A methodology for the assessment of natural hazard vulnerability in U.S. coastal zone using Remote Sensing and GIS

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Abstract

U.S. coastal counties face severe meteorological hazards as compared to any other country in the Earth. Hence in order to formulate a methodology for the quantitative assessment of natural hazard vulnerability due to climate change, the study is attempted. Recent scientific tools such as remote sensing and GIS were integrated. Methodology for developing site specific models for the study is strategically planned and executed. Geo-spatial database for quantitative estimation of natural hazard is also proposed to provide real time natural hazard information to state and local governments in a quick and easy manner. Various levels of integration and participation are emphasized for an effective relational geo spatial database development for natural hazard vulnerability assessment and were briefly discussed in this paper.

Keywords

Meteorological impacts - Natural Hazard – Vulnerability – Remote Sensing and GIS – Geospatial database – Site specific models – Quantitative assessment

INTRODUCTION

Coastal zone is defined as "the coastal waters (including the lands therein and thereunder) and the adjacent shorelands (including the waters therein and thereunder), strongly influenced by each other and in proximity to the shorelines of the several coastal states, and includes islands, transitional and intertidal areas, salt marshes, wetlands, and beaches." Coastal locations were some of the first settled in the country, and have always accounted for a major percentage of the overall population. They were the primary centers for transportation, tourism, recreation, commercial fishing, and other industry. This coastal zone remains a crucial segment of the nation's overall economy. A variety of natural hazards regularly threaten this coastal zone. Severe meteorological events such as hurricanes, tropical cyclones, and nor'easters are particularly harsh on coastal areas, often resulting in damages from high winds, storm surge, flooding, and shoreline erosion. Tsunamis, whose destructive force is characterized by potentially devastating flood inundation, are uniquely coastal events resulting from offshore earthquakes, landslides, or volcanic activity. Coastal locations are also subjected to the impacts of long-term hazards such as chronic coastal erosion, potential sea-level rise, and global climate change.

Coastal hazard events can significantly affect or even alter the natural environment. Their impacts are generally not considered to be "disastrous" unless they involve damages to human populations and infrastructure. When people and property are not present, hazards are merely natural processes that alter the environment. When people and property is present then the impacts of hazards are viewed quite differently. The primary focus is no longer on the natural processes associated with a major hazard event, but instead on the disastrous results that can be measured by lives lost, property damages, and economic and environmental impacts.

The impacts of natural hazards are becoming increasingly costly and devastating. Hazard impacts on the natural environment become more devastating because human development has altered the ability of natural systems to recover from such events. Experts believe that the statistics on disaster losses continue to rise worldwide due to a combination of factors that include a rise in the number of hazard events due to global climate change or natural cyclical trends, and an increase in human exposure in hazardous locations.

Some of the decrease in disaster damages worldwide could also be the result of improvements in disaster monitoring and reporting capabilities, particularly in developing countries. But disaster loss increases in the United States seem to be most closely tied to increased human exposure in high risk areas such as the nation's coasts.

The United States has an expansive and diverse coastline that supports a disproportionate percentage of the nation's population. The nation's 451 coastal counties contain just over 50 percent of the U.S. population, yet only account for about 20 percent of the total U.S. land area. During the last decade, 17 of the 20 fastest growing counties were located along the coast. In addition, 19 of the 20 most densely populated counties in the nation are coastal counties. These coastal counties possess economic gain through natural resources, maritime trade and commerce. These coastal counties also possess economic loss due to the natural hazards, overexploitation and exponential population growth. An assessment of both the economic gain and economic loss is briefly discussed as follows.

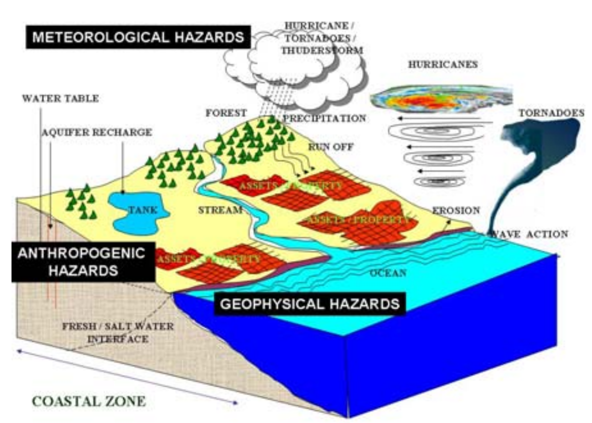

Figure 1. A model representation of a coastal zone

Economic gain in U.S. coastal zone

Nature article (May 1997), a group of ecologists estimated the value on ecosystem in the coastal zone. They estimated that the worth of the services for marine ecosystems is approximately $21 trillion per year. According to Sea Technology magazine, the value of goods and services sold by the ocean/marine industry was estimated in 1995 as $60 billion annually. Offshore oil and gas production has become very important and the 1996 value was more than $8 billion and the annual offshore production is increasing. According to the National Oceanic and Atmospheric Administration (NOAA), 77 million pounds (meat weight) of shellfish were harvested from U.S. coastal waters in 1995, with a dockside value of $200 million.

Current NOAA estimates concerning the recreational uses of U.S. coastal areas includes: approximately 94 million people boat and fish annually; the average American spends 10 recreational days on the coast each year; The coasts (excluding the Great Lakes coastline) support 25,500 recreational facilities; More than 180 million Americans visited ocean and bay beaches in 1993; Recreational fishing contributes $13.5 billion annually to the U.S. economy; Coastal recreation and tourism generate $8 to $12 billion annually.

Economic loss in U.S. coastal zone

Disaster losses in the United States coastal zone are currently estimated conservatively at $50 billion annually. The disaster loss between 1975 and 1994 is estimated as $500 billion. **80 percent** of the losses were imposed by **meteorological events** and **10 percent** were the result of **earthquakes and volcanoes**. A great earthquake (magnitude 8 or larger) has not struck a major metropolitan area since the 1906 San Francisco earthquake. An extreme or catastrophic hurricane (Class 4 or 5) has not directly struck a major urban area since the one that hit Miami, Florida, in 1926. Yet even without such disasters, which might create losses well over $100 billion, the overall costs of natural hazards, such as extreme weather, drought, and wildfires, are estimated at $54 billion per year for the past 5 years, or approximately $1 billion per week. In the United States, the direct costs to repair the damage average about $20 billion per year, of which over $15 billion is due to tornadoes, hurricanes, floods and earthquakes

The FEMA coastal erosion study conducted by The Heinz Center for Science, Economics and the Environment estimates that approximately 25 percent of homes and other structures within 500 feet of the U.S. coastline and the shorelines of the Great Lakes will fall victim to the effects of erosion within the next 60 years. Especially hard hit will be areas along the Atlantic and Gulf of Mexico coastlines, which are expected to account for 60 percent of nationwide losses. The report estimates that costs to U.S. homeowners will average more than a half billion dollars per year, and that additional development in high erosion areas will lead to higher losses. Thirty-four floods have been reported in Wake County (data source: NDCD and SHELDUS). The total coastline of mapped shoreline of Gulf of Mexico coast is about 8058 km out of which 3387 kms is in very high risk, 1056 kms is in high risk, 2968 km is in moderately risk and 547 kms is in low risk category due to sea level rise. So the 42 % of the coast line is in high risk, 37 % moderate risk and 8 % low risk (Robert Thieler et.al. 2001).

Hurricane Mitch, one of the most powerful and damaging storms experienced in Central America, struck between 26 October and 1 November 1998. A Category V hurricane, the event was characterized by intensive rainfall and high winds, dumping a year's worth of precipitation in less than one week on the region, causing the overflow of rivers, floods, mudslides and landslides. Thousands of people were killed and left homeless. Mitch caused billions of dollars of damage, and left huge tasks of reconstruction, resulting in the loss of decades of development efforts in the region.

The Economic Commission for Latin America and the Caribbean (ECLAC) estimates that the direct cost of replacing the lost and damaged infrastructure in the region after Hurricane Mitch is some US$5,000 million (Caballeros, 1999).

Recent large-scale disasters such as Hurricane Mitch and Georges, and the earthquake in Armenia, Colombia have demonstrated the vulnerability of society. It is widely recognized that recent population growth, rapid urbanization and the socioeconomic structure in Central America have increased vulnerability of these countries to natural hazards.

These disasters faced by the inhabitants both by natural and anthropological effects lead to the formation of legislation / laws to govern.

Legislation & major acts in U.S. Coastal Zone

The economic loss and economic yield as such felt by the inhabitants of the Earth has resulted in the formation of legislation. This legislation is framed for the sustainable use of the available natural resources. When the loss is severe or the gain is enormous; the laws needs some revision hence they were amended periodically. Some of the Laws and Acts pertaining to U.S. coastal zone were National Environmental Policy Act, Clean water Act, Marine Protection, Research and Sanctuaries Act, Ocean Dumping Act of

1972, Water Resources Development Act of 1996, Coastal Zone Management Act of 1972, Marine Mammal Protection Act of 1972, Magnuson-Stevens Fishery Conservation and Management Act of 1976 Endangered Species Act 1973, Nationwise Invasive Species Act of 1996, Oil Pollution Act of 1990, Comprehensive environmental response, compensation, and liability act of 1980, Rivers and Harbour Act of 1899, The Submerged Lands Act of 1953, The Fish and Wildlife Coordination Act of 1934, Land and Water Conservation Fund Act of 1965, Outer Continental Shelf Lands Act, Resource Conservation and Recovery Act of 1976 and The Coastal Barriers Resources Act of 1982. Hence in order to amend these laws the integration in different fields is attempted and discussed as follows.

METHODOLOGY

The methodology adopted for the assessment of natural hazard due to climatic impacts is given in Figure 2.

RESULTS AND DISCUSSION

Assessment of Natural Hazard

Natural hazard is a phenomena which occur in proximity and pose a threat to people, structures or economic assets and may cause disaster. They are caused by meteorological, biological, geological, seismic, hydrological, or conditions or processes in the natural environment. Hazard assessment is the process of estimating, for defined areas, the probabilities of the occurrence of potentially - damaging phenomenon of given magnitudes within a specified period of time. Hazard assessment involves analysis of formal and informal historical records, and skilled interpretation of existing meteorological, topographical, geological, geomorphological, hydrological, and land-use maps.

Office of United Nations Development Relief Organization (UNDRO), defines the term vulnerability as: “The degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no damage) to 1 (total damage)”. The vulnerability of an element is usually expressed as a percentage loss (or as a value between 0 to 1) for a given hazard severity level. The measure of loss used depends on the element at risk, and accordingly may be measured as a ratio of the numbers of persons killed or injured to the total population, as a repair cost or as the degree of physical damage defined on an appropriate scale. In a large number of elements, like building stock, it may be defined in terms of the proportion of buildings experiencing some particular level of damage.

Assessment is an interdisciplinary process under-taken in phases and involving on-the-spot surveys and the collation, evaluation and interpretation of information from various sources concerning both direct and indirect losses, short- and long-term effects. It involves determining not only what has happened and what assistance might be needed, but also defining objectives and how relevant assistance can actually be provided to the victims. It requires attention to both short-term needs and long-term implications.

The United States is becoming more vulnerable to natural hazards mostly because of changes in population and national wealth density. Due to this, people and infrastructure have become concentrated in disaster-prone areas. Natural Hazards threaten the sustainable development of United States, destroying years of development efforts and investments, placing new demands on society for reconstruction and rehabilitation, and shifting development priorities away from long-term goals while immediate needs are met. For most of the 20th century, the United States has largely spared the expense for catastrophic natural disaster. Significant progress has been made in understanding the various impacts that hazards produce on human and natural environments. Numerous research activities have been undertaken following the major hazard events of the past few years. Unfortunately, much of this research is piecemeal and has not been incorporated into any type of comprehensive database on disaster losses.

Natural hazards such as hurricanes and earthquakes do not have to become natural disasters. With proper planning, including proper environment management, much of the risk can be reduced. The risks posed by natural hazards in United States are exacerbated by social and environmental trends such as rapid urbanization and unplanned human settlements, poorly engineered construction, lack of adequate infrastructure, poverty, and inadequate environmental practices such as deforestation and land degradation.

Given the significant costs of the nation's catastrophic natural disasters, focus has shifted in recent years to expand beyond emergency preparedness and response to include a more long-term emphasis on disaster loss reduction. Hence it requires for a quantitative assessment of natural hazards vulnerability for coastal zone. This quantitative assessment of natural hazards is aimed to minimize either an individual's or a community's vulnerability to future disaster damages. Over the years, progress has been made in reducing hazard impacts through better predictions, forecasts, and warnings, particularly for meteorological hazards such as coastal storms and floods. General improvements in hurricane and tsunami prediction, and river and lake level forecasting, have been possible using the latest in computer modeling technology. NOAA's National Weather Service (NWS) is currently working with several new technological systems that are intended to significantly improve future flood forecasting capabilities. Though there were lot of techniques available to assess vulnerability due to natural hazard quantitatively still it is necessary to acknowledge the scientific and technological information needs throughout the various hazards-related disciplines and integration. Although significant progress has been made in the research and science associated with natural hazards during the past 20 years, and improvements in technology and understanding about natural hazards and how to access its vulnerability quantitatively requires a real-time networked scientific database.

Universities and research institutions (particularly the National Science Foundation), along with government agencies such as NOAA and USGS that maintain scientific hazards-related responsibilities, have contributed to advances in the scientific study of natural hazards. There is now more quantitative information available about the origins and behavior of hazard events but the concept of integration of the available data sets is lagged.

This study is to integrate all the fields acting in coastal zone for the assessment of vulnerability. Maps delineating hazard-prone areas at national, state, and local levels are needed to provide more comprehensive hazards assessment using information on a variety of natural phenomena, including coastal storms, floods, tsunamis, hurricanes, typhoons, landslides, wildfires, drought, earthquakes, etc. Much of this information already exists, but issues such as data integration, compatibility, scales, accuracy, and resolution need to be addressed to make the information useful at the local level. Better methodologies and models are also needed for conducting hazard vulnerability assessments that can incorporate highly variable local conditions and characteristics. This calls for the site specific models for better estimates.

Computer-based geographic information systems could be used to analyze hazards information and provide national risk assessment data to state and local governments in quick and easy manner. Specific models could be generated by using the GIS software. New high-resolution remote sensing capabilities could be examined for use in large-scale risk and vulnerability assessment. Hence, remote Sensing and GIS is to be intergrated and modeled for the assessment of quantitative natural hazard vulnerability.

Improvements in monitoring, data collection, and data processing account for most of the advancements made in short-term weather-related forecasting. Better modeling capabilities, along with a more thorough understanding of variables, such as global climate change and sea-level rise, are needed to improve long-range forecasting and planning for coastal hazard impacts.

GIS integration / modelling for natural hazard vulnerability

GIS is one of the powerful tools which can be used for the assessment of Natural Hazards Vulnerability (NHV). Due to these techniques, natural hazard mapping and vulnerability assessment could be performed for the coastal zone. These maps will help the authorities for quick assessment of potential impact of a natural hazard and initiation of appropriate measures for reducing the impact. This data will help the planners and decision-makers to take positive steps in time.

GIS applications in the coastal zone are diversified and case-based. Applications studies such as (a) coastal mapping, (b) environmental monitoring, (c) coastal process modelling, (d) navigation and port facilities management, (e) coastal environmental / hazard assessment, (f) coastal management / strategic planning, and (g) coastal ecological modeling could be done through GIS.

Coastal Mapping is mainly focused on thematic mapping in the coastal zone, such as mapping chlorophyll concentration using TM data (Chen *et al.* 1996). Environmental monitoring is one of the routine tasks in CZM, which include monitoring water quality and habitat/biodiversity, and beach watch. Coastal processes modeling of physical environment change in the coastal zone includes the simulation of effects of sea-level rise (Ruth and Pieper 1994, Grossman and Eberhardt 1992, Zeng and Cowell 1998, 1999, Hennecke 2000), the assessment of human intervention of shoreline change (Huang *et a*l. 1999), the use of historical data to predict future coastline change (Sims *et a*l. 1995) and the study of beach morphodynamics (Humphries and Ligdas, 1997). There are another two subcategories of the applications of hazards, namely, short-term and long-term tasks. The former is exemplified with monitoring and predicting oil spill (Belor*e*, 1990), while the latter is demonstrated by coastal hazard / vulnerability assessment due to climate change (Lee *et a*l. 1992, Sims, *et a*l., 1995; Deniels *et a*l. 1996, Hickey *et a*l. 1997, Zeng and Cowell 1999, Hennecke *et a*l. 2000, Esnard *et a*l. 2001). Coastal management / strategic planning involves assessing sustainability of the environment, social and economic viability. The abovesaid studies carried out in coastal zone is to be integrated using remote sensing and GIS for analysis.

The categories of GIS applications in coastal zone could be broadly categorised into three levels.

a) Level 1: as data management and mapping tools,
b) Level 2: as basic data analysis (query) and mapping tools, and
c) Level 3: as decision-supporting tools (modelling / simulation).

Most current implementations of Coastal GIS are still at Level 1 and Level 2. It is expected that Level 3 implementations will rapidly increase in the near future as the continuing improvement in GIS functions and more user-friendly interface become available in the market. Hence for the study of Quantitative Assessment of Natural Hazard Vulnerability Level 3 application is to be adopted.

The two basic approach / analysis, which should be followed for geospatial database development were given below.

Integrated approach:

a) integration of different level of application,
b) integration of vector and raster (data and functions),
c) integration of knowledge of different expertise, and
d) integration of different scales in time and space.

Because of the nature of integration, GIS applications should consider long-term integration. This includes the vertical integration that involves different application (and potential) levels, and horizontal integration that involves other interest groups. Therefore, issues must be addressed from database design, data sharing to tool-making (analysis functions) and experience sharing.

Multi-criteria analysis

a) multi - factors controls

Since coastal system has a complex hierarchical structure with multi-forcing exerting on each of subsystem, no mater which aspect of the system to be investigated, multi-variable analysis is an essential methods in the coastal environment.

b) multi - discipline approach for decision Other than the multi-factors, there are multiple interest groups of coastal community, therefore, good solutions to any coastal issues can only be derived from multidiscipline approach.

Output of the analysis

I. Historical and real-time information with respect to natural hazards will be gathered by satellite remote sensing, aerial photographs and by other conventional means and integrated with GIS RDBMS. This results in an extensive geo-database.

II. Through the modeling technique and by using the GIS RDBMS we can evaluate the likelihood of experiencing specific natural hazard in the future, and an estimation of intensity and probable level of impact.

   Each natural hazard will be evaluated for three characteristics:

   1. Likelihood of Occurrence, i.e., expected frequency;
   2. Likely Range of Impact, i.e., predictable size and location of impact; and
   3. Probable Level of Impact, i.e., estimated strength and damage potential.

III. The level of severity of natural hazards will be quantified in terms of the magnitude of the occurrence as a whole (event parameter) or in terms of the effect the occurrence would have at a particular location (site parameter).

IV. For quantitative natural hazard vulnerability, some weight value has to be added to the attribute column (slope, subsurface geology, current action, wave action, meterology, wind action etc). The values that will be given in the attribute columns could be calculated with the help of the equation 1 modeled in GIS environment.

Natural hazard = (Wgeology + Wslope + Wwind + Wmeteo + Wsiesmisivity + Wgeomorphology + Wetc…) (1)

Based on the above formula, natural hazard vulnerability values could be retrieved by clicking on any land parcels from the coastal zone map. Such kind of values will have no meanings for the end users. To make the result more acceptable, a separate domain is to be created in which the resultant values will be divided into three classes: very high, high, moderate and low hazard areas

Weights Class:

Values below than	30	Low hazard Area
Values between	30-40	Moderate Hazard Area
Values between	40-50	High Hazard Area
Values between	50-60	Very High Hazard Area

V. Hazard mitigation plan is to be developed and it will possess these five steps –
- identification of natural hazards that could impact the community,
- assessment of the community's vulnerability to natural hazards,
- assessment of the community's capability to respond to a natural disaster,
- assessment of the community's current policies and ordinances that affect hazard mitigation, and
- development of hazard mitigation strategies that can be implemented to reduce future vulnerability.

VI. By using all the above factors site specific models for the assessment of natural hazard vulnerability could be generated using GIS for U.S. coastal zone. This will serve as an input for further amendment of legislation concerned with U.S coastal zone.

CONCLUSION

U.S. coastal counties possess economic gain through natural resources, maritime trade and commerce and economic loss through natural hazards, overexploitation and exponential population growth. About 80 percent of the losses were by meteorological events and 10 percent were by earthquakes and volcanoes. Hence in order to minimize the loss due to natural hazard a computer based geospatial database methodology is adopted for natural hazards information retrieval and to provide national risk assessment data to the state and local governments. Site specific models were proposed for U.S. coastal zone by integrating GIS software and high-resolution remote sensing to quantify the large-scale risk and vulnerability. This modeling study could also be applied to developing countries such as India, Pakistan, Srilanka etc. for the natural hazard vulnerability assessment in their coastal zones.

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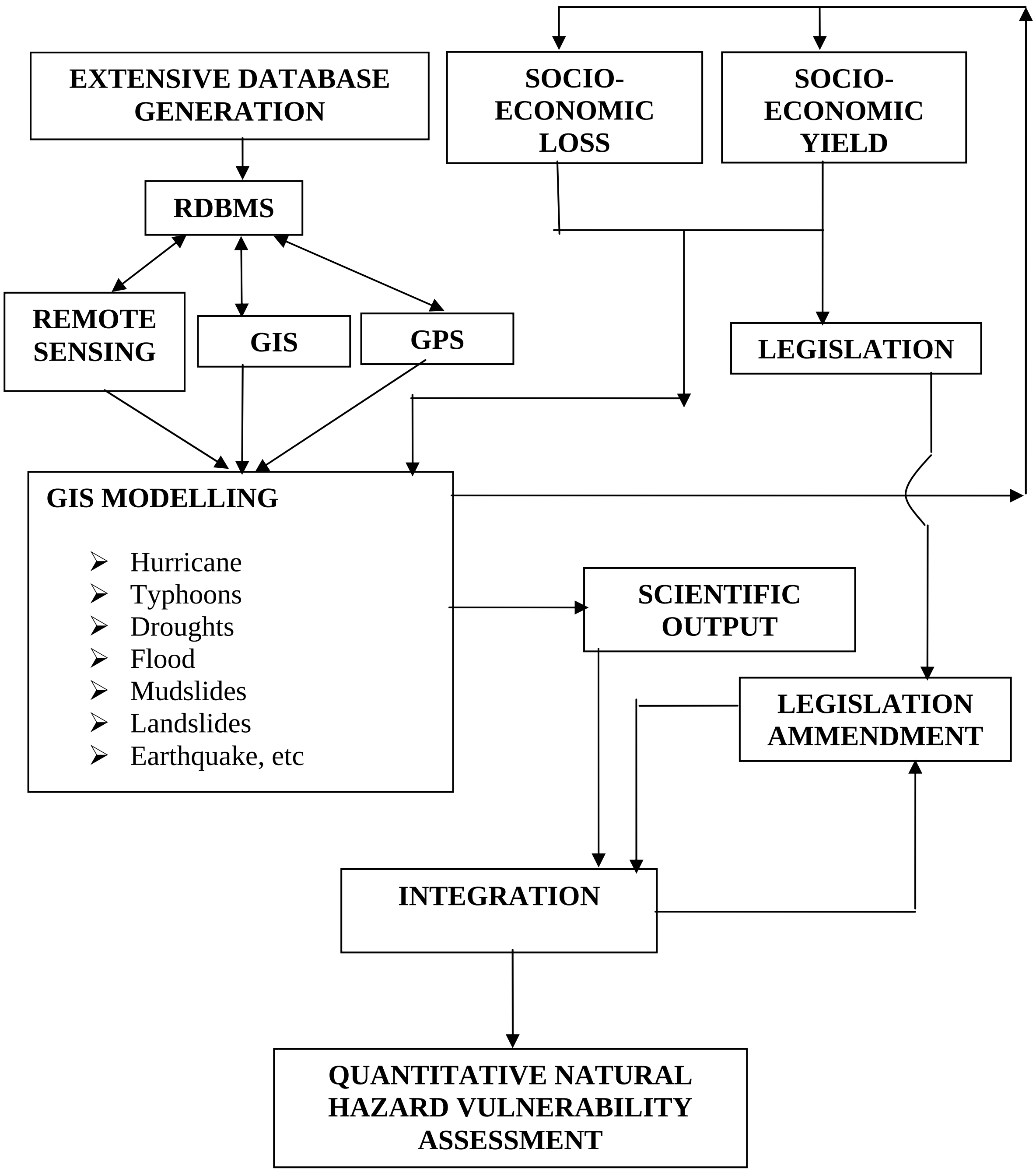

Figure 2. Remote Sensing and GIS Modelling for Quantitative Natural Hazard Vulnerability Assessment