

# Toward a disaster risk assessment and mapping in the virtual geographic environment of Armenia

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**Abstract** This paper presents the results of a research aiming natural and technological hazard, and risk assessment and mapping in Web-based holistic geographic environment, and the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030 in Armenia. A common spatial multi-criteria evaluation method was used for natural and technological hazard, risk and population vulnerability assessments. The virtual geographic environment developed by the authors during the previous period of investigations was upgraded and used for the implementation of this research. It involves the following components: 1. geodatabase, 2. modeling and simulation, 3. interface for digital mapping, 4. metadata, 5. Web-based network service for collaboration. Moreover, the country specific natural and technological hazard, risk and population vulnerability assessment methods were developed, implemented, and appropriate digital maps were created.

**Keywords** Disaster risk reduction · Hazard assessment · Modeling · Virtual geographic environment · Armenia

## 1 Introduction

The territory of the Republic of Armenia is characterized by natural hazardous phenomena and processes such as earthquakes with the intensity of 8–11 according to the Medvedev–Sponheuer–Karnik scale (MSK-64) scale, landslides, rock falls, mudflows, inundations, freezing, strong winds, lightning, droughts, abundance of heavy rains and hail. These hazards seriously affect the economy, residences, transportation network and environment of the country, and threaten the life and health of human beings.

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Districts, prone to the mentioned above disasters, mainly lie within the borders of the populated areas or the adjacent territories, and make the considerable part of the territory of Armenia (almost 45%). These natural disasters bring to human losses and are a source of significant material damage to the population and socio-economic system of the country.

Despite the undertaking of planned measures, and works carried out for the disaster risk reduction (DRR) and disaster prevention, the impact of the mentioned natural hazards still remain in the territory of the Republic of Armenia.

According to the information on emergency situations from 1999 to 2016 provided by Ministry of Emergency Situations, and published by National Statistical Service of the RA, there exist increasing trends in the number of natural and technological disasters, as well as people affected by these disasters in Armenia (Socio-Economic Situation of the RA, January–December 1999–2016). These trends are conditioned by the following factors: the increase in impact of the human activity on the environment, the lack of natural hazards modern monitoring systems, as well as the insufficient conditions of anti-hazard structures.

Therefore, natural and technological hazard and risk assessment and mapping as Disaster Risk Reduction (DRR) activities are the actual areas of scientific research and practical activities in Armenia.

However, an efficient DRR requires up-to-date and reliable data, standardized methods of data collection and database organization, hazard and risk assessment, scientific analyses, as well as innovation technologies to carry out all these tasks. Also, hazard and risk assessment requires availability of data about past events and periodical observations of natural phenomena related to natural and man-made hazards. Although there is a number of institutions (governmental, non-governmental, scientific, and private) implementing both data collection and evaluation, there is a necessity in improvement in the public access to the existing data, and analytical tools in Armenia. Thus, the need of a geoinformation environment serving as a warehouse of all relevant data and providing with the capabilities of modeling, analyzing, predicting, and assessing hazardous events and their consequences arose.

Moreover, flooding, wildfire and industrial event hazard and risk, as well as population vulnerability assessments and mapping based on a common methodological and information basis, have not been implemented for the whole country prior to this research. Because of that, Program on Prevention, Preparedness and Response to man-made and natural disasters in the ENPI East Region (PPRD East) upon the agreements with the governments of the countries involved in the Program initiated this study, aiming to fill the above-mentioned gaps in DRR. In addition, present research aimed to contribute to the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015b) adopted by the UN countries including Armenia. Particularly, the study addresses the scientific objective of the first priority area of action of mentioned document, i.e., understanding disaster risk using geospatial information technologies and multi-hazard approach. This paper aims to describe the functionality of the holistic virtual geographic environment (VGE) used as an innovative tool for solving DRR tasks, as well as to present the developed methods and the implementation of natural and man-made disasters hazard, risk and population vulnerability assessment and mapping in Armenia.

The results of this research are used by Ministry of Emergency Situations of Armenia for planning of Disaster Risk Management (DRM) activities: identification of the priority administrative units of the country and hazards, which require mitigation measures.

## 2 Materials and methods

### 2.1 Conceptual methodology

There are many methods of hazard and risk assessment and mapping (Kohler 2004; EU Commission Staff Paper 2010; Fekete 2012; Merz et al. 2013; Orenco and Fujii 2014; Papathoma-Köhleel et al. 2016). The reasons for this variety are different approaches to solving these tasks, and the objective difference of the essence and physical features of dangerous objects, processes, and phenomena. The factors (such as how well particular hazards and elements at risks are studied, as well as practical objectives of studies) that are not connected with the assessment objects directly also play a specific role in the development of different methods. Besides the mentioned above conditions, the choice of a method for a hazard and risk assessment is based on the types of spatial objects (point, line or polygon) exposed to a hazard.

The mentioned above factors and conditions were taken into account during the implementation of the current research and hence determine the choice of the methods described below. The commonality of the used methods is the common approach to hazard and risk assessment, using a unified geoinformation environment for this purpose. According to the main initial approach, risk is considered as a product of hazard and vulnerability, i.e., as a logical multiplication of these factors. At the same time, according to the nature of a hazard and requirements of DRM, different criteria were used for hazard and risk assessment.

A spatial multi-criteria evaluation method was used for flooding, wild fire and technological event hazard assessment, which depends on a number of factors. Each of factors was considered as a spatial criterion for hazard and risk evaluation. This method is based on the analytical hierarchical process (AHP) developed by Saaty (1980) and allows to estimate hazard and risk quantitatively. Hazard and risk factors were presented as a set of VGE raster layers, and each of these layers' grid cells is presented with specific standardized mean of factor. Then, layers of hazard and risk are created by calculation of target index, which is the sum of weighted means of the criteria in spatially corresponding grid—cells of all layers (Tapas et al. 2013). In some cases, target variable (hazard, risk) is caused by one or more compound factors, which depend on subfactors. In this case, a criteria “tree” was compiled. For example, the vulnerability index calculated in this research consists of five levels of criteria. The output of this method is “composite index map,” which indicates the critical locations of hazard factors and risk areas for various ranges.

For the implementation of AHP method, the following main steps were carried out:

- Identification of the factors causing hazard, and establishment of the quantitative criteria of their impact on hazard occurrence probability and a damage scale by ranking and standardization.
- Development of the hierarchic structure of the factors (criteria) and establishment of their comparative weights.
- Final spatial summation of the weighted criteria as described above.

Used weighting coefficients were derived by experimental method for the investigated territory or neighbor countries; published data were also used (Demek 1972; Kourgialas and Karatzas 2011; Huan et al. 2012; Tehrany et al. 2013; Ouma and Tateishi 2014; Kazakis et al. 2015; Kazakis and Voudouris 2015).

The methods and data used for the VGE development, as well as each type of hazard and population vulnerability assessment and mapping, are described below.

## 2.2 VGE development

The geoinformation environment that addressed the discussed problems of the disaster risk assessment and mapping has been formed during a long period of authors' research in geoinformation science. The functionality of the environment in its current state is determined by the practical requirements of the tasks being solved, the trends in the development of geoinformation systems in Armenia, and the spatial data infrastructure organization and usage. The content of the geodatabase was formed due to the needs of implemented studies on various thematic subjects, including geographic and geological space, natural and anthropogenic processes, carried out in VGE. For this reason, at first, the basic thematic layers have been imported to the geodatabase in order to completely represent the geographic conditions and the main features of the geological structure of the country. Then, with the development of the geoinformation environment of Armenia, the geodatabase was appended with new derivatives and thematic layers of original content. Metadata for layers have been compiled in order to facilitate the navigation in a large geodatabase and provide information on data sources, as well as protect the rights of authors of the thematic layers.

In a certain sense, the geoinformation environment presented in this article has the features of a Geoportal for Armenia as Spatial Data Infrastructure (SDI) defined by INSPIRE documents (DIRECTIVE 2007/2/EC). The further development of this Web-based geoinformation environment has brought it to the condition, which corresponds to the main principles and functionalities of VGE as it is described by Batty (1997, 2008).

VGEs are used for virtual representations of physical geography, cultural geography and imaginary geography. They have two cores (geodata and geomodels) that are centered by virtual environments and established with the support of modern technologies for information collection (such as remote sensing, global navigation satellite systems, and photogrammetry), huge volume data storage, wide band networks, high-performance computation, high-fidelity graphics rendering and multiple-channel human-computer interaction for the representation, computation, simulation, and analysis of geophenomena and geoprocesses to explain “what” the geographic phenomena are and to discover “why” and “how” the phenomena act (Gong and Lin 2006; Lin et al. 2012; Xu et al. 2013).

In the current state, the logical architecture of the geoinformation environment of Armenia consists of the following components: 1. datasets, 2. modeling and simulation, 3. interface for digital mapping and integration to geodatabase, 4. metadata, 5. Web-based network service for collaborative use (Lin et al. 2013) (Fig. 1).

Thus, the implemented geoinformation environment for the territory of Armenia includes the main components of a complete VGE. From the mentioned above, the VGE is described according to its logical structure and functionality. At the same time, the authors of this research have an objective to develop the VGE in the future.

## 2.3 Geodatabase

The geodatabase of the VGE of Armenia consists of multi-thematic datasets, which are grouped into seven thematic groups described below. All digital maps cover the territory of Armenia and have resolution, which corresponds to 1:200000 scale and larger.

Group 1. Basic Maps

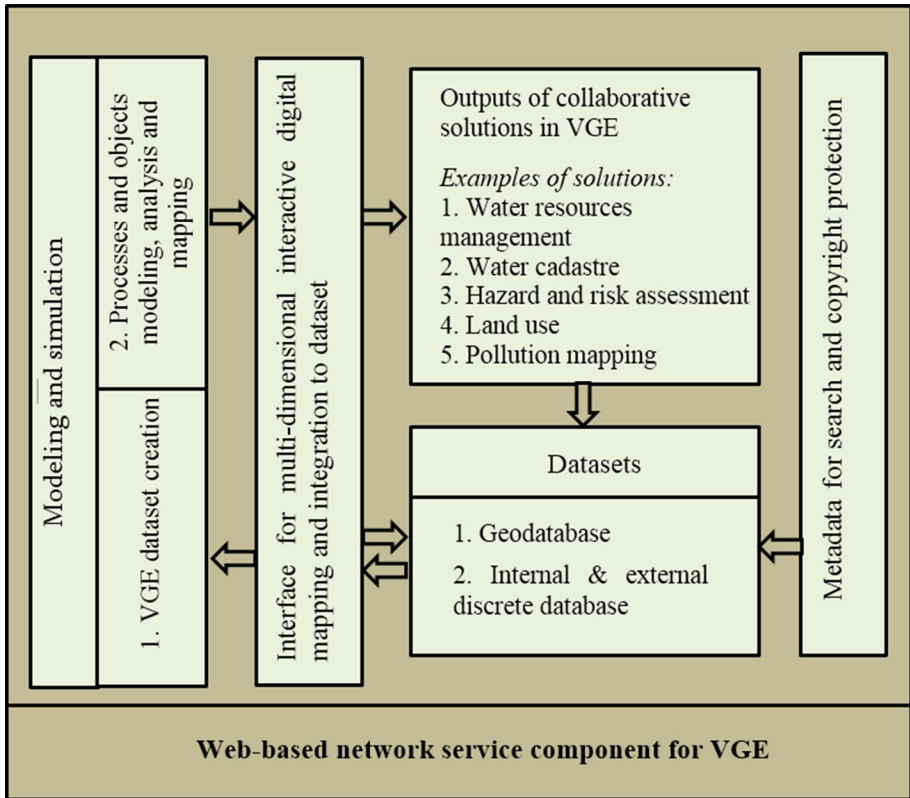


Fig. 1 Logical architecture of the VGE of the RA

- Administrative—State borders of Armenia, Marz borders, District borders, Settlements, Demography;
- Infrastructures—railways, roads

Group 2. Natural conditions

- Geomorphology and geomorphometry—geomorphology zones, DEM, slope, aspect, elevation zones, landscape types
- Hydrology—main river basins, river network, lakes, reservoirs
- Geology, lithology, tectonics,

Group 3. Natural resources

- Non-metallic deposits, ore deposits (operated), ore occurrence, fresh drinking groundwater deposits, hydrogeological wells, soil types, landscape types, forests.

Group 4. Natural hazards and risks

- Earthquake hazard and risk thematic layers—recent earthquakes, historical earthquakes, seismic zones
- Landslide hazard and risk layers—landslide location, landslide slope, landslide risk map, land use in landslide areas, landslide bedrock geology and landslide hazard per region.
- Flood hazard and risk layers—historical flood events (point and polygon), embankments, restrictions to water flow (canals), flood hazard by river basins, flood hazard by regions, flood hazard by regions.
- Forest fire hazard layers—wildfire hazard in June, July and August, wildfire hazard distribution by elevation zones, and forest types.

#### Group 5. Industrial events hazard and risk

- Technological event hazard and risk layers—layers of installations, which may trigger risks, technological event hazard layers and risk layers by regions, and administrative divisions.

#### Group 6. Critical Infrastructures

- Spatial data for the following assets—administrative buildings, airports, health facilities, roads, tunnels, bridges, railway, power plants, high-voltage-power lines, electric substations, telecommunication stations, industrial buildings, water use, water extraction, water discharge, drinking water pipe lines, chemical factories, petrol and gas stations, reservoirs, tailing dams, solid waste, rescue divisions and fire rescue centers, mines, enrichment plants.

#### Group 7. Population Vulnerability and Capacity

- Vulnerability index and its component layers by administrative regions—layers of vulnerability index, susceptibility, coping capacity and adaptive capacity indicators.

## 2.4 External datasets

One of the main advantages of the presented VGE is that it supports information integration from various data sources and different formats.

VGE has ability to establish links with external databases. These may be spatial databases installed on other servers, as well as databases containing observation and monitoring data series.

The examples of external datasets can be the hydrometeorological monitoring databases of State hydrometeorological service, landslide automated monitoring databases of the Ministry of Emergency Situations (MES) of Armenia, air and water quality monitoring databases, etc. Since these databases are constantly updated, it is not expedient to keep them directly in VGE. Besides that, data providers can independently manage the content and volume of transferred data, thus controlling intellectual property issues.

For example, for the development of flood hazard layer, the multi-year observation databases of river flow characteristics, precipitation, and evaporation of the State

Hydrometeorological Service were used. These databases can also be used in VGE for flood monitoring and early warning system creation.

Data gathered by sensors of Landslide automated monitoring system of MES can also be integrated in VGE and joined to spatial layers.

## 2.5 Metadata

In order to support data search function and achieve interoperability of the VGE of Armenia with other Geoportals, metadata for all layers are created according to ISO 19115/19119/19139 standards. Discrete units of metadata are: map title, keyword, spatial resolution, scale, responsible institution, source, author(s) and short description. Metadata also improve a data quality control and promote respect of intellectual property rights, and this fact can encourage other organizations and authors for cooperation in scope of VGE.

## 2.6 VGE software

The virtual geographic environment is a Web-based tool providing capabilities to store both basic and derived spatial data, including hazard and risk spatial and attributive data created as a result of present research.

VGE is built on open-source software, which allows easy accessibility and high interoperability with national systems, standards and data formats. It is based on a Linux (Debian) server, and Apache and Tomcat web servers.

PostgreSQL is used as a relational database management system. GeoServer allows users to share, process and edit geospatial data.

GeoServer also displays data on any of the popular mapping applications such as Google Maps, Google Earth, Yahoo Maps, and Microsoft Virtual Earth. In addition, GeoServer can be connected with traditional GIS architectures, such as ESRI ArcGIS. Also, OpenLayers is used for displaying maps on web browsers as tiled web maps.

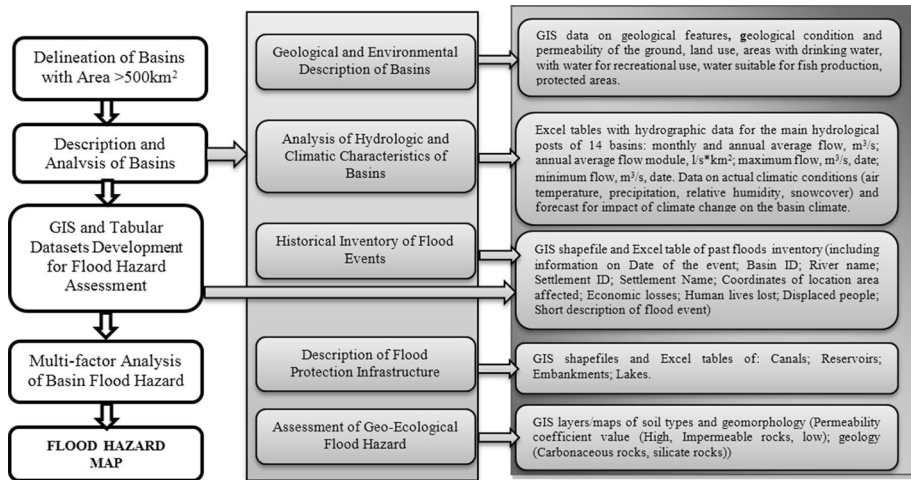
## 2.7 Flood hazard

### 2.7.1 Data collection

The methodology for data collection and organization for the flood hazard assessment within country has been developed based on the principles defined within the Flood Directive (DIRECTIVE 2007/60/EC). The purpose of the EC directive is to establish a framework for the assessment and management of flood risks, aiming at the reduction in the adverse consequences for human health, the environment, cultural heritage and economic activity. The methodology considers the initial stages of the directive and will allow flood-prone areas to be identified and mapped onto a GIS (Fig. 2).

The objectives of the methodology on data collection and organizing are:

- Development of layers for multi-criteria flood hazard assessment and mapping,
- Estimation of the potential flood hazard based on hydrometeorological, geoecological and geomorphometric factors,
- Identification of the settlements with high potential flood risk based on evaluation of past flood events,
- Development of the initial flood hazard GIS layer.



**Fig. 2** Flood Hazard Assessment and Map Development Flowchart

The necessary data for flood hazard assessment has been collected for the 14 basins of Armenia with an area of more than 500 km<sup>2</sup>.

### 2.7.2 Flood hazard index (FHI) assessment method

The above-mentioned datasets served as a basis for the flood hazard assessment using index-based approach and Analytical Hierarchy Process (AHP) (Saaty 1980; Kazakis et al. 2015).

Following factors have been considered for flood hazard index (FHI) assessment using AHP:

- flow accumulation (F);
- drainage distance (D);
- elevation (E);
- land use (U);
- rainfall intensity (I);
- slope (S);
- geology (G).

The input data on each factor is processed in a GIS environment. Layers of elevation, slope and flow accumulation are products of the digital elevation model (DEM). The geology layer is developed by the authors of this article based on the Geological Map of the Republic of Armenia (Scale: 1:500,000—Geological Agency of the Ministry of Nature Protection of Armenia, 2005).

Source map is generalized to define rock types with the same permeability and to represent their spatial distribution. The source of land use layer is the European Space Agency's GlobCover v2.3 layer (<http://due.esrin.esa.int/globcover/>). The rainfall intensity was expressed using the Modified Fournier Index (MFI) (Costea 2012). The monthly and

annual data of precipitation monitoring points have been used for MFI calculation. After the calculation of MFI, point data have been interpolated using Spline method.

### 2.7.3 Relative weights of the criteria

FHI method considers the above-mentioned factors, and the weight of each factor determines its role in the final result. Thus, a spatial analysis of the flood hazard should evaluate each grid cell on every factor, and all the datasets should be converted into raster format. Then, according to the local conditions, each grid point has been assigned a value in a scale between 2 and 10 (rating score) using “Reclassification tools” of GIS.

The identification of the classes of the factors and appropriate weights is a complicated task. The factor weights are accepted from the methods presented in similar studies (Demek 1972; Kourgialas and Karatzas 2011; Ouma and Tateishi, 2014; Kazakis et al. 2015; Kazakis and Voudouris 2015). The factor classes are location dependent and should be adjusted to local characteristics of each studied area. In Table 1, parameter classes are summarized for entire territory of Armenia using mathematical statistics methods and GIS tools. The datasets of historical inventory of flood events, hydrometeorological characteristics, elevation, geology and land use have been analyzed.

The acquired values need to be processed in order to calculate the relative significance of each criterion and the corresponding weighting factor ( $w$ ). Following the calculation of the weights, the FHI can be calculated using Eq. (1).

$$FHI = \sum_{i=1}^n r_i \cdot w_i = F \cdot w_F + I \cdot w_I + G \cdot w_G + U \cdot w_U + S \cdot w_S + E \cdot w_E + D \cdot w_D \quad (1)$$

where  $r_i$  the rating of the factor in each cell,  $w_i$  the weight of each factor,  $n$  the number of the criteria.

## 2.8 Wildfire hazard

### 2.8.1 Data collection

The factors which contribute to the wildfire hazard cover data on Digital Elevation Model (including elevation, slope, and aspect), temperature, precipitation, and land cover as fuel type. Appropriate thematic layers of the VGE–Armenia were used for the assessment and mapping of the wildfire hazard. Elevation zones, slope and aspect layers were generated from DEM (ASTER GDEM), Land Cover layer was developed using Globe Cover Global Data v 2.2. Data from WorldClim archive were used for the generation of monthly mean temperature and monthly precipitation data. Temperature data for June, July and August have been used for processing, since those are the months when the probability of occurrence of wildfire is highest.

### 2.8.2 Wildfire hazard assessment method

The wildfire hazard factors are divided in two groups, and hierarchical sub-layers were developed which identify fuel condition and weather triggers. A target fire hazard output is produced by combining these sub-layers using a weighted approach (Fig. 3)

**Table 1** Classes of the factors and appropriate weights

Factors	Classes	Rating	Weight
Flow Accumulation (km <sup>2</sup> )	> 1700	10	3
	800–1700	8	
	480–800	6	
	170–480	4	
	< 170	2	
Distance from drainage network (m)	< 20	10	2.1
	20–50	8	
	50–150	6	
	150–300	4	
	> 300	2	
Elevation (m)	< 800	10	2.1
	800–1200	8	
	1200–1500	6	
	1500–2000	4	
	> 2000	2	
Land use	Urban	10	1.2
	Pastures	8	
	Agricultural	6	
	Sparsely vegetated	4	
	Forest	2	
Rainfall intensity, mm (MFI)	> 80	10	1
	60–80	8	
	40–60	6	
	30–40	4	
	< 30	2	
Slope (%)	0–3	10	0.5
	3–6	8	
	6–18	6	
	18–36	4	
	> 36	2	
Geology	Crystalline rocks	10	0.3
	Carbonates	8	
	Neogene sediments	6	
	Continental deposits	4	
	Alluvial deposits	2	

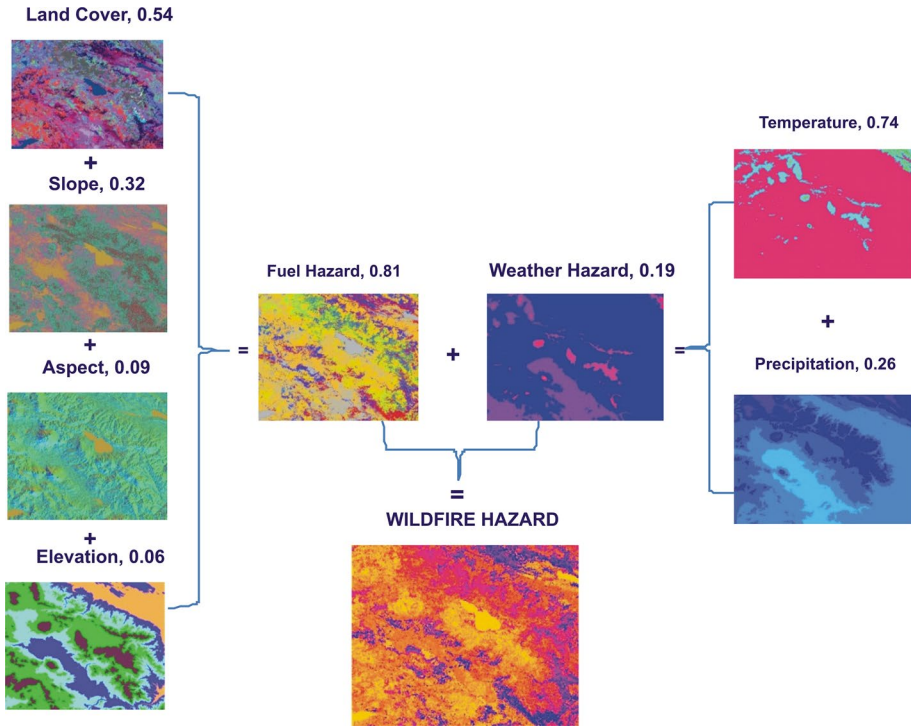
For the territory of Armenia, the following variables and equations have been used to calculate sub-layer criteria:

Fuel hazard = 0.54(Fuel type) + 0.32 (Slope) + 0.09 (Aspect) + 0.06 (Elevation);

Weather hazard = 0.74 (Temperature) + 0.26 (Precipitation).

The composite index of wildfire hazard was calculated from the following expression:

Wild fire hazard = 0.81 (Fuel) + 0.19 (Weather).



**Fig. 3** Wildfire hazard criteria and index map

The values of weighting coefficients in the equations are selected on the basis of the results of research on the territory of Armenia and neighboring countries (« Wildland Fire Hazard Modeling in Georgia », developed as a part of « MATRA » project) (van Westen et al. 2013).

The fuel hazard type takes into account land cover and hazard standardized value specified for each land cover type (Table 2).

The slope hazard index has been established according to several rules related to wildfire behavior. Since steep slopes tend to increase the rate of fuel burning, higher values will be given to those, compared with flat surfaces or lower slope gradients. Slope hazard fire index is based on the following classification and standardization. Slope gradient from flat up to 40 degree and more was divided into nine classes from very low up to very high fire hazard probability. Classes have been assigned to hazard indices, and then their values were standardized from very low to high.

The aspect factor is the most important, because it has effect on wind conditions, air moisture and is related to how dry the fuel is and spread of fire. Four aspects have been considered for this layer: North, West, East and South with standardized value of hazard index from 0.1 to 1.0.

The elevation impact is based on the following assumptions: higher elevations are known to experience greater rainfall and an impact on the vegetation type, humidity and temperature. Five Hazard classes have been defined as follows (Table 3).

**Table 2** Land cover classification and hazard indices according to International Geosphere–Biosphere Program (only types available in Armenia)

Land cover type	Snow and ice	Permanent wetland	Barren	Croplands	Cropland/Natural vegetation mosaic	Mixed forest	Open shrub land	Closed shrub land	Grassland
Hazard index(0–Min, 16–Max)	0	1	2	4	5	10	14	15	16
Standardized value	0.000	0.063	0.125	0.250	0.313	0.625	0.875	0.938	1.000

**Table 3** Elevation ranges and fire hazard indices

Elevation (m)	0–483	484–1074	1075–1709	1710–2435	> 2436
Fuel hazard	High	Medium	High medium	Medium low	Low
Fuel hazard index	5	4	3	2	1
Standardized value	1.000	0.667	0.200	0.400	0.067

Weather factors have influence on fuel moisture and fire spread. The main factors are monthly maximum temperature (Table 4) and precipitation (Table 5) of long term observations, which are considered for the fire hazard assessment.

## 2.9 Technological event hazard

### 2.9.1 Data collection

The two groups of factors were considered for Technological Event hazard evaluation. The first of them includes inherit properties of installations such as industrial type, dangerous substances and their quantity existing in or proceeding in installation, site setting category, possible natural and man-made event triggers. The second group of factors relates to the capacity of the installation operators to prevent and mitigate the impacts of an industrial event triggered by man-made or natural factors.

In case of man-made factors, industrial accidents (e.g., fire, explosion, and mechanical failure), collisions, human errors, systems failures have been considered as possible triggers.

Landslides, avalanches, floods, earthquakes and wildfires have been considered as natural triggers for technological disasters. Statistical and spatial data on natural and man-made disasters have been collected from Ministry of Emergency Situations and have been analyzed to assess the hazard levels of installations.

- Site Setting Categories for installations have been identified according to the following baseline data: Geographic boundaries of the hazard, i.e., how far could the hazard extend in case of a technological event. Different accident scenarios have been con-

**Table 4** Temperature hazard indices

Temperature (°C)	0–3.2	3.3–6.4	6.5–9.5	9.6–12.9	> 12.9
Weather hazard	Low	Medium low	Medium	Medium high	High
Weather hazard index	1	2	3	4	5
Standardized value	0.067	0.200	0.400	0.667	1.000

**Table 5** Precipitation hazard indices

Precipitation (mm)	429–685	686–861	862–992	993–1180	> 1.181
Weather hazard	Low	Medium low	Medium	Medium high	High
Weather hazard index	5	4	3	2	1
Standardized value	1.00	0.67	0.4	0.20	0.67

sidered, such as vessel rupture, pipe rupture, leak, fire, explosion, installation security (e.g., unauthorized personnel entry).

- Existence of a credible hazard transportation mechanism, such as air (wind direction, strength), surface water (rivers, canals, drinking water supply) and groundwater.
- Recurrence of a technological event by available qualitative or quantitative data.

Information on the level of preparedness of installations, as well as the industrial type, and existing dangerous substances has been collected from Ministry of Emergency Situations and National Statistical Service of Armenia.

### 2.9.2 Technological event hazard assessment method

Hazard assessment tables and matrix approach were used for the country specific technological event hazard assessment and mapping. The method presented below makes it possible to perform an initial assessment of industrial accident hazard for regions and the whole country using available data without detailed evaluation of risks posed by an individual installation. The following steps were implemented for the technological hazard event assessment and mapping.

After the development of complete database and GIS layers of industrial installations currently operating in Armenia and natural hazards (earthquake, landslide, flooding, and avalanche), the hazardous installations were identified according to the external factors and their intrinsic properties which potentially contribute to hazardous occurrences. For this, the industrial type of an installation, quantity of existing dangerous substances, and site setting categories including natural triggers have been analyzed. Also, potentially hazardous installations were divided into (1) explosive, (2) oxidizing, (3) easily flammable, (4) flammable, (5) toxic, (6) harmful, (7) corrosive classes according to the EU Council Directive 67/548/EEC.

Then, the probability of occurrence of a Technological hazard event for each installation (Table 6) and its disastrous impact were assessed through the analysis of their typical examples. As a result, four classes of hazardous installations were distinguished (Table 7).

To assess Risk Management Category and Preparedness level of an installation, the following options were discussed:

**Table 6** Occurrence frequency of the specific type of installations

Frequency index of the specific type of installations	Occurrence frequency of the specific type of installations	Category type name
1	Once in 50 years	Airports, metal products manufacturing, mineral extraction and processing, water supply
2	Once in 20 years	Organic and inorganic chemical production
3	Once in 10 years	Hazardous waste, electricity generation, cement works
4	Once in 5 years	Oil and gas processing, food, beverage, tobacco products, electrical and electronics, animal products
5	Once a year	Municipal solid waste

**Table 7** Hazard categories by installation type

Hazard index	Hazard level	Category name
1	Low	Food, beverage, tobacco products, electrical and electronics, municipal solid waste
2	Medium	Cement works, airports
3	Fair	Oil and gas processing, animal products, metal product manufacturing, electricity generation
4	High	Organic and inorganic chemical production, mineral extraction and processing, hazardous waste, water supply

- Existence of formal, documented Risk Assessment for each installation.
- Planned and implemented measures to limit and mitigate consequences of a hazardous event.
- Training plans of personnel in the organization, responsibilities and emergency response procedures described, and trainings conducted.

Consideration of the above mentioned for each installation, would indicate if:

- An installation could present a potential hazard;
- There is a credible set of conditions which could trigger a Technological Event;
- Technological Event could adversely impact vulnerable receptors;
- The installation Owner/Operator has put in place hazard mitigation measures, which would eliminate or significantly reduce the impact of an event on the receptors

The preparedness level of potentially hazardous installations were evaluated by Baseline Data and expressed by Preparedness Index (Table 8).

The final integrated industrial event hazard level for each installation is calculated by summing up the factors according to Tables 6, 7 and 8. The following expression was used to calculate multi-criteria hazard index for each installation: Target index =  $0.4 * [\text{Installation Type Index}] + 0.2 * [\text{Occurrence Frequency Index}] - 0.4 * [\text{Preparedness Index}]$ .

The potential hazard of technological events for the administrative unites of Armenia was assessed. The total hazard was evaluated as a sum of technological hazard values of all installations located in each unit.

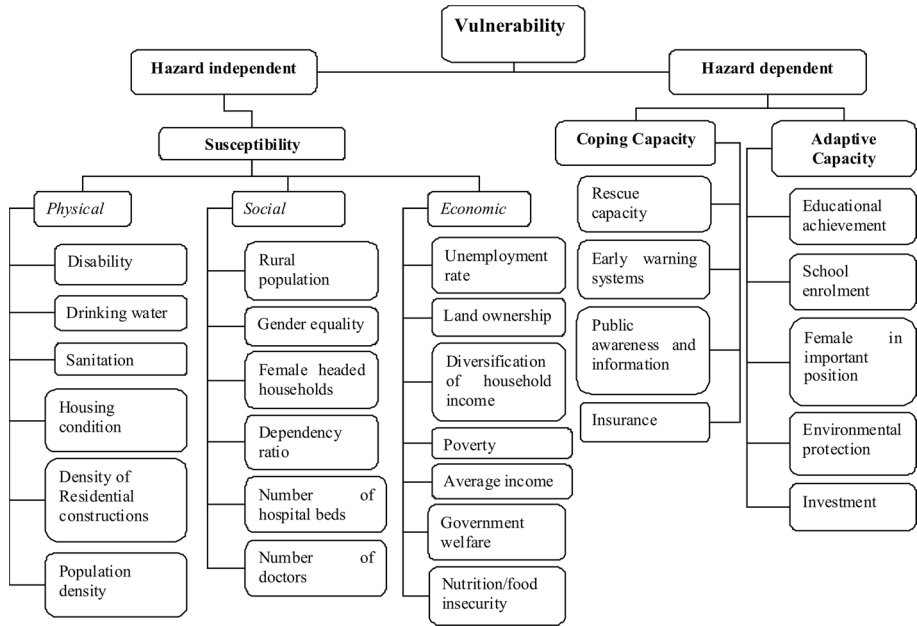
## 2.10 Population vulnerability

### 2.10.1 Data collection

Three dimensions of vulnerability were evaluated: susceptibility (World Risk Report 2014), coping capacity (UNISDR 2009; World Risk Report 2014), and adaptive capacity (Birkmann 2007; World Risk Report 2014). The selection of suitable indicators and their metrics took into account the developing country context and the particular factors influencing vulnerability in Armenia, as well as the availability of data. The theoretical background of vulnerability metrics described in the literature was also considered (Cutter et al. 2003; Dwyer et al. 2004; Brooks et al. 2005; Neil Adger 2006; Birkmann 2007; Flanagan et al. 2011; Beccari 2016).

**Table 8** Installation preparedness

Preparedness index	Preparedness level	Preparedness baseline data description- installation operator has
0	None	No document on disaster risk reduction
1	Poor	Regional plan of action in an emergency situation (RPA)
2	Faire	RPA and certificate of technical safety
3	Good	RPA and certificate of technical safety, own plan of action
4	Prepared	RPA and certificate of technical safety, own plan of action, emergency drills practiced regularly



**Fig. 4** Hierarchical structure of the population vulnerability index

A total of 29 metrics were used for population vulnerability assessment. These metrics were organized hierarchically presenting susceptibility, coping capacity and adaptive capacity (Fig. 4). Metrics of susceptibility were divided in three groups showing physical, social, and economic aspects of population vulnerability.

Different sources were used for data collection. The main source of the data was the population census of Armenia (Census of RA 2011). Also, data from Socio-economic development plans of administrative unites, Ministry of Emergency Situations, Ministry of Territorial Administration and Development, Rescue Services of regions, different water supply sewerage companies working in the territory of Armenia, and a community database developed by UNDP were used.

Three factors of susceptibility were considered in this research: physical, social, and economic.

Physical susceptibility was estimated by aggregation of normalized values of percent of people having disabilities, without access to appropriate drinking water, sanitation, households living in poor housing conditions, as well as the density of population and residential constructions.

Social susceptibility was estimated by aggregation of normalized values of percent of rural population, female population, households led by women, dependency ratio, and availability of medical services, particularly: number of hospital beds and doctors per 10 000 people.

Economic susceptibility was estimated by aggregation of normalized values of percent of unemployed labor force, households without landownership, receiving government welfare, people living below the poverty line and consuming food with less than 2100 kcal daily, as well as average monthly income and diversification of household income.

Coping capacity indicator is based on a number of metrics that determine the capacity of a given study area to immediately react to or manage the impact of a hazardous event. It includes continuing awareness, resources and good management, both in normal times and during disasters.

Thus, the coping capacity indicator was estimated by aggregation of normalized values of rescue capacity (number of fire and rescue teams normalized by number of population), early warning systems (percent of communities having early warning technical means), access to the information among the population (percent of households with constant internet connection), and insurance.

The adaptive capacity indicator was estimated by aggregation of normalized values of educational achievement (percent of people who finished primary and secondary education), school enrollment (percent of pupils, aged between 7 and 18, enrolled in school education), female in important positions, environmental protection (expenditures for environmental protection), and investments in the fixed capital.

### 2.10.2 Population vulnerability assessment method

There are several definitions of vulnerability and various approaches of its assessment and mapping. In this research, we considered approaches and methods of population vulnerability analysis in the context of natural hazards.

In all definitions, the key components of the vulnerability are the stress to which a system is exposed, its susceptibility, as well as coping and adaptive capacities (Cutter et al. 2003; Brooks et al. 2005; Neil Adger 2006; World Risk Report 2014; Li et al. 2015).

Comparative analysis of widely used methods and approaches of vulnerability assessment was carried out to choose the most appropriate method (Guidelines for emergency assessment 2005; Wood and Jelínek 2007; UNISDR 2009, 2015a, b).

A qualitative multi-criteria method was used for vulnerability assessment at sub-national administrative level in this research. Thus, 10 regions and Yerevan city, the capital of Armenia, were the study areas of this research, since Yerevan has the same administrative status as regions.

Composite vulnerability index was estimated as an aggregation of its three main indicators: susceptibility, coping capacity, and adaptive capacity. In this research, the exposure was not considered as a component of population vulnerability, since it was used as a separate component in final risk assessment.

The main steps of the vulnerability assessment and mapping implemented were as follows:

- Selecting vulnerability components, indicators and their metrics;
- Developing a hierarchic structure of the composite vulnerability index;
- Identifying data sources;
- Collecting data;
- Comparing and validating data;
- Calculating the values for each indicator and composite vulnerability index according to the predesigned equations;
- Developing final vulnerability database;
- Developing vulnerability and its components' maps.

Because of the heterogeneity in data type, relative values were assigned to metrics, instead of using their exact measures (Lin and Morefield 2011; Flanagan et al. 2011). Therefore, for each of the metric, the range of data was divided into quintiles, and each region was assigned to a quintile. Each region was assigned a score from 1 to 5 for each metric, where 5 represents the greatest vulnerability, and 1 represents the lowest vulnerability.

In case of scoring of medical services (social indicator), diversification of household income and average monthly income (economic indicator), the system of scoring was reversed, since high values of these metrics decrease the level of the vulnerability.

Also, two approaches to scoring of the metrics of coping and adaptive capacities were applied. The reversed system of scoring was used in case of calculation of the composite index of vulnerability, while the normal scoring was used to consider them individually.

This approach enabled to calculate and map three indicators (susceptibility, adaptive capacity, and coping capacity) and the composite index of vulnerability (Brooks et al. 2005). Since there is no empirically or theoretically approved weighting system (Ge et al. 2013; Brooks et al. 2005; Li et al. 2015), each indicator or factor of the vulnerability was considered to have an equal contribution or weight to the overall vulnerability.

Also, to visualize and analyze relative weights and influence of the physical, social and economic factors in the overall susceptibility for each region and Yerevan city, a 3D diagram was created (Lin, and Morefield 2011). The 3D diagram enables to present joint distribution of the three components of susceptibility and to identify the specific vulnerability factors of each region.

A vulnerability relational database was developed. The database includes five tables: “Regions,” “Vulnerability,” “Susceptibility,” “Coping capacity” and “Adaptive capacity.” Each table contains ID numbers and values of metrics. The table “Regions” contains name, area and population data for each region of Armenia.

The tables “Susceptibility,” “Coping capacity” and “Adaptive capacity” were connected to the table “Vulnerability,” which was, in turn, connected to the table “Regions.” All tables were connected to the appropriate digital layers of a geodatabase included in the VGE.

Four separate thematic layers representing vulnerability indicators (Susceptibility, Coping capacity and Adaptive capacity) and composite vulnerability index at administrative level were developed. The “Susceptibility,” “Coping capacity” and “Adaptive capacity” maps show spatial distribution of vulnerability factors separately, while the “Vulnerability” map shows distribution of composite vulnerability index in the territory of Armenia.

## 2.11 Other models

The simulation function of the VGE is implemented by a group of models concisely described below. Some of these models were used in this research. They are the inseparable components of the VGE and constructed during the whole period of its development.

- DEM was used for mapping of shaded relief, slope, aspects, plane and vertical curvatures. This model is used for the relief evaluation as a natural factor in natural hazards assessment and efficient use of natural resources.
- The land surface hypsometry model of the selected areas and river basins. The distribution of the areas for specified altitude zones was calculated; histogram and integral hypsometric curves were created. The data were used for quantitative description of the relief of territories, and for the analysis of the erosional evolution of the river basin relief (Avagyan et al. 2010a).

- The morphostructures were distinguished, based on the DEM through the analysis of geomorphometric maps. This model was used by authors for the distinction of ring structures in the territory of Armenia (Piloyan and Avagyan 2016). This model in conjunction with the visual analysis of geomorphometric maps can be used for lineament extraction from DEM as well.
- K-means unsupervised classification methodology has been used for classifying landform elements from DEM of Armenia based on geomorphometric parameters of relief (elevation, slope, profile curvature, plane curvature and flow path length). The classification has seven landform classes. Overall, landform classification is performed in the form of a three-level hierarchical scheme. The resulting map reflects the general topography and landform character of Armenia. Taking into account the very complicated and mountainous characteristics of the topography of Armenia, we argue that this methodology can be important in applications dedicated to disaster risk assessment and management (Piloyan and Konecný 2017). Erosional development of streams by comparing the theoretical shape of the equilibrium longitudinal profile with the shape of the real river bed.
- Using this model, the form of the longitudinal profile of streams was typified and the classification of the rivers by this feature was carried out, as well as the zoning of the basin of the high-mountainous Lake Sevan was performed (Avagyan et al. 2010b).
- Coding of rivers and catchments considering their ecological characteristics. The model offers a system for coding water objects of the selected territory by a set of their spatial features and attributes defined by the requirements of the EU Water Framework Directive (WFD) and the country's water legislation. The structured code of each water body consists of the following groups of codes: an identifier in the hydrographic network of the country and in the EU coding system, codes of static attributes in the EU WFD system, codes of dynamic attributes determining the anthropogenic impact on the water body's quality and the ecological state of the water body. The inclusion of static and dynamic attributes of water objects in the coding system allows to unify the assessment and automate the mapping of the ecological state of water objects (Avagyan and Arakelyan 2011).
- Water bodies' delineation by following features: hypsometric position of the basin, hydrographic features, types of sources of anthropogenic pressure, level of hydromorphological change in the beds (Arakelyan and Piloyan 2011).
- Calculation of dependence of annual average flow module from weighted average elevation of watershed areas. Model includes the database of multi-year hydrologic monitoring, DEM, application for annual average flow module calculation at any cross section of river (Mnatsakanyan et al. 2010).
- River basin form and river basin structure classification based on DEM.
- Water balance calculation model on example of Meghri River Basin. This model allows to calculate water balance of watersheds, using as an input data of hydrometeorological observations and hypsometry.

### 3 Results

The information and functional capabilities of the VGE were used for the natural and technological hazard, risk, and population vulnerability assessment and mapping in Armenia for the first time. As a result of this research, the modeling component of the VGE was

appended with a new simulation function using multifactor spatial hierarchic method for hazard and risk assessment and mapping. This method was used for different types of risks and cases, when hazards and elements at risk were studied at different levels. This approach made it possible to carry out required and actual hazard and risk assessment and mapping without any expensive preliminary studies for a detailed evaluation of the potential damage of the elements at risk at regional and country levels.

A series of natural and technological hazard, risk, and population vulnerability maps were developed as a result of this investigation. The results of hazard and risk assessment and mapping are presented below.

The results of the flood hazard index calculation using AHP are raster layers of flood hazard for each of main river basins of Armenia. Each cell of the layers contains the value that represents flood hazard index.

The results of the application of this methodology are:

- A register of locations on rivers, where there is a known probability of floods within the defined structure,
- Description of basins,
- Metadata on all existing hydrologic models available in country along with other flood maps,
- Flood hazard map based on the register of past flood events,
- Understanding of flood hazard potential based on geomorphometric and geocological characteristics.

The results of the methodology application were aggregated by the river basins, which were classified by the flood hazard level into four categories: extreme, high, middle, low (Fig. 5) (Avagyan et al. 2016).

Communities at high flood risk identified based on the analysis of the data of register on past flood events. The register includes data on economic and life losses, displaced people and description of flood event. Below is the map of the settlements affected by floods (Fig. 6).

The results of wildfire hazard assessment are wildfire hazard raster layers raster layers of 1 km × 1 km resolution per month for June, July, and August. Also, layers of wildfire hazard distribution by elevation zones and forest types have been created.

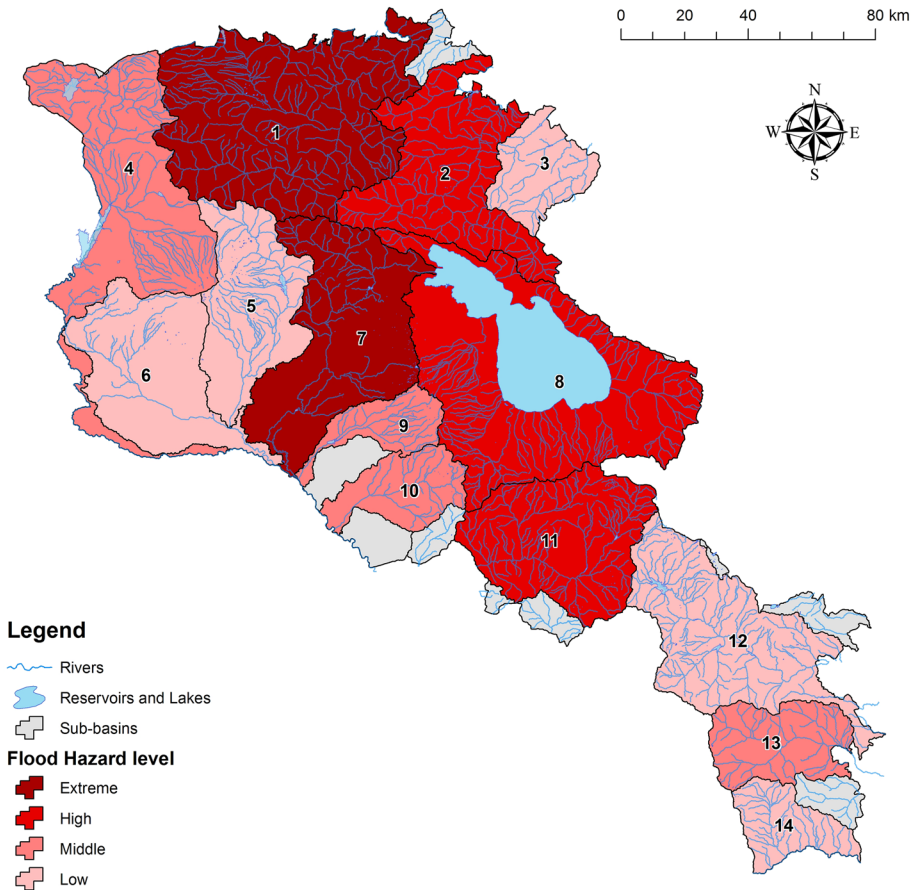
The results of technological event hazard assessment are the layers of potential hazardous installations and technological event hazard for administrative regions of Armenia.

The results of population vulnerability assessment are layers of population vulnerability index (Fig. 7), coping and adaptive capacities, as well as susceptibility for Armenia. Also, a 3D diagram of components of susceptibility was developed, showing the influence of each component on the averaged susceptibility indicator for all studied areas (Fig. 8).

## 4 Discussion and conclusion

The international experience and published methods were adapted to carry out country specific hazard, risk and population vulnerability assessment and mapping. The combination of the two main means of research was used for the achievement of the research goals.

The first mean of the research was the VGE, which includes the necessary geodatabase, geoinformation methods, and technologies for hazard and risk spatial analyses and digital mapping, as well as interactive web services for public use of the data. At the same time,



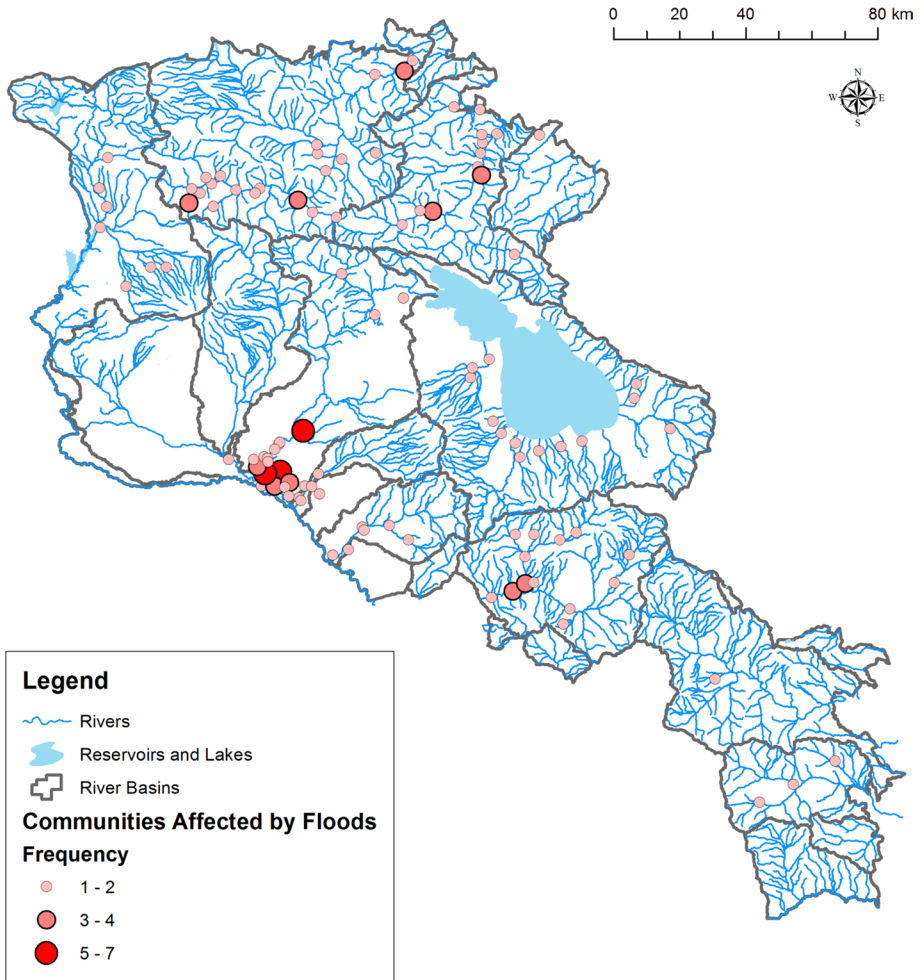
**Fig. 5** Initial flood hazard map

this research appended the modeling components of the VGE, which was the supplementary result of this research. The mentioned above environment was developed during the many years of multi-thematic researches of the authors resulting to the formation of a geodatabase covering a wide range of content.

At the same time, the authors outline the necessity of the further functional development of the VGE to achieve sufficient comfortable conditions for the interactive collaboration of the scientific community of the country.

The second main mean used in this research was the spatial multi-criteria evaluation method based on the Analytical Hierarchical Process of factors assessment taking into account the dependence of hazard and risk on inherit properties and external natural and man-made triggers. This method is efficient for assessment of both point sources of hazards and polygonal objects (community and administrative units). The advantage of this method is multi-criteria approach, though it requires concise definition of the relative weight for the each factor. Particularly, it was revealed during the population vulnerability assessment.

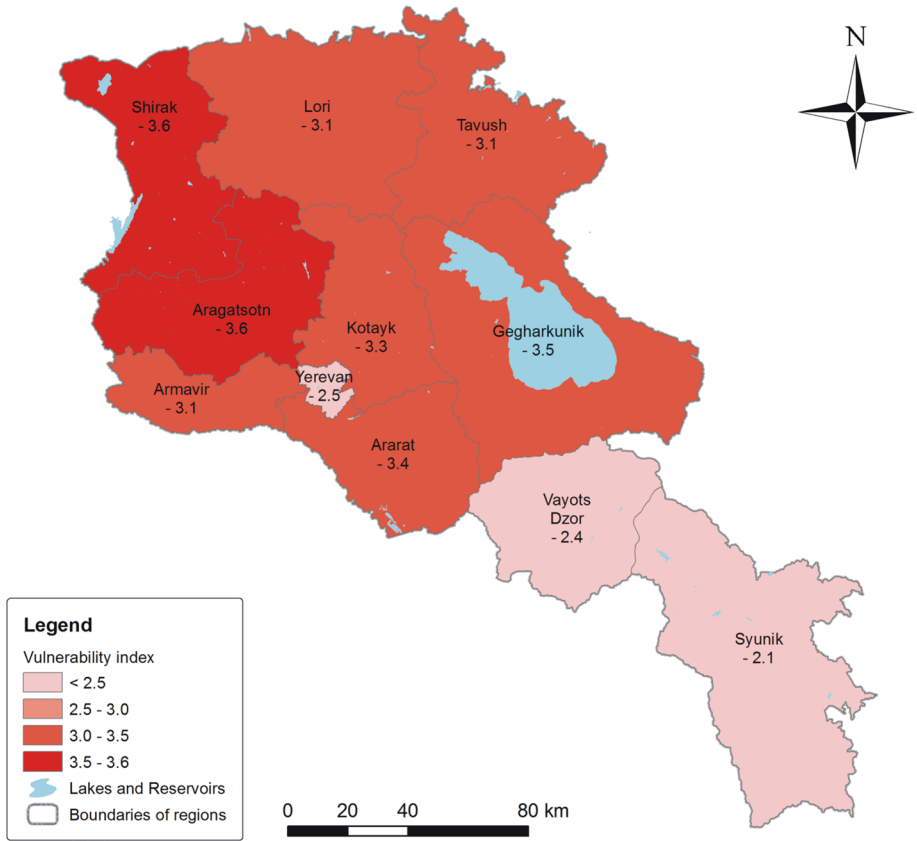
Analyses show insufficient capability of population to anticipate, cope with, resist, respond and rehabilitate from the impact of hazards in these regions. To reduce the



**Fig. 6** Map of communities affected by floods

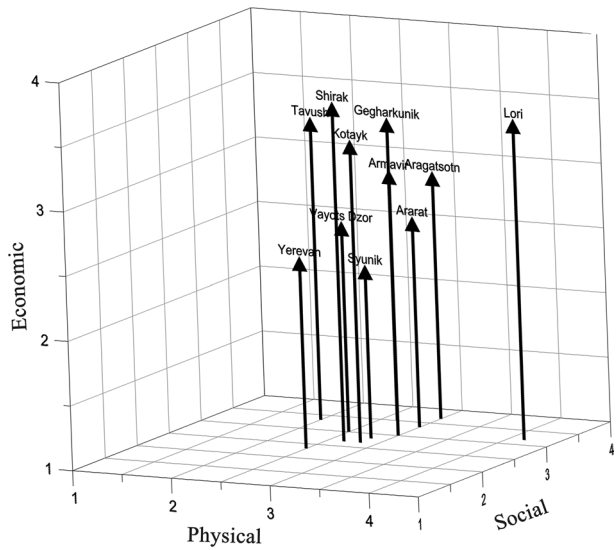
population vulnerability in Aragatsotn region, measures should be taken to improve coping (particularly early warning system, public awareness/information accessibility, insurance) and adaptive (particularly environmental protection) capacities, and social situation (particularly medical services). In Shirak region, measures should be taken to improve coping (particularly early warning system) and adaptive (particularly education, environmental protection, investments) capacities, and economic (particularly poverty, government welfare) state of population.

Thus, this research has provided governmental institutions and regional administrative organizations with high-quality hazard, risk and population vulnerability assessment data and maps at regional and country levels. These data have been used by regional administrative units for the development of emergency preparedness and response plans, which have been included in Development Program of each region.



**Fig. 7** Map of population vulnerability of Armenia

**Fig. 8** Diagram of physical, social and economic components of susceptibility



Hazard, risk and population vulnerability assessment at local or community levels, as well as the development of measures for particular disaster events will be subject to further studies.

Further research is needed to carry out:

- The VGE functionality extension by adding country specific and customized modeling and simulation capabilities.
- Community level population vulnerability assessment and mapping, comparison of rural and urban population vulnerabilities, as well as validation of the results of the estimations.
- Flood hazard classes definition for each of main river basins of Armenia.
- Development of more detailed flood hazard map.
- Revision and empirical justification of parameter weights for each type of hazard.

Also, the authors think that other natural hazards, specific for the territory of Armenia (earthquake, landslide, rock fall), should be included in the VGE during its further development. This will make it possible to carry out integrated multi-hazard risk assessment considering possible cascading disasters and to develop comprehensive hazard mitigation measures.

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