation derived from remote sensing. The magnified view shows (a) the urban structure types and (b) the spatiotemporal evolution of the area covering the Osh/Jalalabad region.

3 January 1911, which killed several hundred people (Abdrakh-matov *et al.*, 2003), and the Almaty (Kazakhstan) earthquakes in 1887 and 1910 (Khalturin *et al.*, 1997). On 19 August 1992, an earthquake of magnitude **M** 7.3 struck the western part of the Suusamyr valley in the north Tien Shan region of Kyrgyzstan.

The high level of seismic hazard (Giardini *et al.*, 1999; Bindi *et al.*, 2012) coupled with a potentially high physical vulnerability of the building stock results in a high seismic risk for the region. A workshop held in Almaty in October 1996 on the "Strategies for urban earthquake risk management for the Central Asian Republics" pointed out that the seismic resistance of Soviet-era buildings was significantly lower than was officially proclaimed. Analyzing the devastating effects of the 1988 Armenian and 1995 Sakhalin earthquakes, the authors observed that "Millions of people in Central Asia live in the same types of buildings as those collapsed in Armenia and Sakhalin. If an earthquake of the same size occurs near one of the Central Asian capitals, the tragedies of Leninakan, Spitak, and Neftigorsk will be repeated on a much bigger scale, unless urgent measures are taken (Khalturin *et al.*, 1997)."

King *et al.* (1999) provided an overview of common construction types and their vulnerabilities in the different post-Soviet Central Asian countries. It becomes evident that the different countries share a largely similar set of building types as the result of a common history during Soviet time. The current classification and characterization of the building types manifested in the respective building codes, however, varies significantly between the countries (see EMCA Building Typology section). There seems to be a rather good understanding about the composition of governmental buildings that were constructed mainly during the Soviet era. However, information about the building stock of the private sector that developed mainly after 1990 is largely missing in exposure and vulnerability models. Moreover, a lack of resources to keep track of the increasingly high spatiotemporal development especially in the main urban areas can be observed. As a result not only sparse data are available about exposed assets but, moreover, the few available data are largely outdated, spatially fragmented, or highly aggregated and are strongly heterogeneous especially across the national borders.

METHOD

The approach followed in this study for the assessment of exposed assets is based on different data sources and acquisition techniques that are combined in the framework of an integrated sampling scheme (Fig. 2). In a hybrid top-down/bottom-up approach, the processing scheme moves from regional scale to neighborhood and per-building scale and back, involving three analysis tiers that interact with each other and that are based on the analysis of different data sources. Across this pyramidal searching, only the necessary data is acquired and processed, and the focused geographical extent is narrowed. The aim is to minimize acquisition costs and processing time and to guide more detailed per-building surveys. At the per-building scale, any
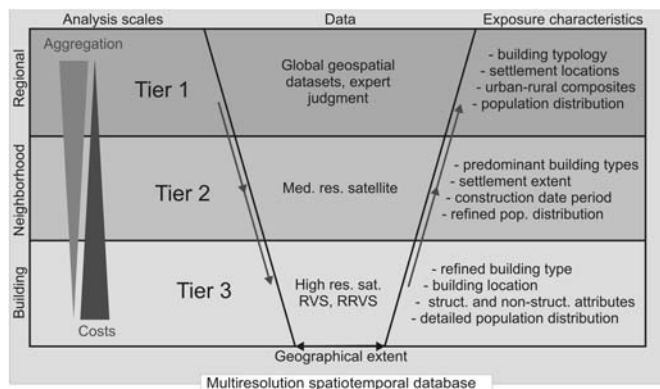
▲ **Figure 2.** Outline of the approach to multiscale exposure estimation from multiple sources with considered analysis scales, input data, and relevant scale-dependent exposure information.

information is defined at the most detailed level of individual buildings, whereas at the broader neighborhood and regional scales, exposure information is aggregated. The neighborhood scale ranges from one to several blocks, whereas the regional scale ranges from city to district or country-wide aggregation.

A multiresolution spatiotemporal database forms the back end of the EMCA exposure model. The database model holds the data at the multiple spatial scales and has a temporal support to document changes to exposed assets in space and time. The latest version of the GEM building taxonomy (Brzev *et al.*, 2012) has been implemented in the database model to describe the characteristics of exposed assets.

Exposure analysis at a tier 1 level involves the design of a harmonized, regionally valid, and agreed-upon building typology and an assessment of dominant building types and their relative frequency in the different Central Asian countries. Combining prior distributions from local expert judgment with global geospatial datasets (e.g., GeoNames; http://www.geonames.org, last accessed May 2014, OpenStreetMap; http://www.openstreetmap.org, last accessed May 2014) a consistent exposure information layer for the whole study area is defined. In a tier 2 analysis, free-of-cost medium-resolution satellite images are analyzed to outline the extent of built-up areas and to delineate them into areas of relatively homogeneous urban structure at an aggregated neighborhood scale. The tier 2 analysis provides a detailed processing mask for exposure (Wieland *et al.*, 2012a), and the resulting zonation concurs to define the spatial base layer for a stratified sampling to optimize *in situ* data capturing at the most detailed per-building scale. In a tier 3 analysis, per-building data is acquired and integrated using standard rapid visual screening (RVS; Federal Emergency Management Agency [FEMA] 154, 2002), novel remote rapid visual screening (RRVS) from omnidirectional camera images (Wieland, Pittore, Parolai, Zschau, Moldobekov, *et al.*, 2012) and high-resolution satellite image analysis (Wieland *et al.*, 2012b).

EMCA Building Typology
Despite the fact that the countries of Central Asia share a decades long common political history and largely similar construction practices coming from the Soviet era, the current

classification and characterization of the building types manifested in the national building codes varies strongly between the countries. The Kyrgyz building code divides the national building stock into 10 groups with a total of 31 subgroups. In the Tajik building code, 11 groups are divided into 20 subgroups. The building code of Turkmenistan distinguishes between 9 main groups and 14 subgroups, whereas the Uzbek code splits the building stock into 24 groups. The different classification schemes evolved naturally on a national basis after the collapse of the former Soviet Union. The national typologies are reasonable in the context of country-specific policies and regulations. However, a unified building typology that is characterized on the basis of an international standard building taxonomy is crucial for a regional cross-border risk assessment.

To this regard, the national building typologies were carefully reviewed and a limited set of building types that are representative for Central Asia was agreed upon amongst experts on building construction from all Central Asian countries during a joint workshop on exposure and vulnerability that was organized by the EMCA project in Kyrgyzstan in April 2013. The resulting EMCA building typology consists of 6 main building types with a total of 16 subtypes (Table 1). The main building types are distinguished based on the main structural type, construction material, and building height. The refinement into subtypes is based on differences within the main construction materials and structural type classes that can significantly influence the performance of a structure in case of ground motion. Moreover, the construction date period was considered to be an important attribute for the classification of EMCA building types, because significant changes to the respective building codes have appeared in the past. The EMCA building typology, moreover, provides look-up tables that link the EMCA building types to the building types in the respective local building codes. This guarantees transparency and allows for forward and backward transformation between the typologies. An example that links the EMCA type to the building types of the Kyrgyz building code is given in Table 1. National building types that were not considered as being representative for the Central Asian building stock were not included into the EMCA typology as separate subtypes, but could be mapped to the respective main types for consistency.

Building reports have been compiled for each EMCA building type and subtype with a standardized characterization of structural and nonstructural attributes following the GEM Building Taxonomy (Appendix). Attributes covered by the EMCA typology include material technology and type, lateral load resisting system, system ductility, foundation, plan shape, irregularities, number of floors above and below the ground, floor system material and type, roof system material and type, and date of construction and occupancy.

Exposure Zonation from Remote Sensing
Urban structure types can provide a valuable concept for the zonation of a city into meaningful spatially defined units that reflect well the actual composition of exposed assets. With respect to mapping exposure from satellite images, urban structure types are, in the following, defined as spatial units of the

Table 1
EMCA Building Types Showing Their Connection to the Local Building Codes for the Example of Kyrgyzstan

EMCA Type	Subtype	Building Class	Building Subclass	Country Code
EMCA-1	1.1	Load bearing masonry wall buildings	Unreinforced masonry, buildings with walls of brick masonry, stone, or blocks in cement or mixed mortar (no seismic design), wooden floors. Built between 1940 and 1955. 2–4 stories.	KY-1.4
	1.2		Unreinforced masonry, buildings with walls of brick masonry, stone, or blocks in cement or mixed mortar (no seismic design), precast concrete floors. Built since 1975. 1–2 stories.	KY-1.5
				KY-1.6
	1.3		Confined masonry. Built since 1960. 1–5 stories.	KY-1.1
				KY-1.2
	1.4		Masonry with seismic provisions (e.g., seismic belts). Built between 1948 and 1959. 1–3 stories.	KY-1.3
EMCA-2	2.1	Monolithic reinforced concrete buildings	Buildings with monolithic concrete moment frames. Built since 1950. 3–7 stories.	KY-2.1
	2.2		Buildings with monolithic concrete frame and shear walls (dual system). Built since 1987. 7–25 stories.	KY-2.2
	2.3		Buildings with monolithic concrete frames and brick infill walls. Built since 1975. 3–7 stories.	KY-2.3
	2.4		Buildings with monolithic reinforced concrete walls. Built since 1980. 8–16 stories.	KY-4
EMCA-3	3.1	Precast concrete buildings	Precast concrete large panel buildings with monolithic panel joints, Seria 105. Built since 1964. 1–16 stories.	KY-3.1
	3.2		Precast concrete large panel buildings with panel connections achieved by welding of embedment plates, Seria 464.	KY-3.2
	3.3		Precast concrete flat slab buildings (consisting of columns and slabs), Seria KUB. Built between 1980 and 1990. 5–9 stories.	KY-2.8
	3.4		Prefabricated reinforced concrete frame with linear elements with welded joints in the zone of maximum loads or with rigid walls in one direction, Seria 111, IIS-04. Built between 1966 and 1970. 6–7 stories.	
EMCA-4	4.1	Nonengineered earthen buildings	Buildings with adobe or earthen walls. Built since 1850. 1 story.	KY-9.5
EMCA-5	5.1	Wooden buildings	Buildings with load bearing braced wooden frames. Built between 1950 and 1970. 1–2 stories.	KY-9.7
	5.2		Building with a wooden frame and mud infill. 1–2 stories.	KY-9.6
EMCA-6	6	Steel buildings		KY-8

built environment at an aggregated neighborhood scale, which are relatively homogeneous in terms of their physical appearance (land-cover) and usage (land-use) as well as their approximate construction date. The delineation of a city into areas of relatively homogeneous urban structure types aims at creating the base layer that provides the computational units for risk assessments and provides a generalized but spatially defined description of an exposed building stock. Moreover, it provides information about the spatiotemporal development of exposed assets and forms the strata for selecting samples for a detailed per-building analysis (see Sampling for Per-Building Assessment section). The sample information coming from other acquisition techniques at the finer per-building scale or from statistical inference can in return be used to enrich the information content of the remote sensing base layer.

The extraction of urban structure types is carried out on the basis of medium-resolution multispectral satellite images of the Landsat satellite sensors. The images are available for free with a global coverage and image archives date back to the early 1970s. The ground sampling distance varies between the sensors from 15 to 60 m with a spectral resolution of 4 to 10 bands. In successive stages of zonation, the image pixels are clustered and labeled depending on their approximate construction date and predominant building types using change-detection analysis and machine learning assisted image analysis. The zonation steps are explained in detail in Wieland et al. (2012a). Complementary information about parameter tuning and training of image analysis algorithms along with a performance evaluation of different machine learning classifiers that were used for the urban pattern recognition is given in Wieland and Pittore (2014).

For the exposure model derived in this study, a regional classification of 130 Landsat images is carried out over an area of approximately $800,000 \text{ km}^2$ and a time period of 40 yrs with 3 main timestamps (1970s, 1990s, and 2010s). The resulting tier 2 exposure information layer for the study area is depicted in Figure 1 with a magnified view of the cities of Jalalabad and Osh in Southern Kyrgyzstan.

Sampling for Per-Building Assessment

Estimating exposure information on an aggregated neighborhood scale can be regarded as the problem of estimating a parameter of interest by sampling it over an unknown population (Cochran, 1977). In the case of exposure estimation, the considered population is functionally dependent on several physical attributes of the building stock. It can be estimated at a per-building scale by visual observation, and it can be approximated by a spatial function of the geographical position. The urban structure types base layer derived from satellite image analysis, therefore, forms a suitable zonation of the buildings population into relatively homogeneous subpopulations and is considered the strata from which to draw samples from using a stratified random sampling with proportional allocation.

The sampling strategy followed within this study for selected urban areas combines the zonation provided by the base layer with a 1D street network of the same area. A route is calculated along the network where a buffer around the streets is taken into account for sample area definition. From each unit of each stratum of the population of interest, only the building population that is actually visible from the street is sampled. It is therefore designed for *in situ* street surveys that set out to capture building characteristics, either by a car using an omnidirectional camera system or by foot using standard RVS techniques (FEMA 154, 2002). The sampling strategy aims at reducing the overall driving or walking length of *in situ* surveys to minimize costs and time for a field trip and to avoid the capturing of redundant data. All stratum units of the base layer within a predefined area of interest shall be covered by the sampling. Therefore, the algorithm designed to compute the sample areas identifies for each unit a point on the street network that is inside the unit, closest to its centroid, and selects it as stop for the routing. A Dijkstra algorithm (Dijkstra, 1959) is used to determine the best route through the series of ordered stops (Lenstra and Kan, 1975) with a minimum cost. Figure 3 shows an example of a route calculated for an *in situ* survey with a mobile mapping system (see Per-Building Assessment section) in the city of Jalalabad in Southern Kyrgyzstan.

Per-Building Assessment

The per-building assessment of exposed assets within EMCA can be divided into three main parts based on the type of data acquisition:

1. Digitization, geocoding, and harmonization of exposure data from RVS surveys by local structural engineers
   Screening procedures similar to FEMA 154 (FEMA 154, 2002) have been carried out in the different Central Asian countries by local engineers for many years for detailed per-building analysis. Because of the large time and costs involved with such surveys, the data are only sparsely available throughout the study area. Currently, datasets were made available to EMCA by local partner institutions for the cities of Bishkek and Dushanbe. For the cities of Almaty and Tashkent aggregated data from screening surveys were provided. Difficulties arose concerning the data harmonization with respect to differences in data format, choice of attributes, taxonomic description of the collected attributes, and geocoding. Therefore, extensive preprocessing of the available datasets was carried out in close collaboration with the respective partner institutions. Depending on the processing level of the gathered screening datasets, several actions had to be undertaken to preprocess them. In this context, paper forms were digitized into tabular format, inventory tables were translated from Russian to English, attributes and assigned building characteristics were transformed into the GEM Building Taxonomy, and address locations were transferred into a coordinate-based geocoding system.

2. Omnidirectional imaging and RRVS surveys
   A mobile mapping system (GFZ-MOMA) has been developed for efficient *in situ* exposure data capturing on a per-building level (Wieland, Pittore, Parolai, Zschau, Moldobekov, *et al.*, 2012). The system is composed of a Ladybug3 omnidirectional camera, a Global Positioning System (GPS) receiver, a data capturing and storage device, and a navigation unit. The camera system is mounted on the roof of a car, the position of which can be tracked using the GPS signal. The position can be displayed in real time by the navigation unit, therefore allowing an operator to navigate the car along precalculated routes.
   An analysis of the captured omnidirectional image sequences (Fig. 4) is performed through visual image interpretation by local structural engineers. Because of its similarities to commonly used screening procedures, the difference being that it is performed remotely, this novel technique is referred to as RRVS. A specific RRVS system has been implemented to allow for user-friendly, rapid, and standardized image analysis. The system is composed of a map-interface, an omnidirectional image viewer and a customizable data entry form that currently supports the GEM Building Taxonomy and is linked to the EMCA exposure database (see Multiresolution spatiotemporal Database Model section). The map-interface is based on QGIS and allows the display of building locations along with the GPS locations of the images captured during the field survey. Once a building of interest has been located in the map-interface and the nearest captured omnidirectional image has been identified and displayed in the image viewer, the building can be screened remotely by structural engineers. Uncertainties related to the assignment of attribute values can be quantified by the operator through additional qualifier attributes. In the current implementation of the RRVS tool, the degree of belief is supported as a qualitative measure of uncertainty for each attribute.

Omnidirectional images have been acquired for the cities of Bishkek (Kyrgyzstan; Wieland *et al.*, 2012a), Osh (Kyrgyz-
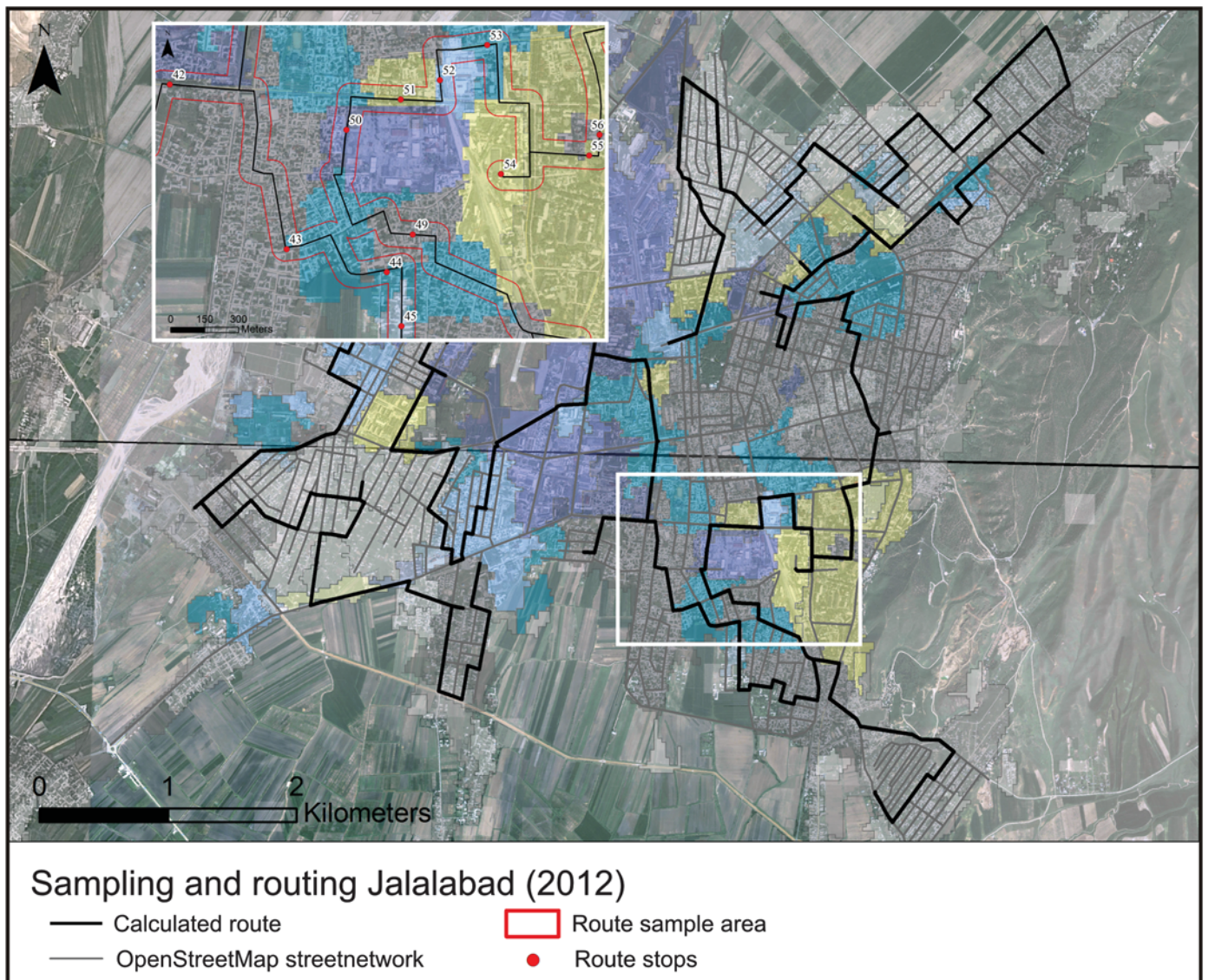
▲ **Figure 3.** Example of a sample route calculated on the basis of the remote sensing base layer and a 2D street network for the city of Jalalabad, Kyrgyzstan.

stan), Jalalabad (Kyrgyzstan), Dushanbe (Tajikistan; Pilz *et al.*, 2013), and Khorog (Tajikistan). Field surveys are easy to perform, and operators do not necessarily have to be skilled engineers because the screening of building is carried out at a later stage by analyzing the captured images. If combined with a smart sampling, this can make *in situ* surveys potentially time and cost efficient. The surveys in Central Asia took 1–3 days per city depending on the overall sample size (ranging from 50 to 200 km). Using the RRVS system, in average approximately 400 buildings could be screened by a skilled operator within one week. Decentralized data analysis by a group of experts working on the same dataset could even speed up the analysis process.

3. High-resolution satellite image analysis

An additional source of exposure information on a per-building scale are high-resolution satellite images with a ground sampling distance < 1m. A semiautomated image processing and analysis chain has been developed to extract a detailed built-up mask from multispectral satellite images such as Ikonos, Quickbird, and WorldView-2. The analysis chain utilizes a multiscale segmentation with succeeding classification stage based on machine learning algorithms (Wieland and Pittore, 2014). The resulting built-up mask provides information about the location and floor area of buildings. It also functions as base layer for a full enumeration of the number of buildings and for a detailed disaggregation of population statistics. A detailed description on how the number of buildings and population distribution is derived with the use of high-resolution multispectral satellite images is given in Wieland *et al.* (2012b).

Cities for which results from high-resolution satellite image analysis are included in the EMCA exposure model are Bishkek, Osh, Jalalabad, and Karakol in Kyrgyzstan, Almaty in Kazakhstan, Tashkent in Uzbekistan, Ashgabat in Turk-

▲ **Figure 4.** Omnidirectional image acquired during an *in situ* survey in Khorog, Tajikistan, 2012.

menistan, and Dushanbe in Tajikistan. Where available, we used data directly from the population and housing censuses of the National Statistical Committees as the basis for a disaggregation of population numbers from administrative units to the built-up units. The dasymetric method is used for disaggregation as it is commonly regarded as providing a stable and accurate model that depends less on the image classification accuracy than on the quality of the ancillary data used as input (Wu *et al.*, 2005). To estimate population density of built-up units for parts of a city where no or incomplete population statistics are available, regression models are deployed, using the built-up area and population numbers as independent and dependent variables, respectively. For each city the built-up units, which overlap with the source zones and for which population numbers could be directly disaggregated from the census data, were used as input for the regression. This means that the population over all the source zones is used in the regression, therefore providing an estimation of the average population per built-up area, which is independent of a specific source zone. As the census data are related to resident population, only residential areas are taken into account for the population estimation.

Multiresolution Spatiotemporal Database Model
A multiresolution spatiotemporal database model has been developed that functions as back-end for the storage and management of exposure data from different sources, at varying scales and changing over time. To deal with the representation of spatial objects at different scales, a bottom-up approach is followed in which datasets of different scales are linked using additional attributes, which identify the corresponding objects in the lower levels of detail while being reactive to geometry changes. A bitemporal representation of time has been implemented, which distinguishes transaction time from valid time as different types of time. The transaction time (or registration time) indicates the time an event is recorded in the database. The valid time (or real world time) refers to the time when an
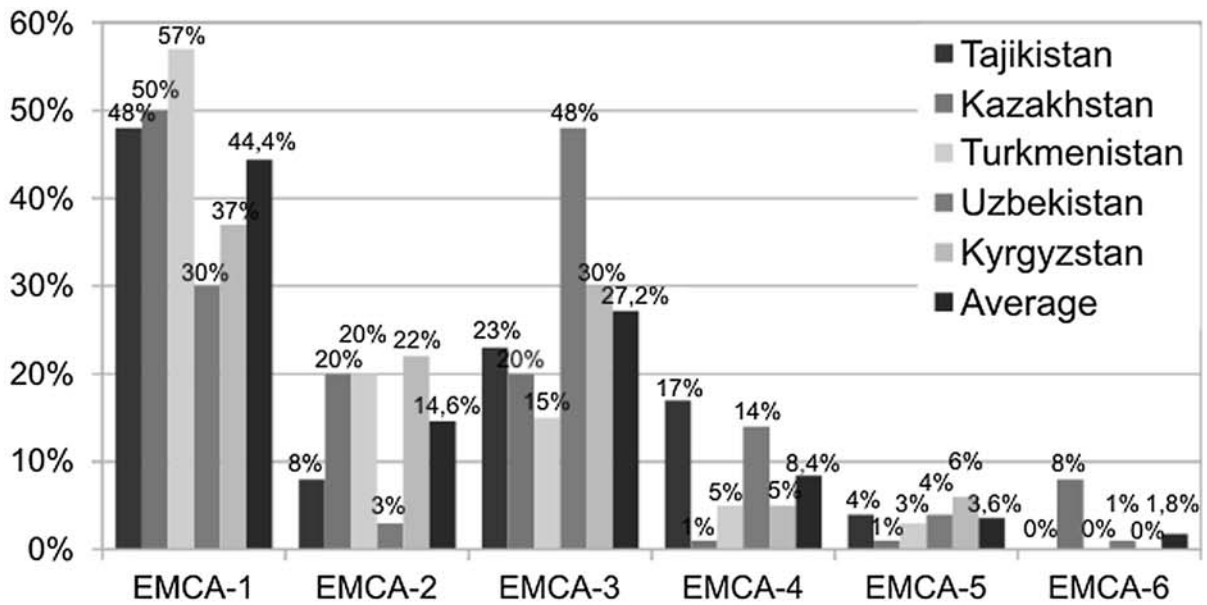
event actually happened in the real world. Therefore, real world changes (e.g., a new building has been constructed) can be distinguished from database updates as a result of new information becoming available. This also allows to model the lifespan of objects and to keep track of the evolution of the database content. The database model has been designed to be able to integrate and manage exposure attributes that follow possibly different taxonomies that are, moreover, likely to depend on the type of hazard and the geographical region of interest. In its current implementation, the model could be validated against the GEM Building Taxonomy. Uncertainty can be attributed in the data model in the form of attribute qualifiers such as accuracy or degree of belief.
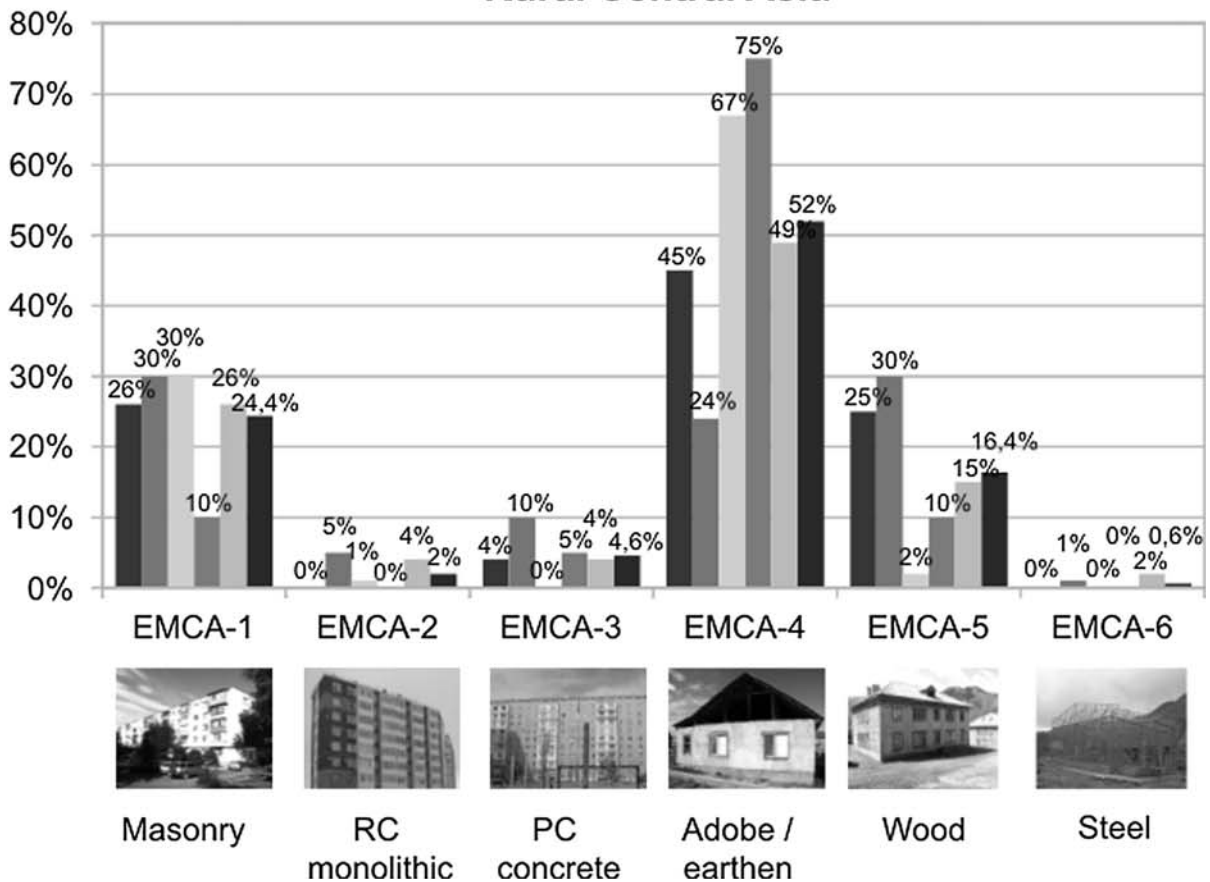
RESULTS

A prior distribution of EMCA building types throughout Central Asia has been derived as part of a tier 1 exposure model. The model describes the predominant residential building types in Central Asia through a second-level model following the EMCA building typology. The first level is an aggregated description based on 6 main building types. A second level provides a more refined description based on 16 building types. The expected composition of the residential building stock in each of the represented countries has been estimated on both levels, also considering the difference between urban (applied to settlements with more than 50,000 inhabitants) and rural environments. Figure 5 shows the estimated composite model for urban and rural settlements considering the first level exposure model. This initial regional exposure model has been devised through several rounds of consultation with local experts. The prior distribution of building types could be spatially resolved through combination with settlement locations derived from OpenStreetMap and Geonames. Hot-spot areas in terms of seismic risk are modeled at a higher level of detail integrating sampled per-building information from *in situ* surveys. Also capital cities are considered separately, because often their building stock shows significant differences with respect to urban settlements in the rest of a
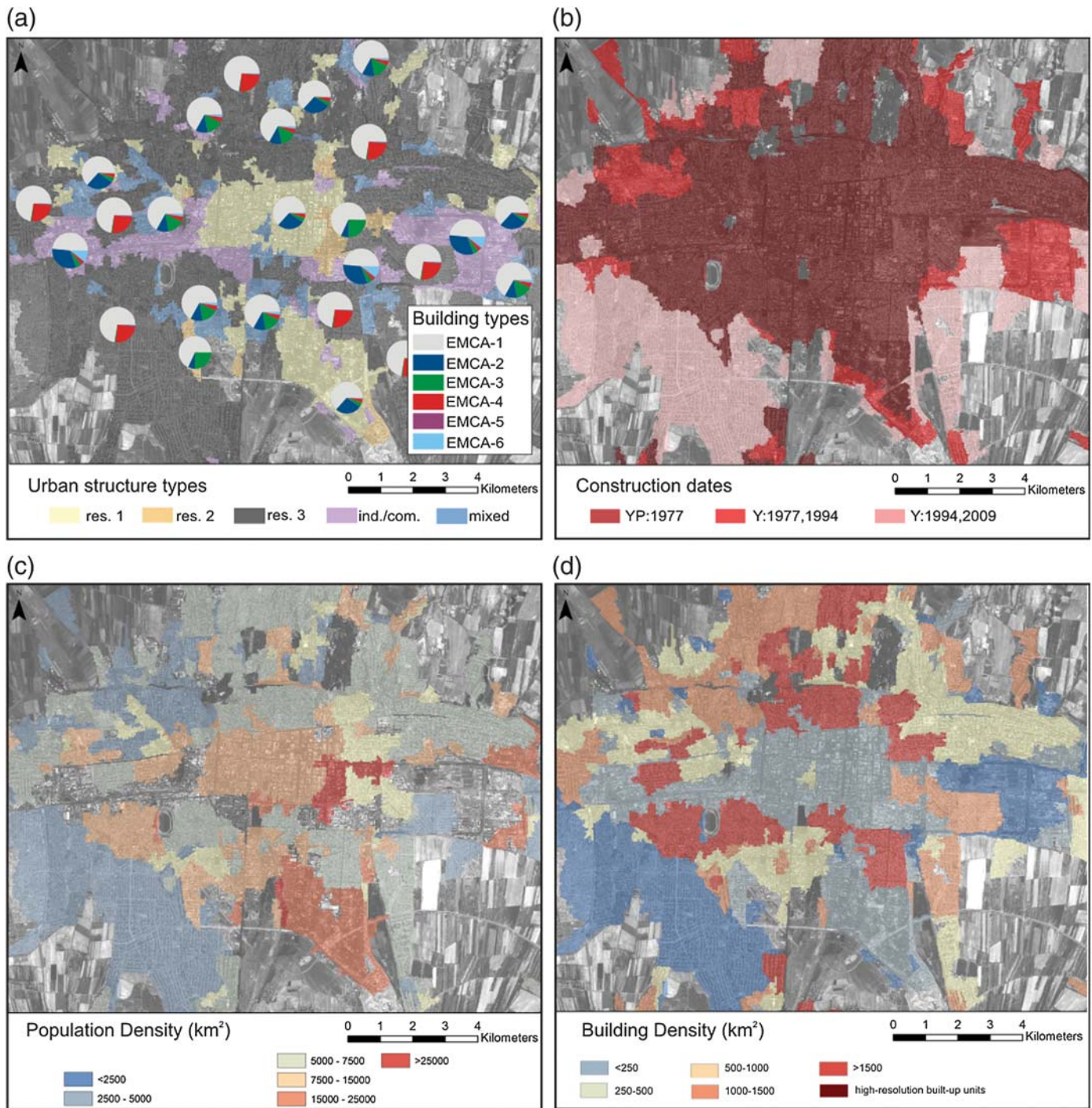
Figure 5. Tier 1 exposure model derived from local expert judgment. The model separates urban and rural areas for the different Central Asian countries and gives an estimate of the composition of building types according to the Earthquake Model Central Asia (EMCA) building typology. The distribution for urban areas is not considering capital cities.

▲ **Figure 6.** (a) Tier 2 urban structure types zonation of Bishkek, enriched by composite models of EMCA building types from a tier 3 analysis. (b) Spatiotemporal evolution of the built-up area with approximate construction date periods. (c) Population density per zone. (d) Building density per zone.

country. In the following, results are presented for Bishkek, the capital of Kyrgyzstan (Fig. 1).

For the main urban area of Bishkek, approximately 110,000 buildings and almost 850,000 inhabitants along with their spatial distribution have been estimated from an analysis of satellite images under consideration of local census reports. Detailed conclusions can be drawn about the distribution of urban structure

types (Fig. 6a) and the spatiotemporal evolution of the city (Fig. 6b), including information about population (Fig. 6c) and building (Fig. 6d) counts, and their density distributions. Accuracy assessments of the derived information products are presented in Wieland *et al.* (2012a) and Wieland *et al.* (2012b).

The zonation of the urban environment into structure types has been used to select a stratified random sample of

buildings to be surveyed in detail using the RRVS of omnidirectional images captured in Bishkek. Almost 700 buildings have been screened with this procedure for structural and nonstructural characteristics by local engineers. This data were combined with a set of 1400 buildings previously screened using a standard RVS procedure. For both datasets, EMCA building types were assigned based on main structural type, material, and height attributes. In the presented example, these attributes were available for all the buildings, and a deterministic classification was carried out using the values provided in the EMCA building typology. In case of sparse information availability, a probabilistic information integration procedure based on Bayesian networks is proposed (Pittore and Wieland, 2013). Composite models of EMCA building types were created for each structure type and assigned to the respective zones throughout the city (Fig. 6a). Combining the relative distribution of EMCA building types with the estimated number of buildings per zone enabled deriving a composite model for the whole city (Fig. 7). From Figure 7, it can be seen that the EMCA-1 building type is clearly dominating the urban environment of Bishkek covering 70% of the buildings in the city. EMCA-4 building types account for 21% of the building stock, followed by EMCA-2 and EMCA-3 types with 5% and 3%, respectively. EMCA-5 and EMCA-6 types are hardly present accounting for less than 1% of the building stock of Bishkek. The spatiotemporal patterns of the urban sprawl (Fig. 6b) indicate that the urban expansion between 1977 and 1994 concentrated mainly on the suburban eastern and northern parts of the city. From 1994 to 2009, large quarters have been built in the northern parts of the city. The main urban expansion during this recent time period, however, takes place in southern direction toward the Issyk-Ata fault. These areas close to the fault system, where many new buildings of potentially vulnerable EMCA-4 type are still being constructed, show the highest seismic hazard in the study area (Erdik *et al.*, 2005), indicating a trend toward an increased seismic risk in Bishkek.

DISCUSSION AND CONCLUSIONS

This paper provided an insight into the development of a harmonized multiscale exposure model for Central Asia. Main challenges that have been tackled include a general lack of up-to-date exposure data in Central Asia at all analysis scales, lack of cross-border standards (related to building typology and exposure characterization) and heterogeneity of available data in terms of quality, spatial coverage, and level of detail. Data management, harmonization, and integration concepts were provided and new data collection techniques were developed and tested as part of the EMCA exposure model activities.

The presented multiscale exposure modeling approach provided a tier 1 regional assessment that covers all the Central Asian countries, incorporates local expert-knowledge, and is spatially resolved at the settlement level while considering differences between urban and rural areas. A tier 2 exposure information layer was independently derived from remote sensing. It represents a useful zonation that is closely linked
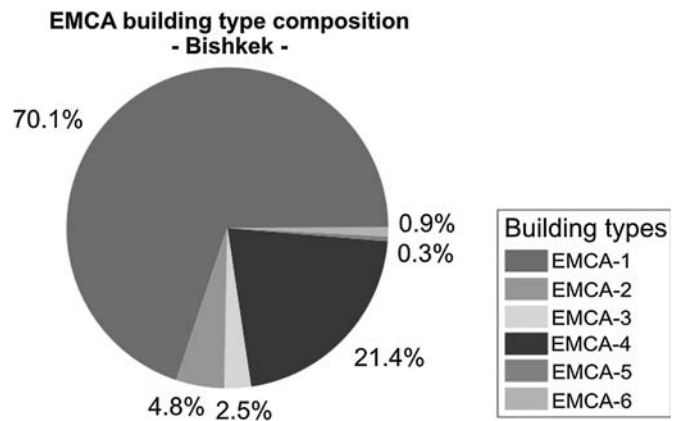
▲ **Figure 7.** Composite model of EMCA building types for the city of Bishkek derived from tier 2 and tier 3 analysis results.

to the actual physical appearance of the exposed assets. Because of the pyramidal structure of the approach, the geographical analysis focus could be narrowed and cost and time resources for *in situ* surveys could be minimized through the use of sampling strategies. High-resolution satellite image analysis and the proposed GFZ-MOMA system in conjunction with a RRVS procedure could further enhance the efficiency of *in situ* data acquisition. A comprehensive cost-benefit analysis that compares commonly used approaches (grid-based zonation and standard RVS field surveys) with the EMCA approach is still to be carried out to sufficiently benchmark the new techniques.

A major step toward a cross-border harmonization of risk assessment could be achieved through the development of a harmonized building typology for Central Asia as a result of the collaborative efforts by experts from all the relevant countries. Not only a harmonized typology was agreed upon but also the building types were characterized following the GEM Building Taxonomy, and the relative frequency of occurrence of the different building types in the various countries was assessed as prior information for a tier 1 exposure information layer. Open points with respect to a characterization of exposed assets include a possible extension of the taxonomy to support other (nonstructural) elements (e.g., socioeconomic attributes) and the development of vulnerability curves for the different EMCA building types.

During the development of the data model, particular focus was given to account for spatial, temporal, and spatiotemporal query capabilities that allow modeling the life time of exposed assets and their evolution in space and time. In this context, a comprehensive testing of the spatiotemporal database of the EMCA exposure model is still to be carried out. Uncertainties are managed within the EMCA exposure model at the database level through attribute qualifiers. For the remote sensing products detailed accuracy assessments are carried out, whereas for the RRVS procedure explicit uncertainty measures are implemented in the data entry form. For information integration and finally vulnerability assessment, Bayesian networks can provide a flexible and transparent technique to account for uncertainties. A case study on probabilistic infor-

mation integration and vulnerability assessment based on some of the data sources described in this paper is provided in Pittore and Wieland (2013) for the city of Bishkek. More research in the direction of probabilistic information integration is currently being undertaken and also an assessment of the influence of scale and quality of exposure information on the final loss estimation is planned.

In conclusion, the development of the exposure model proposed within this study is to be regarded as an iterative process that aims at a continuous model updating rather than at a static modeling at a single timestamp. The current state of the model should be used as input to optimize future data collection in the sense that it most efficiently improves the overall model accuracy and takes into account new evolutions in the exposed environment like urban growth patterns. In seismic risk assessment the significant dynamics are not introduced by the hazard component but by changes of the exposed assets and their vulnerability. Therefore, a continuous updating of the exposure model is important to avoid information obsoleteness and to keep the overall risk model valid. This becomes particularly important in regions like Central Asia where in recent years an increasingly high spatiotemporal variability and concentration of exposed assets in hazardous areas could be observed. ⧉

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GEM Building Taxonomy Report
PreCast building type 3.1
EMCA working group

Taxonomy string:
DX /CR+PC /LWAL+DUC /DY /CR+PC /LWAL+DUC /YBET:1964,2012 /HBET:1,16+HBEX:1+HFBET:1,1.8+HD:0 /RES+RES2F /BPD /PLFR /IRRE /EWC /RSH1+RMN+RC+RC3+RTDP /FC+FC3+FWCP /FOSDL

Material type (direction 1):
  Concrete, reinforced
Material properties (direction 1):

Lateral load-resisting system (direction 1):
  Wall
Material type (direction 2):
  Concrete, reinforced
Material properties (direction 2):

Lateral load-resisting system (direction 2):
  Wall
Foundations:
  Deep foundation, with lateral capacity
Type of Irregularity:
  Regular structure
Plan structural irregularity - primary:

Plan structural irregularity - secondary:

Roof shape:
  Flat
Roof system material:
  Concrete
Roof connections:
  Roof tie-down present
Floor system material:
  Concrete
Floor connections:
  Floor-wall diaphragm connection present
Exterior walls material:
  Concrete
Date of constrution:
  Bounds for the date of construction or retro 1964-2012
Number of storeys above the ground:
  Range of the number of storeys   1-16
Height of the grade above ground floor:
  Range of height above grade   1-1.8
Occupancy type - general:
  Residential
Country:
  Unknown
Summary:

Material technology (direction 1):
  Precast concrete
Material techonology (additional, direction 1):

System ductility (direction 1):
  Ductile
Material technology (direction 2):
  Precast concrete
Material techonology (additional, direction 2):

System ductility (direction 2):
  Ductile
Plan shape:
  Rectangular, solid
Building position within a block:
  Detached building
Vertical structural irregularity - primary:

Vertical structural irregularity - secondary:
  No irregularity
Roof covering:
  Concrete roof, no covering
Roof system type:
  Precast concrete roof with RC topping

Floor system type:
  Precast concrete floor with RC topping

Number of storeys below the ground:
  Exact number of storeys   1
Slope of the ground (for buildings on slopes):
  Slope of the ground   0
Occupancy type - detail:
  50+ Units
Region (province, state, etc.):
  Central Asia

Floor is solid and relies on 4 walls.

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