Towards a Geospatial Approach to Post-Disaster Environmental Impact Assessment

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ABSTRACT

Natural disasters often leave profound impacts on the environment. Existing disaster impact assessment methods fall short in facilitating the relief work and in conducting cross-sectional comparison of various facets of such impacts. The development of a standardized index for measuring/monitoring the environmental impacts of disasters is necessary to address this gap. This paper proposes a conceptual framework to study the environmental impacts via remote sensing/GIS based geospatial analytical approach by developing a post-disaster environmental severity index. It considers physical, social and built-in components of the environment and identifies several key indicators of disaster impacts. Through statistical decomposition of a large number of environmental impact indicators, the study proposes a composite post-disaster environmental severity index (PDESI). Mapping of the proposed index would help identification of areas and component of the environment that are severely affected by a disaster, and formulation of disaster mitigation and damage recovery plans accordingly.

Keywords

Rapid Environmental Impact Assessment (REA), Post-Disaster Environmental Severity Index, Remote Sensing, GIS.

INTRODUCTION

The most important component of the study of natural disasters is the understanding of their nature and the severity of damages they cause. In recent decades, a significant portion of natural hazard research has focused on rescue, recovery, and mitigation but paid minimal attention to the post-disaster environmental impacts. Existing environmental impact assessment methods have proved to be inefficient in handling the disaster crisis as evidenced during the Hurricane Katrina and Asian Tsunami (UNEP, 2006). These methods have several major drawbacks in regard to the timing of assessments, which ranges from several weeks to several months after the event, and the descriptive nature of data collection which typically yield qualitative data with little utility in devising environmental policies and future mitigation and adaptation strategies.

Efficient plans for mitigating the environmental impacts of natural hazards requires quantitative indicators to assess the severity of such impacts (e.g., scale and intensity of the impacts), which can also be used as a means of monitoring, testing and comparing the environmental consequences of alternative mitigation measures over space and time. Quantitative indicators also provide a means to measure the relative importance of the complex, interrelated issues within the disaster complex that influence and/or are influenced by environmental conditions. To ease the use and application of such indicators, they should ideally be collapsed into a singular measure, a post-disaster environmental severity index, which encompasses all such indicators according to a robust weighting scheme. Such index can be used to rank and compare the impacts of disasters on the environment, in the same manner an index such as the Human Development Index developed by the United Nations Development Program (http://hdr.undp.org/hdr2006) is used to ranks countries in terms of human welfare.

Over the last several decades, geospatial technologies such as GIS and Remote Sensing have been used extensively in managing and tracking changes in pre and post disaster situations as well as in the environmental impact assessment (EIA) processes (Lein, 2002). Using such technologies not only helps in reducing the risk and loss of lives and economy, but also gives us the ability to prevent damages (Radke et al., 2000). The role of GIS and Remote Sensing in disaster situations is well documented in the literature, and the challenges faced have been discussed by several authors (Zerger and Smith, 2003; Cutter, 2003; Metternicht et al., 2005). The purpose of this paper is therefore not to discuss the role of geospatial techniques in disasters but rather is to review the theoretical and methodological considerations in developing a set of quantitative indicators for assessing the environmental impacts of natural disasters, as a first step in developing and testing a post-disaster environmental severity index (PDESI). To attain this purpose, we first explore the various facets of disaster environmental impacts and propose a conceptual model for organizing criteria by which we can possibly measure and compare the environmental impacts of disasters. In light of these criteria, we examine the gaps in existing methods for assessing the environmental impacts of disasters. We then propose an analytical model that addresses some of these gaps to guide the development of a proposed PDESI. We also discuss the technical considerations in translating this model into a geospatial methodology. The geospatial approach will not only encompass GIS, but will also include remote sensing image processing and analyses, and spatial statistics. We conclude with a brief discussion of the potential use of the proposed index and highlight the scope of future research towards further development and implementation of the proposed methodological model.

ENVIRONMENTAL IMPACTS OF NATURAL DISASTERS

Natural disasters can be of atmospheric, lithospheric, or biospheric origin. Atmospheric disasters originate from local, regional and global climatic and weather anomalies that cause flood, soil erosion, drought, tsunami, and hurricane to name a few. These disasters affect large geographic regions, and large populations: their environment and economic activities. Lithosphere disasters such as volcanic eruptions, earthquakes, and tsunamis occur during plate movements, and they affect much localized geographic area and its population. Biotic disasters results as certain biotic organism grow and spread over geographic area and cause loss of human and animal lives, and lead to economic loss. They also cause large human causalities and major degradation of the natural environments.

Hurricanes, floods, tsunamis, and earthquakes are the most prominent natural disasters considering their frequency of occurrence, severity of destruction, and nature and degree of environmental impacts across the globe. Impacts of natural disaster can be short-term and long-lasting. Loss of human and animal lives, destruction of property and economic structure sudden increase in unemployment, economic crisis are the examples of short-term impacts of natural disasters those occur immediately and/or during the disaster. Long-term impacts of disasters are mostly environmental in nature (i.e. droughts) and they occur much slowly after the event; continue for long time period and bring substantial changes in the local regional and global environment and ecosystems.

Both hurricanes and tsunamis destroy building structures, coastal embankments, and affect inland and coastal plant and animal species. Strong ocean waves and tidal surge cause flooding of human settlements and kill coastal aquatic and non-aquatic organisms; and increase inland water and soil salinity and toxicity that affect human, plant and animal lives for long term periods (Esworthy et al., 2005). Hurricanes and tsunamis can also yield extremely large volume of solid wastes, debris and toxic chemicals from broken houses and buildings which, in the long-run, severely degrade the inland and coastal environments (UNEP, 2006). Unlike hurricanes and tsunamis, prolonged flooding affects large areas of standing crops and vegetation; destroy municipal sewage system; increase soil and water toxicity that poses serious health threats to urban and rural populace. It also affects the economy by devastating transportation and communication lines (Smith, 1999). Earthquakes causes land slides, mud slides, which can destroy structures, as well as power, water, sewage and communication systems, and affect both physical and biological environment. Delayed recovery of earthquake related dead bodies can give rise to growth and spreading of bacteria and viruses that pose threats to living humans. Destruction of sewage and drinking water supply systems also pose major health threats to humans.

A CONCEPTUAL MODEL FOR MEASURING THE ENVIRONMENTAL IMPACTS OF DISASTERS

Recognizing the range of environmental problems that can be induced by disasters, scientists in recent years have been advocating more sustainable, environmentally sensitive approaches to disaster and risk management. Two of such approaches are the sustainable hazards mitigation framework suggested by Mileti (1999) (also see Cutter, 1994) and the framework of vulnerability analysis in sustainability science suggested by Turner et al. (2003). At the heart of both of these frameworks is the emphasis on the need to develop measures that inform the development of environmentally-sensitive hazard mitigation policies.

We utilize in this paper some aspects of the above mentioned frameworks to propose a conceptual model for identifying assessment criteria that can ultimately be integrated into a single PDESI to measure and compare the environmental impacts of various disasters. The proposed conceptual model is shown in Figure 1, which recognizes the differences but interrelated dependencies among the various environmental subsystems and components that could ultimately lead to significant variations in the consequences of impacting disasters (Turner et al., 2003). As the conceptual model indicates, the concept of “Environmental Subsystem” is not limited to the physical aspects of the environment (i.e., land, marine, plant species, etc) but also extends to include social environments and the role of institutions in shaping differential environmental consequences of disasters.

A detailed examination of the range of measurement criteria that can be derived from the proposed conceptual framework is still work in progress and beyond the scope of this paper. However, given the conceptual emphasis of this paper and to set the stage for rationalizing the need for the PDESI, we give some examples below as to how the proposed model can be utilized to guide the identification of criteria that can ultimately be used to measure the environmental aspects of disasters. Such aspects include the physical impacts and social impacts (i.e. which incorporate psychological changes in victims, demographic impacts, and economic losses), and destruction of plant, marine and animal lives and their habitats.

Since the natural disasters cause death of humans and live stock animals, destroy economic structures, brings major changes in land use/land coverage, and degrades the environmental qualities (soils, water, and air), the primary scope of the proposed PDESI is to collect and preserve the following broad list of indicators/criteria to incorporate a complete environmental assessment (Figure 1):

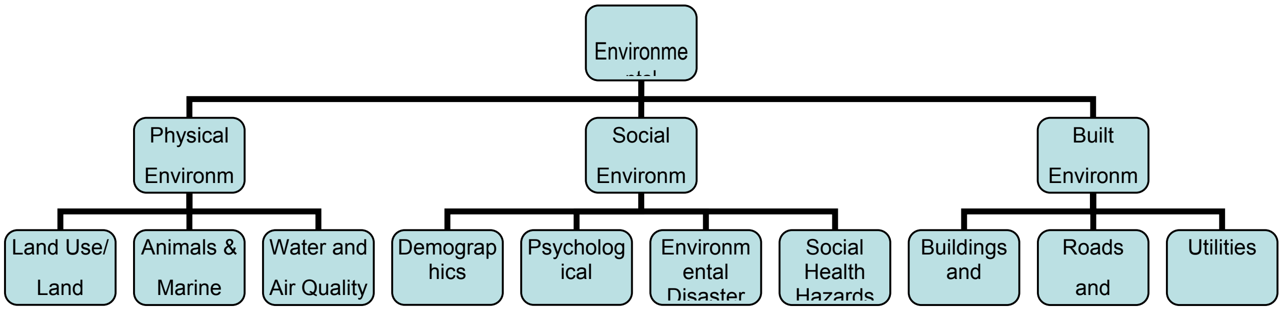
I. Land use/land cover
II. Animals and marine lives
III. Water and air quality
III. Demographics
IV. Psychological effects
V. Environmental Disaster Perceptions
VI. Social Health Hazards
VII. Buildings and Infrastructures
VIII. Roads and Bridges
IX. Utilities

A comprehensive and comparable database via the uses of most available advanced technologies and mapping devices should be created for the above list of data and quantitative methods for assigning weights for these indicators and aggregating them into a singular PDESI will need to be developed. The database would include information on a very basic geographic unit (census tract) which can be collated to form a larger geographic unit.

ENVIRONMENTAL ASSESSMENT IN POST-DISASTER SITUATIONS: A SURVEY OF METHODS

To assess the implications of human actions and natural disasters on the environment (both on short and long term basis), the federal government in the United States has created a systematic process called environmental impact assessment (EIA) that identifies the environmental consequences of natural and human activities. However, the EIA assessment is often conducted weeks or sometimes months after the disaster happens, does not necessarily address all the criteria and issues that can be depicted from the conceptual model shown in Figure 1. Furthermore, within such long time period, various environmental changes could take place. Sometimes, these changes are dramatic in nature and take place within hours and continue to do so for several days or weeks. A more systematic assessment procedure is therefore needed to overcome the shortcomings of the currently operational EIA. A challenge in devising this assessment stems from the need to balance the tradeoff of being holistic in nature (i.e., measure the various environmental subsystems shown in Figure 1) and in the same time being simple enough to be conducted in a repeated timely interval and to produce results that are easy to contrast and compare (i.e., produces a singular aggregated measure or index that is easily utilized in the decision making process).

Recently, the Benfield Hazard Research Centre and the Canadian International Development Agency (CIDA) have developed the Rapid Environmental Impact Assessment (REA) surveying system. Both methods emphasize the need for identifying and integrating environmental issues in the earlier stages of disaster response. The methods enable rescue and relief workers to perform faster comprehensive relief and rescue operations (Benfield Hazard Centre REA Guide). The REA method is especially designed to operate in a small area where the assessment survey and data collection performed need to employ very few human personnel in a very short period of time The method collects data through a systematic survey questionnaire that is composed of simple structured, census-based qualitative assessment processes incorporating narrative descriptions, rating tables, and figures. Thus, it does not yield any quantitative data. As discussed earlier in this paper, quantitative data is very crucial when measuring, analyzing and comparing and contrasting damages caused by natural disasters at various scale and



Environmental Systems	Indicators	Variable Definitions
Physical Environment	Land Use/ Land Cover	Percent change in land use categories during pre- and post-disaster situations.
	Animals & Marine Lives	Number of deaths of wild animals and marine lives.
	Water and Air Quality	Change in water pH, and air concentration of chemicals and aerosols quantity.
Social Environment	Demographics	Difference between population before and after the disaster.
	Psychological Effects	Percent change of patients affected by psychological breakdown in each census units.
	Environmental Disaster Perceptions	Percent change of people's perception affected by the disaster.
	Social Health Hazards	Percent change in the number of people affected by various disaster related diseases.
Built Environment	Buildings and Infrastructure	Percent change in the number of buildings and their monetary values.
	Roads and Bridges	Percent change in the number of roads and bridges destructed.
	Utilities	Percent change in the number household lacking power, water, gas, and telephones after the disaster.

Figure 1. Various Components of the Environmental Systems and Major Indicators of Environmental Impacts of Disaster.

interval in various parts of the world. It allows researchers to observe the changes that take place before and after the disastrous events, inform the design of simulation models of disaster patterns as well as the identification of relationships between various spatial components of the environment.

In addition to lack of quantitative analysis, there are several additional drawbacks of the REA method. For example, the existing REAs are reactive in nature and do not directly address environmental management practices or ecological conditions prior to the occurrence of the disaster (See Figure 1). Also, existing REAs are influenced by the perceptions of individual surveyors. This not only introduces a significant difficulty in providing a comprehensive picture of the environmental impacts, but also proves to be extremely hard in testing the applicability of methods and the generation of standardized quantitative metrics to measure performance and compare the disaster impacts.

Furthermore, while REA may be applicable for all natural hazards type, it is to be conducted in the local areas affected by the disaster. However, some natural hazards such as hurricanes and floods typically induce environmental impacts at a regional scale consisting of several states or the whole coastal area of a country. Current REAs are not designed to provide environmental assessment for such a large regional area. For a complete assessment process following such events, REAs should be repeated several times by the assessors. However, without any systematic database updating and observing processes, the gathered data for such areas can be difficult to analyze and as a result, they do not offer any significant and useful results.

Finally, existing REA methods do not collect and preserve the pre-disaster demographic, socio-economic, land use/land cover data for larger geographic units. In the absence of pre-disaster data, understanding the degree of severity and evaluation of changes in demography, socio-economy, and land use/land coverage caused by the disasters becomes impossible; and inadequate comparability of pre- and post-disaster information makes formulation of long-term environmental impact mitigation and adaptation difficult.

MEASURING THE ENVIRONMENTAL SEVERITY OF DISASTERS: AN ANALYTICAL FRAMEWORK

Considering the weaknesses and inadequacy of the existing REA methods, it can be argued that a geospatial approach may help address some of those weaknesses by allowing disaster planners to visualize and analyzing damages caused by natural disasters at a regional scale within a short time period at a fairly low monetary and labor cost. In order to do so, we propose below an analytical, geospatial-based framework for creating a PDESI (see Figure 2). At the heart of the framework will be the use of remote sensing imagery, REA survey, and GIS ancillary data that are relevant in detecting changes in each of the environmental components addressed in Figure 1.

Research is ongoing to translate the proposed framework into a more comprehensive technologically advanced environmental impact assessment method (AREA) that will be cost effective, accurate and time saving and will be able to cover large geographic area to acquire large amount of pre- and post disaster information, including those relating to all the environmental subsystems and components displayed in Figure 1.

Methods of Data Collection

The data for the index should be gathered primarily from two sources: remote sensing satellite imageries and REA field survey. The demographic and socio-economic data for the pre-disaster period can be obtained from the national census of the countries involved and/ most vulnerable. Post disaster data on these variables needs to be collected through a modified REA survey procedure that is quantitative in nature either through numerical data or through the use of Likert scales. The physical destruction to urban structures and land use/land coverage data for both pre- and post-disaster periods can be obtained from the remotely sensed images. Data on livestock population, plant and animal species may also be collected through REA or if severe enough, through remote sensing imagery. Finally, data on soil and water qualities should be collected through direct observation and collection of samples during the pre- and post-disaster periods. The REA data may also be used for accuracy assessment and classification of the remote sensing imagery.

Analytical Methods

The AREA involves the analysis of a large volume of quantitative numerical data collected from census enumeration, field surveys, remote sensing imageries, GIS sources. An analytical framework to obtain and process raw data and computation of PDESI is proposed here in Figure 2. To process these wide ranges of raw data, various analytical approaches should be adopted. An important task in the AREA is to quantify and compare temporal (pre- and post-) disaster data variables. Remote sensing image processing techniques such as Spectral Mixture Analysis (SMA) could be used to extract pre- and post-disaster data on urban and industrial land uses, cropland, water bodies and vegetation types. The Normalized Difference Vegetation Index (NDVI) and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) can be used to quantify vegetation abundance and agriculture quality. Other image based indices can used to measure soil salinity and quality and air quality. In addition to remotely sensed measured, water and soil quality degradation (pH, toxicity and chemical compositions, salinity changes) data can also be supplemented by national and international agencies through direct sample analyses.

Demographic and psychological data can be collected through census enumeration and direct questionnaire interviews with the victims. Demographic change such as loss of population due to death and migration can be assessed through comparison of pre-disaster published census data with post-disaster household enumerated data in a geographic unit. Natural disasters most commonly affect human psychology and behavior. To obtain data relating to any damage in human psychology and perception, direct interviews with the victims should be conducted. The data can be converted into Likert scale quantitative format.

Computation of the Post Disaster Environmental Severity Index

The percent change data for each variables representing demographic, socio-economic, land use/land cover/ soil and vegetation changes due to the occurrence of a disaster may be statistically analyzed to create the PDESI, which will be useful for planning mitigation options. The AREA method will yield large number of numerical data variables that need to be statistically decomposed to create a fewer number of representative variables that can be used to compute an index. Factor analysis technique is known for grouping large number variables into few new variables or factors that clearly represent the original set of variables (Shaw and Wheeler, 1985). In this type of study, for example, statistical decomposition of percent change data of large number of variables can be done by using a *varimax* rotated factor analysis. Factor scores would be ranked into following quintiles: scores >1.5 (5), 1.5 to 0.5 (4), 0.5 to –0.5 (3), -0.5 to –1.5 (2), and <-1.5 (1). High rank scores would indicate high degree of environmental impacts (for details see, Tata and Schultz 1988). Rank scores of factors representing demographic and socio-economic variables will be added to compute a human and socio-economic impact index; rank scores of factors representing land use/land cover change, soil and water and vegetation quality changes will be added to compute an environmental impact index; and rank score of all factors indicating change in demographic, socio-economic and environmental conditions will be added to obtain an total Post-disaster Environmental Severity Index (PDESI). Finally, the pre- and post-disaster data, their changes, and impact indices can be mapped by using GIS techniques and these maps may be used for mitigation planning.

CONCLUSIONS

As discussed earlier, the REA method is limited for its inadequacy in data collection and processing for environmental impact assessment and planning mitigation options. The AREA is aimed to collect and process large volume of multidimensional data for very larger geographic area as well as for both pre- and post disaster period. In doing so, the AREA would provide a means for calculation PDESI values that in turn would have a greater utility and applicability to plan for mitigation of both short and long-term impacts of natural disaster on human and natural environment. The database will also be useful to provide rapid information to both developed and developing countries when needed.

The AREA method expands the existing REA method through incorporation of three independent data components: REA field survey, remote sensing imagery, and GIS ancillary data. Pre-disaster remote sensing imagery serves as the base layer to compare and identify the areas affected. It should meet the spatial, spectral, and temporal requirements for the analysis. REA field survey data serves two purposes: collection of data that may be limited by remote sensing imagery (i.e. perception or psychological effects of the victims after the disaster) and assessing the accuracy of the SMA results. Finally, GIS will serve as the platform for combining the two sources of data in an organized fashion for visual and spatial analyses.

The overall goal of AREA is the creation of a post-disaster severity index, which will serve two purposes. First, it will enable researchers to rank natural disasters on a standardized scale based few important socio-economic and environmental damage variables. Such ranking will not only allow them to compare the damage severity within specific type of disasters, but also among other types of disasters, whether they are natural or human-induced. The potential use of such index will ultimately allow researchers and national governments to focus their investigations and financial resources on the critical environmental issues unique to the distinct types of natural hazards.

In conclusion, the AREA should have credibility for its integration of remote sensing and GIS technologies not used in the REA. Use of Remote Sensing imageries enhances the capabilities to observe and identify the areas affected by the disaster, and sequential changes in the landscape and environment. Because an AREA needs to be conducted on a daily basis after the disaster to keep up with the latest environmental effects, the amount of data is fairly large and the GIS database can be the guiding tool for updating such data and it can also display the results in the form of a map. This enables management personnel to analyze and visualize where the changes are taking place and which area requires their immediate rescue or relief assistance. But its most important significance lies in the fact that it provides a foundation to prepare and monitor the impact of mitigation policies and post-disaster relief activities on the environment.

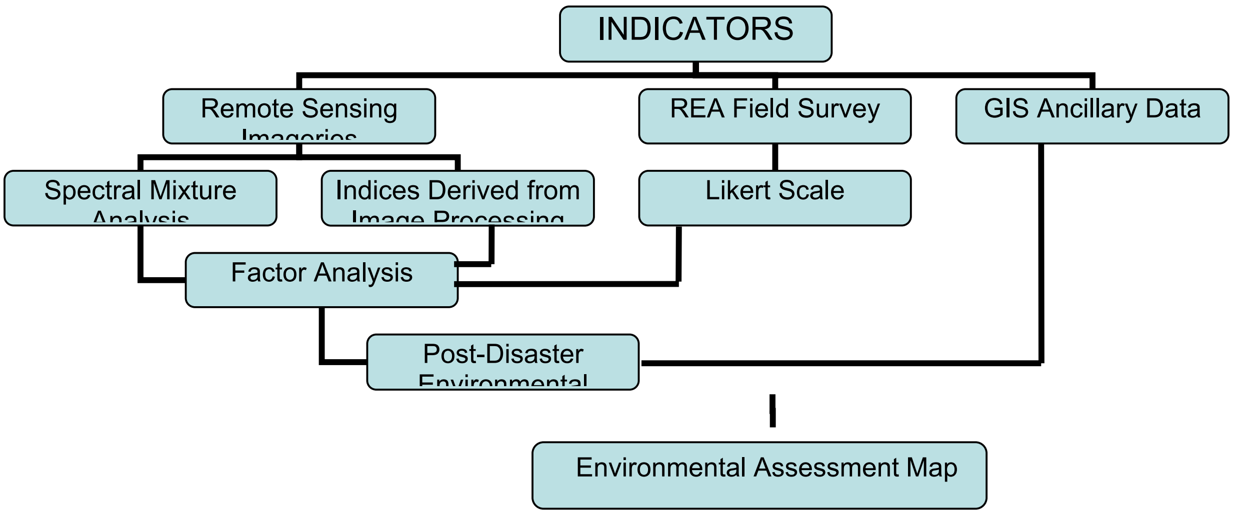


Figure 2. Analytical Framework for Creating Post-Disaster Environmental Severity Index

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