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REVIEW PAPER

A review on hazard risk assessment using remote sensing and GIS

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Highlights

- The risk assessment process should use the latest methods such as remote sensing and GIS to take preventive measures and reduce risk.
- Risk assessment process components including hazards, elements at risk, and vulnerability, are assessed in details for the particular purposes.
- Multi-hazard risk assessment presented through an integrated process using GIS.

Graphical Abstract

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Abstract

All over the world, disasters are on the increase. Disasters result from the interaction between hazards and elements at risk exposed to potential phenomenon leading to vulnerability. Therefore, it is necessary that risk assessment is carried out using the latest means like remote sensing and GIS to undertake preventive, mitigation, or risk reduction measures. The paper starts with a reflection on basic definitions mostly derived from UNISDR 2009 and develops the rudimentary understanding required for building on the subject. Risk assessment is data intensive activity, so the latest trends and sources for data acquisition or extraction are identified. It is also important to establish frameworks like disaster risk management, risk analysis, and risk assessment before dwelling on the paper's main part relating to the risk assessment process. In the risk assessment process, three components, namely hazards, elements at risk, and vulnerability, are focused in detail highlighting their characteristics, data acquisition using remote sensing platforms globally available for the purpose and application of GIS for analysis, evaluation, and visualization of risk from a particular hazard against a particular segment of society. In the end, multi-hazard risk assessment is focused on shown through an integrated process using GIS.

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1. Introduction

Every second day one has become accustomed to listening news about disasters resulting into adverse consequences, occurring in different parts of the World. Particularly those disasters which occur instantaneously and leave wide spread losses and human sufferings like earthquakes, floods, tsunamis and hurricanes etc receive immediate and maximum media attention whereas those hazards which are slow developing like soil erosion, land degradation, desertification, deforestation, glacial retreat, sea-level rise and loss of biodiversity etc having long run impacts generally receive less attention (Mouri et al., 2013). A hazard on interaction with vulnerability becomes disaster resulting into physical, social, economic and environmental impacts on individuals, communities, societies and countries at local, national, regional or international levels. The magnitude and scale of damage and loss of a disaster will characterize its impact value and accordingly it will draw attention by the concerned organizations and people. Technically hazard and disaster are two different terms carrying different connotations but these are commonly used interchangeably conveying same sense. Per say, both words have an accepted sense related to destructive or catastrophic effects (Chapman and Arbon, 2008).

The concept of disaster management is evolving. It has transitioned through a long way from response; recovery stage after the disaster to the preparedness and prevention / mitigation stages before a hazard interacts with vulnerability. Likewise the concept has also transformed from managing a disastrous event to managing and reducing the risk related to a particular hazard. Reduction or management of risk related to a particular hazard will only be possible if the risk is correctly identified and assessed in qualitative or quantitative form otherwise the efforts in that direction will fall short of the desired goal. Since Hyogo Framework for Action 2005, the focus of global community and disaster related organizations has largely shifted to substantial reduction of disaster risk to protect human lives, their assets, livelihood and environment from the adverse impacts of disaster. It has, therefore, become obligatory for us to put in efforts to identify and assess the hazards, the vulnerabilities and risks so as to undertake measures for their reduction (Enia, 2013).

Since hazard risk assessment is highly complex process where all stakeholders and concerned departments have to contribute in providing data particularly with its spatial dimension, so besides the colossal effort it becomes time consuming as well as cumbersome (Jiang et al., 2009). The efficient and quick means of carrying out hazard risk assessment is therefore to seek assistance from remote sensing means and GIS techniques in acquiring required data and making the accurate assessment. Required data can sufficiently be obtained from open sources besides tapping the organized spatial data reservoir available with SUPARCO and GIS techniques can then be aptly applied to integrate various layers of data to create desired visualization about the potential impact of various hazards. The objective of this paper is to give an overview of geo-information science and Earth observation platforms in analysis of hazard and risk. Therefore paper focuses on risk assessment process in a manner that after having gone through, the understanding about application of remote sensing and GIS becomes clear to the reader.

2. Reflecting on rudiments

To establish correct understanding of the subject, it shall be necessary to reflect on the basic definitions of those terminologies which shall be referred to time and again during the paper (De Boer, 1990). These definitions as derived from UNISDR 2009 are:

a) ***Hazard***. A dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihood and services, social and economic disruption, or environmental damage. Each hazard has a probability of occurrence, speed of on set, time of occurrence, area and duration of impact, with a given intensity and severity unfolds in a single, sequential or combined form. A hazard can be natural like hydro-meteorological (floods, wave surges, storms droughts and related hazards like extreme temperatures, forest/scrub fires, landslides and snow avalanches or glacial lake outbursts), geo-physical (earth quakes, tsunamis and volcanic eruptions) or biological (epidemics and insects infestations), human induced like industrial pollution, nuclear and radio activities, toxic wastes, dam failures, transport, industrial or technological accidents such as explosions, fires and oil spills etc.

b) ***Disaster***. A serious disruption of the functioning of a community or a society involving wide spread human, material, economic or environmental losses and impacts, which exceed the ability of the affected community or society to cope using its own resources. Hazards will turn into disasters due to the combination of exposure to hazard, vulnerability conditions and insufficient capacity or measures to reduce or cope with the potential negative consequences.

c) ***Elements at risk***. These include population, properties, economic activities including public services, or any other defined value exposed to hazards in a given area. The amount of elements at risk can be quantified either in numbers (of buildings, people etc), in monetary value (replacement costs, market costs etc), area or perception (Importance of elements at risk).

d) ***Exposure***. Exposure indicates the degree to which the elements at risk are exposed to a particular hazard. Spatial interaction between elements at risk and the hazard footprints are depicted in GIS by simple map overlaying of the hazard map with element at risk map.

e) ***Vulnerability***. The conditions determined by physical, social, economic or environmental factors or processes, which increase the susceptibility of a community to the impact of hazards. This can be further categorized as physical, social, economic or environmental vulnerability.

f) ***Capacity***. Combination of all the strengths, attributes and resources available within a community, society or organization that can be used to achieve agreed goals

g) ***Coping capacity***. The ability of people, organizations and systems, using available skill and resources, to face and manage adverse conditions, emergencies and disasters

h) ***Consequence***. Expected damages and losses in a given area as a result of given hazard scenario.

i) ***Risk***. The combination of probability of an event and its negative consequences resulting from interaction between the hazard and vulnerable conditions in a given area and time period

j) ***Geographical information system*** *(GIS)*. It is an automated set of functions that provides professional with advanced capabilities for the storage, retrieval, manipulation and display of geographically located data. As a system it provides decision support involving integration of spatially referenced data in a problem solving environment.

k) ***Remote sensing***. It is the science of acquiring information about the earth surface without being actually in contact with it. This is done by sensing and recording reflected or emitted energy and processing, analyzing and applying that information.

3. Trends in disaster statistics

Data on disaster occurrences, their effects upon people and their costs to countries are very important for disaster risk management. There are now a number of organizations that collect information on disasters, at different scales and with different objectives. This data can be relevant while undertaking hazard and risk assessment. Some of the online sources are:

a) Centre for Research on the Epidemiology of Disasters (CRED) is maintaining an Emergency Events Database since 1988.

b) Disaster data base maintained by Asian disaster Reduction Centre (ADRC) but the name of Glidenumber-2010.

c) Disaster information can be collected from DesInventor-2010.

d) A joint venture by Global Risk Identification Program (GRIP) and CRED have called DisDat provides country based information about disasters.

4. Frameworks

Disaster risk management according to UNISDR 2009 is defined as the systematic process of using administrative directives, organizations, and operational skills and capacities to implement policies, strategies, and improved coping capacities to lessen the adverse impacts of hazards and the possibility of disaster. This includes all forms of activities, covering structural and non-structural measures to avoid or to limit adverse effects of hazards (Fig. 1 explains the Risk Management Framework in detail).

There are three important components in risk analysis i.e. hazards, vulnerability and elements at risk. They are distinguished by both spatial and non-spatial attributes. Each one is described below:

a) ***Hazards***. These are characterized by their temporal probability and intensity derived from frequency magnitude analysis. Hazards also have an important spatial dimension both related to location and area of spread.

b) ***Elements at Risk***. These elements have spatial as well as non-spatial distinctiveness. Their various types can be classified into different ways like number of people, number of buildings, economic value or qualitative rating according to their importance. The spatial interaction between the elements at risk and the hazards footprint are depicted in GIS by overlaying their maps on each other (Chapman and Arbon, 2008).

c) ***Vulnerability***. The vulnerabilities of communities and households can be analyzed in a holistic qualitative manner using a large number of criteria that characterizes physical, social, economic and environmental vulnerabilities. Importance of each of these indicators is evaluated by assigning weights and combining them using spatial multi-criteria evaluation.

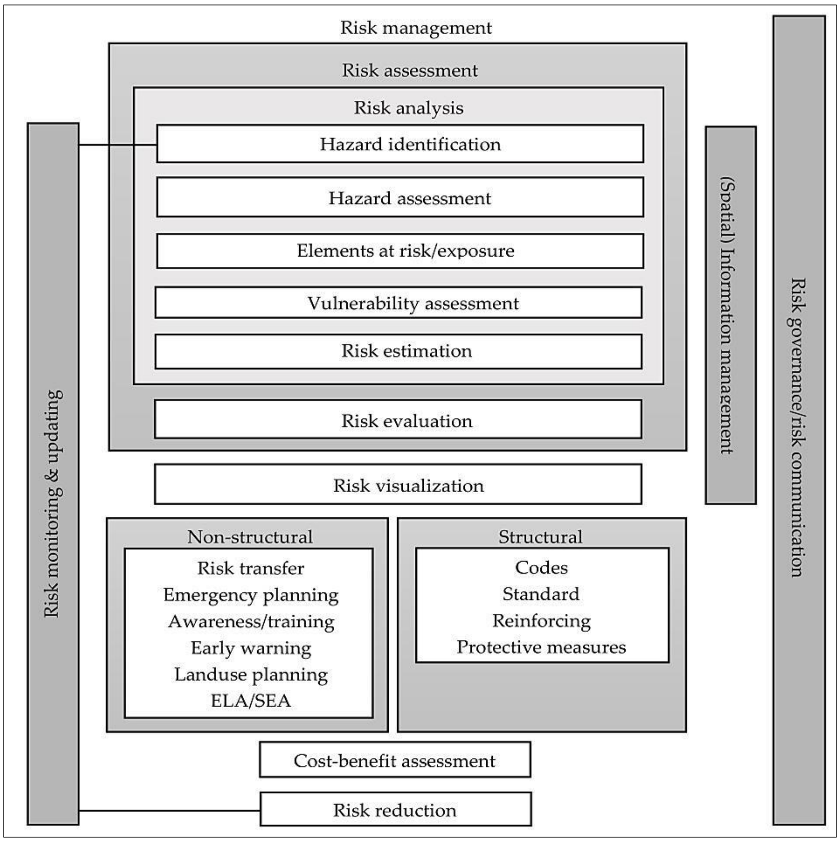

Fig. 1. Risk management framework.

Risk assessment is the combination of risk analysis and risk evaluation. Risk assessment is a purely scientific enterprise at one end but on other, it is a collaborative activity that brings professionals, disaster managers, local authorities and communities living in an exposed area together. In the entire risk assessment framework, spatial information plays a crucial role, as the hazards are spatially distributed as well as are the elements at risk (Chen et al., 2011; Enia, 2013). Risk analysis and risk evaluation are explained below:

a) ***Risk analysis***. The risk analysis is the use of available information to estimate the risk to individuals or population, property or the environment from hazards. Risk assessment generally follows the steps as hazard identification, hazard assessment, elements at risk/exposure analysis, vulnerability assessment and risk estimation. Risk Analysis and its components are as shown in Fig. 2.

b) ***Risk evaluation***. This is the stage at which values and judgments enter the decision process, explicitly or implicitly, by including the consideration of the importance of the estimated risks and the associated social, economic and environmental consequences, in order to identify a range of alternatives for managing the risks.

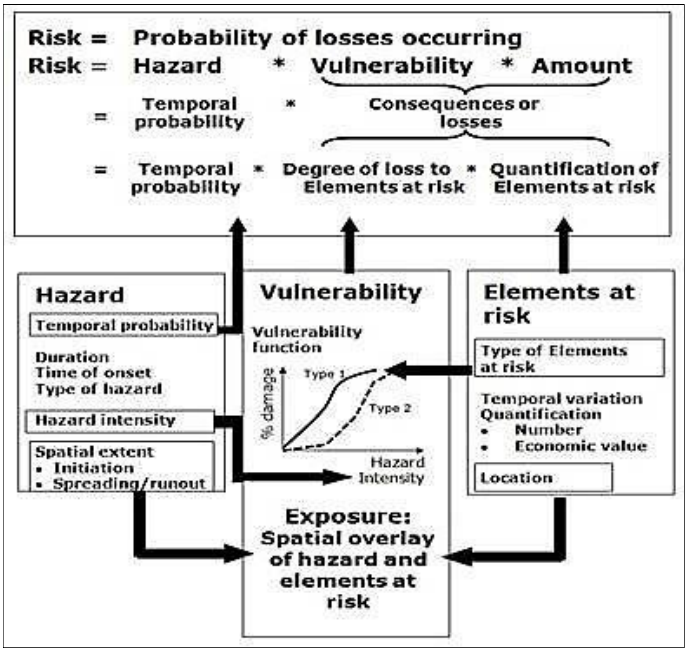

Fig. 2. Risk analysis and its components.

Hazard assessment is a complex phenomenon due to its relationship with the causal factors, primary as well as secondary hazards. Hazard triggering events which may be endogenic or exogenic in nature precipitate other events. These events cause direct effects such as ground shaking resulting from an earthquake as well as indirect effects or secondary events such as landslides caused by ground shaking in mountainous areas (Xu and Yi, 2009). These secondary hazards are also called concatenated or cascading hazards. Natural hazards and their cause effects relationship that is shown in Fig. 3. Volcanic eruption, earthquakes and meteorological extremes are triggering events which can lead to more events having intricate relationship with each other.

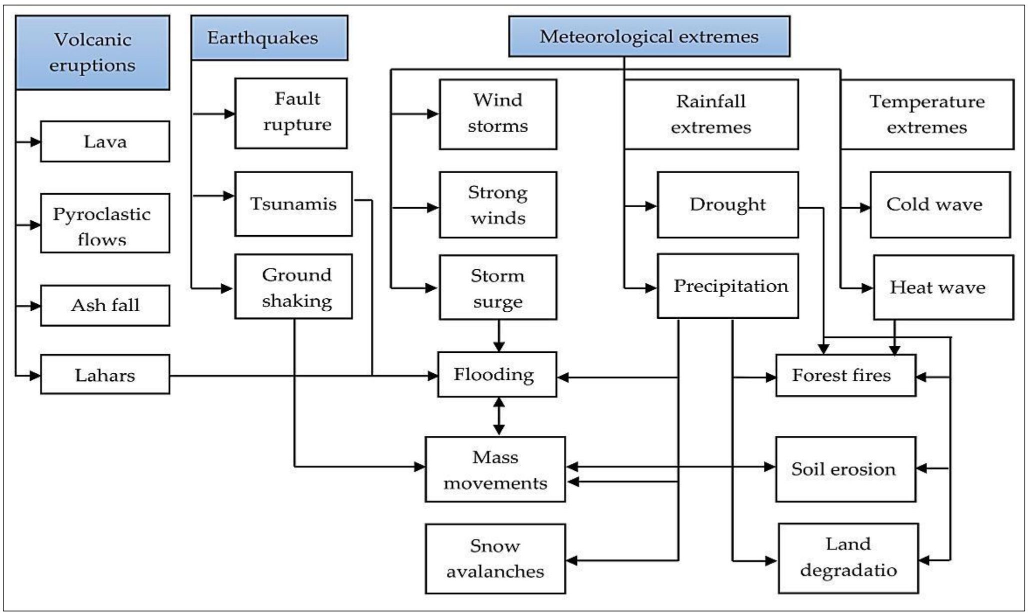

Fig. 3. Multi hazards and their interaction requiring risk assessment.

Using GIS, hazard assessment can be carried out at different geographical scales. Factors which determine what scale of hazard and risk assessment should be selected include aim of the hazard assessment, type of hazard, operational scale at which these hazards are triggered, size and characteristics of the study area, the available data and resources and the required accuracy of the assessment (Witham, 2005). For very large areas like national level, small scales like 0.1 to 1 million cartographic scales and 0.1 to 1 km spatial resolution for an approximate area up to 600,000 km^2 can be used. Whereas for smaller area like 10 km^2 say for a community level assessment large scale, may be greater than 1:25000 for cartographic and 1-5 meters for spatial resolution, can be used. For provincial and district levels, suitable scales in between these two limits can be chosen.

Multi hazard risk assessment is a very data intensive activity. Accessibility to certain types of spatio-temporal data can be a major constraint in undertaking specific type of analysis. Main GIS data layers required for various hazard and risk assessments can be grouped into following three categories:

a) ***Hazard inventories***. These inventories give an insight into the profile of previous hazards covering their types, mechanism, causal factors, and frequency of occurrence, intensities and damages suffered. Simplest way of generating hazard inventories is by taking direct measurement of the phenomenon through networks of stations like seismic networks, flood discharge stations, meteorological stations and coastal tide gauging stations etc having a comprehensive spatial coverage. Since this scale of coverage through ground based stations is not possible it therefore becomes imperative to use satellite based information for generating hazard inventories. Earth observation satellites can be used for mapping flooding including its direction of current, depth, duration and inundation etc. Geomorphologic information can be obtained using optical data acquired through LANDSAT, SPOT, IRS or ASTER and microwave data acquired through ERS, RADARSAT, ENVISAT or PALSAR. For very high resolution imagery data acquired from satellites like QuickBird, IKONOS, WorldView, GeoEye, Spot -5 (Spot - 6 has also been launched) etc can be used (Montoya, 2003).

b) ***Triggering events***. Triggering events like earthquakes covering fault rupture, Tsunamis or ground shaking and meteorological extremes like winds, tides, snow, rainfall, temperature variations etc can be easily measured through satellites. For visual interpretation of triggering event that cannot be automatically obtained from satellite images and geomorphologic interpretation of mountainous areas, stereoscopic imagery from high to very high resolution is required which due to its high cost may be an inhibiting factor for a particular study area, especially for multiple dates after the occurrence of main triggering events but this is being successfully applied at international level.

c) ***Environmental factors***. Environment has direct bearing on occurrence of hazardous phenomena. GIS data layers related to environmental factors can be utilized to depict future events. Basic data under these factors can be divided into more or less static data like geology, soil types, geomorphology and topography and the dynamic data like meteorological, hydrological, land use and land cover data which needs regular updating ranging from hours, days to months and years. Topography being one of the major factors in most types of hazard analysis, the generation of digital elevation model (DEM) and geo-morphometric analysis plays a critical role. Commonly used sources of global DEM in hazard and risk analysis but have low vertical accuracy are GTOPO30 and shuttle radar topographic mission (SRTM). ASTER derived DEMs are also frequently used for hazard assessment. DEMs from high resolution images from Quick Bird, IKONOS, ALOS PRISM, and Cartosat provide best options for smaller areas assessment. Using LiDAR, detailed DEMs can be generated which can be used for geo-morphologic mapping and terrain classification (Alparslan et al. 2008), glacial hazards, coastal hazards, flood modeling, landslide hazard assessment and quantifying rate of fluvial process like river banks erosion etc.

Hazard and risk assessment need a large amount of data from various sources. It is, therefore, important to evolve a strategy for data availability. Data quality, metadata, and multi-user databases are required for accurate and timely information. This requires that potential users know the type and location of data for easy access. Spatial risk information is normally derived from spatial data infrastructure (SDI). Without establishing national SDI, it is not possible to share basic GIS data amongst technical and scientific organizations involved in hazard and risk assessment. Through a well thought out strategy, data at national, provincial, district, tehsil, union council and community levels need to be acquired, stored, retrieved, manipulated and applied for effective hazard and risk assessment.

After having assessed the hazards, in risk assessment, next is the evaluation of elements at risk, vulnerability of which shall be subsequently assessed identifying the risk from a particular hazard in a particular area. Elements at risk will include population, buildings, transportation networks, lifelines, essential facilities and elements related to agricultural, ecological, industrial and economic assets etc. Land use and land cover maps prepared by image classification at small scales or through visual interpretation at large scale, contain most of the details about elements relating to built environment, economic activities and vegetation and facilitate preparation of elements at risk inventories. Some of the ways for collecting data for few elements at risk are discussed as under:

a) ***Information collection.*** Information about elements at risk can be collected from a wide variety of sources. Countries where digital data does not exist, there analogue maps may be digitized to collect spatial information and if that also does not exist then collaborative maps in the field may be prepared using the concept of mobile GIS by loading high resolution images on a palmtop computer or smart phone and linking it with attributes information collected from the field (Montoya, 2003). For collaborative mapping of topographic features, several initiatives internationally established referred to "Crowd sourcing" can be effectively used for elements at risk information collection.

b) ***Population records.*** Most important of elements at risk are the people. Data related to people have static as well as dynamic components. Number of inhabitants per mapping unit and their characteristic will be mostly static whereas their activity pattern and distribution in space and time will be dynamic in nature which may also include information on age, gender, income, education and migration etc. Scale of analysis and the availability of information will dictate the data collection and representation in risk assessment. Demographic data is extracted from census data. Since census data is expensive in collection and needs updating which may be done after an extended period of time say 10 years and beyond, it therefore mostly becomes unreliable. At this stage, application of remote sensing and GIS, based on number of factors as land use, roads, slopes and night time illuminations, becomes a suitable choice for information collection. Global population data can be extracted from Land Scan Global Population database that makes available average population over 24 hours, in a 1 kilometer resolution grid (Mouri et al., 2013). Where census data is not available, using high resolution satellite imagery or through a building foot print map, static population information can be easily derived for a reasonably correct risk assessment.

c) ***Building statistics.*** Built environment in a particular area is the second most important element at risk after the population. Built environment includes buildings which house people, facilities and economic, industrial or water retention infrastructures etc. While analyzing the built environment, potential losses and degree of damages to buildings as a result of negative effects of a hazard is assessed in terms of human fatalities, injuries, displacements and assets destruction in terms of replacement value. Impact on buildings can be in different ways depending upon the type of hazard. Buildings may be impacted by mass hitting, undercutting, shaking, inundation, fire, loss of support, gases or loading, damaging effect for each situation can be evaluated by assessing its characteristics like structure, material, building codes, age, maintenance, roof type, height, floor, space, volume, shape, proximity to other buildings, hazard source, vegetation and openings etc. Building statistics can be gathered through many ways. Data is normally available in form of building footprint maps but if it does not exist, then these maps can be generated from high resolution satellite images, Interferometry Synthetic Aperture Radar (InSAR) or Light Detection and Ranging system (LiDAR) (Xu and Yi, 2009). From LiDAR data, other relevant information about calculation of shapes, height and volumes used in risk assessment can also be extracted.

Out of all the components in risk assessment, vulnerability assessment is the most complicated and complex in nature, primarily for the reason the concept has wide range of interpretations. Vulnerability is multi-dimensional, dynamic, scale dependent and site specific and can be differentiated based upon qualitative as well as quantitative approaches. Out of all dimension of vulnerability, physical dimension is assessed through quantitative methods whereas others like social, economic and environmental vulnerabilities are determined through qualitative methods (Zhang, 2004). Physical vulnerability is the degree of loss to built environment and population due to a hazard and is expressed from 0 (No damage) to 1 (Complete damage). Physical vulnerability per say is not a spatial component itself but is determined from the spatial overlay of hazard and elements at risk. Economic vulnerability is the susceptibility of economic assets, activities and processes (Business interruption, job loss etc) to the potential impact of a hazard. Social vulnerability is the potential impact of hazard on groups of a society (Poor, Children, elderly and women etc). Environment vulnerability will encompass potential impact of hazard on flora, fauna, ecosystem and biodiversity etc. Except physical vulnerability, all other categories of vulnerability are assessed using indicators or qualitative approaches under different situations and scenarios. Physical vulnerability can be measured using empirical or analytical methods for each type of element at risk against each hazard and under varying intensities and situations and visualization is developed after the analysis using GIS (Chen et al., 2011).

All possible hazards in one area, community or a country can be integrated together using GIS. A framework of the use of GIS for multi hazards assessment based on Van Westen 2013 (Fig. 4) which shall give an understanding of each component (Van Westen, 2013).

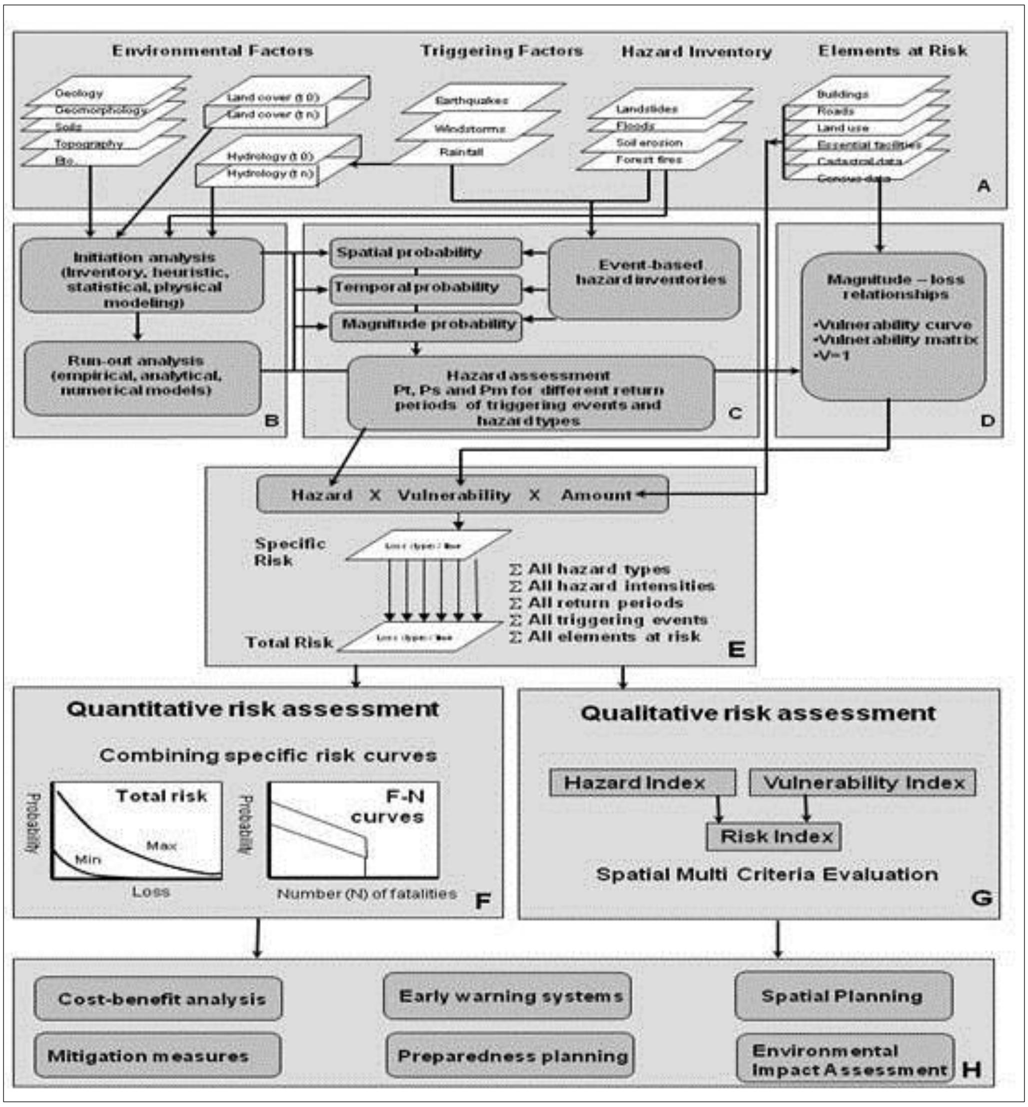

Fig. 4. Framework for use of GIS in multi hazards risk assessment.

In the figure, block shows the input data, divided into data sets required for generating susceptibility maps. Block B focuses on susceptibility assessment which is further divided into modeling of areas where hazard may occur and modeling of its potential spreading. Block C focuses on hazard assessment using magnitude-frequency information giving spatial, temporal and magnitude probabilities. Block D focuses on vulnerability assessment giving different vulnerability approaches that can be used. Block E covers risk assessment integrating hazard, elements at risk and vulnerability. Block F represents quantitative risk assessment in risk curves showing potential losses against the probability of occurrence for individual hazard as total risk with minimum and maximum curves as well as in F-N curves. Block G represents qualitative risk assessment indicated as hazard, vulnerability and risk indices. Finally the block H deals with use of risk information in various phases of disaster risk management (Jiang et al., 2009).

Different hazards will impact elements at risk in different ways and therefore it is necessary to establish risk for each sector like housing, agriculture, transportation, education, health, tourism, protected areas, forests, wetlands etc. Risk assessment may be done quantitatively or qualitatively but should be done by incorporating all stakeholder for creating requisite awareness and ownership. Furthermore risk need to be assessed starting from highest say national, through all the tiers like provincial, district, tehsil, union council down to community level.

5. Conclusion

The paper provides a broad framework for understanding hazards, elements at risk and vulnerability assessment as a component of risk assessment process with its spatial dimension using GIS. During discussion, it has revealed that data collection, analysis and modeling is a complicated and effort intensive task and at the same time is dynamic in nature. As each component of risk assessment is changing with its spatial and temporal probabilities so the process will require regular updating and revision. Environmental changes particularly global warming resulting into climate change has become catalyst in dictating the need to take stock of all probable hazards, identify exposure of elements at risk and find out the vulnerabilities using remote sensing and GIS means with a view to undertake preventive, mitigation or risk reduction measures to obviate the potential damages and losses to our societies.

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