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Research and Theory in Advancing Spatial Data Infrastructure Concepts (preprint)

The Role of Spatial Data Infrastructure in the Management of Natural Disasters

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Abstract

High profile natural disasters like the Asian Tsunami of 2004 and Hurricane Katrina of 2005 emphasize the need for a systematic approach to the integration of geospatial technology in support of disaster management. In this paper, the data and information needs of various users involved in the disaster management cycle are analyzed for the preparedness, early warning, response, recovery and reconstruction phases. A risk characterization process that is evolving in southern Africa is presented. The process involves using historical geospatial data to develop baseline hazard and vulnerability profiles during preparedness planning. The profiles are integrated into a response plan for reducing the risk associated with various hazard scenarios. During actual hazard events, an appropriate risk profile is selected based on real time hazard and vulnerability information, and the associated activities included in the response plan are implemented. The paper emphasizes the diversity of data sources that must be integrated both in developing baseline risk profiles and in real time event analysis. It also highlights the diversity of data producers and users who must be linked through the risk characterization and communication process. Integrated products such as the "Atlas for Disaster Preparedness and Response in the Limpopo Basin", and national contingency plans are presented as useful for communicating risk and for initiating personal and communal preparedness activities. However, these tools must be kept current as vulnerability and hazard profiles frequently change. Data production, integration and dissemination systems that are dynamically linked using service architecture are proposed as the most practical means of ensuring that multi-sectoral disaster managers have access to the most current hazard and vulnerability information to minimize loss of life and property damage.

Introduction

In December 2004, the Asian Tsunami produced a widespread disaster (Inoue, 2005; Aitchison, 2005) with unprecedented death and destruction spanning the continents of Asia, Australia and Africa. Less than a year later, in August 2005, Hurricane Katrina, the strongest storm to hit the United States mainland in the last hundred years, caused massive destruction and flooding along the Gulf Coast, particularly in the city of New Orleans (Graumann et al., 2005). When the total cost for cleanup is assessed, Hurricane Katrina is expected to become the most expensive storm in U.S. history with a total cost of over $100 billion. Concurrently, multiyear droughts have devastated food and water supplies on which agro-pastoralists in the Greater Horn of Africa rely for their livelihoods, resulting in human and animal deaths. High profile natural disasters like these emphasize the need for a systematic and integrated approach to the development of disaster preparedness and response systems in order to minimize loss of life and damage to property (Wilson and Oyola-Yemaiel, 2001).

The need for geospatial data in natural hazard characterization and response planning has never been greater. For the Hurricane Katrina event, weather scientists relied on remotely sensed data from satellites such as the Tropical Rainfall Measuring Mission (TRMM) to monitor the evolution of the storm. Meteorological forecasts of the storm's path and intensity based on this technology are widely acknowledged to be more accurate and reliable than was possible prior to the TRMM satellite. Taken together, the Asian Tsunami and Hurricane Katrina resulted in the transfer of a record volume of satellite imagery from the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) to end users around the world in 2005. These satellite data sets were used in a wide variety of applications, most significant of which was mapping the spatial extent of the disasters. Yet few would attempt to argue that the Katrina disaster was well managed. A report on the federal response to the disaster found that information available to the various response agencies and field units was inconsistent, poorly integrated and often inadequate to facilitate an effective response (The White House, 2006). Data integration problems were documented at the Federal, State and local levels. Although there were other shortcomings in response coordination, it is clear that a major problem was the ineffective conversion of meteorological hazard information into response actions based on assessments of physical, humanitarian and economic impacts. As a result, several individuals and institutions charged with managing different facets of the response were forced to rely on incomplete or unfamiliar data in determining the actions that needed to be taken.

Remote sensing technology has provided us with a variety of geospatial data, such as optical and radar imagery, LIDAR elevation grids and Global Positioning Systems (GPS), that aid the identification of areas and features impacted by natural hazards (Tralli et al., 2005). In addition, large databases of digital orthophotography, and infrastructure data such as transportation, storm drains, canals and levees, population and socio-economic variables, soils, and land use/land cover have all been created. These datasets have been linked together into a national Spatial Data Infrastructure (SDI) through the Geospatial One-Stop initiative (http://www.geo-one-stop.gov/). Clearinghouse technology, data and metadata standards, procedures and policies are used to promote coordination among data providers and dissemination of geospatial data among users around the nation. Yet no integrated products describing the impacts of the hazard and actions that needed to be taken were available to disaster managers. It could consequently be argued that poor vertical integration of geospatial data hampered the response to Hurricane Katrina.

The impact of Hurricane Katrina on the U.S. Gulf Coast was not unprecedented in scope. During the first three months of 2000, the Indian Ocean coast of Mozambique was struck by a series of tropical storms, four of which achieved hurricane force winds (Christie and Hanlon, 2001). These cyclones (as hurricanes are called in the Indian Ocean) created a series of flood inundation waves along many large rivers in the region. The most severe of these storms was Cyclone Eline which resulted in record flooding in the lower reaches of the Limpopo River. Record expanses of inundation extended over 30 kilometers in width, and water depths greater than 10 meters were recorded in places that are normally dry. In the aftermath of these storms, Mozambican authorities worked with staff from a number of international agencies, including the U.S. Geological Survey, to improve their disaster preparedness (INGC et al., 2003). The USGS is also involved in disaster preparedness in southern Africa through its involvement with the regional flood monitoring network of the Southern African Development Community (SADC) and the Famine Early Warning Systems Network (FEWS NET), as well as the International Charter "Space and Major Disasters" and the Global Earth Observing System of Systems (GEOSS).

This paper examines information needs at various points in the disaster management cycle and the role that spatial data infrastructure can play in meeting these needs. It draws on the southern Africa experience where robust approaches for living with a wide range of natural disasters are evolving. Relevant datasets generated before and during a major hazard event are described, as are ways of effectively integrating these datasets in order to disseminate pertinent information to the various entities responsible for disaster management.

Disaster Management Cycle

Appreciation of the data integration challenges associated with disaster management requires a basic understanding of the phases of the disaster management cycle as it applies to various types of hazard events. Although alternate classification schemes exist, this study uses a disaster management cycle comprised of five phases: preparedness, early warning, response, recovery, and reconstruction (Fig. 1). The preparedness phase should begin long before any specific hazard event is detected. It begins with the perception of an elevated potential for a natural hazard to occur at particular location. This perception of hazard potential could be attributed to historical precedent, proximity to a source of hazards, or the condition of leading indicators.

In the case of historical precedent, the local historical time series of events is the primary dataset used to determine hazard potential. For example, tornado preparedness activities are undertaken regularly in the central U.S. (commonly referred to as Tornado Alley) because of a well-documented history of severe storms in the region. In contrast, there have been renewed efforts to implement tsunami preparedness activities in many coastal areas of the world that have no history of tsunami events due to the perceived tsunami hazard potential associated with proximity to oceans (Collins, 2005). This perception may have been fuelled by data from a tsunami event occurring elsewhere, in this case the Indian Ocean tsunami of 2004. When leading indicators are the source of elevated hazard potential, a determination is made based on prior understanding of the natural system that a hazard is likely to develop. An example of a leading indicator is the use of sea-surface temperatures to forecast seasonal precipitation totals and the level of cyclonic activity. In this setting, the sea-surface temperatures are not hazards in themselves. Rather they point to the potential for a hazard to develop sometime in the future. Whether initiated by historical or current data, preparedness activities are triggered when it is determined that there is a need to reduce vulnerability to a future hazard.

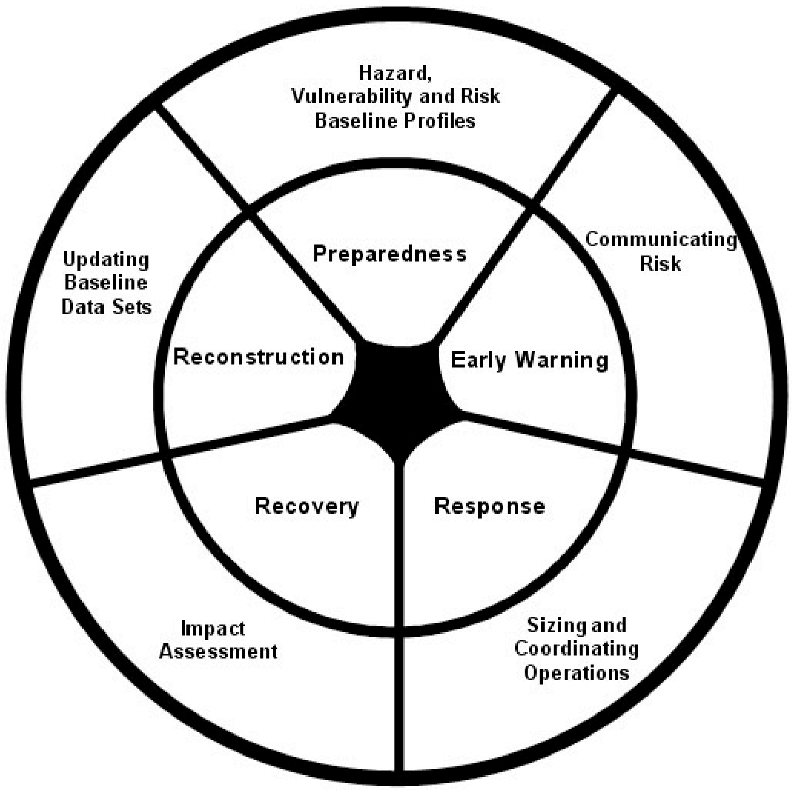

Figure 1: The role of spatial data infrastructure in the disaster management cycle

The early warning phase of the disaster management cycle is initiated after a specific hazard has been observed. The emphasis during this phase is on generating and transferring actionable information to disaster managers and vulnerable individuals. A variety of geospatial information is also required to track the position of the hazard relative to vulnerable population centers, physical infrastructure and zones of economic activity. The integration of hazard and vulnerability information forms the basis for determining which individuals and infrastructure components are at risk, and warning messages are generated with recommendations for urgent action to minimize loss of life and damage to property.

After the hazard has occurred, a response phase is initiated to minimize damage to property and loss of live by removing any secondary hazards such as fallen power lines, and to provide humanitarian assistance to those in urgent need. Baseline geospatial information is invaluable for identifying secondary hazards and for planning response activities such as rescue efforts and the delivery of humanitarian supplies. However, such information must be accurate and available in a form that is easily integrated with other information such as damage reports and the location of temporary accommodation centers. Poor quality baseline information becomes a hindrance to response efforts and is quickly abandoned by field crews as they become more familiar with the landscape and develop their own geographic baseline based on field observations. Opportunities to further assist the disaster management effort grow progressively smaller as the disaster enters the recovery and reconstruction phases. During these phases, focus shifts to logistics associated with the movement of people and supplies, financial resources and construction materials.

Information management during these phases centers on tracking transactions and stocks of materials rather than on spatial information. The challenge for the geospatial community is therefore to develop and integrate spatial databases well before any hazard events or risk becoming irrelevant to disaster management efforts.

Disaster Risk Analysis Framework

Given the importance of spatial data in the preparedness and early warning phases of disasters, it seems prudent to identify the main players and their data requirements. There are numerous types of natural disasters, including floods, cyclones, tornadoes, droughts, hurricanes, fires, snow storms, avalanches, cold spells, heat waves, landslides, earthquakes and volcanic eruptions. While we cannot hope to characterize each of these natural disasters in this paper, we will develop a common framework within which some general spatial data integration concepts can be explored. Disasters such as droughts evolve slowly over a period of months or even years while others such as floods develop over time periods on the order of days or even minutes. Some disasters such as earthquakes may even occur with no apparent warning at all.

As a starting point, we adopt the definition of risk as a measure of vulnerability to a hazard. This definition is well suited to natural disaster management because it implies an analysis of both the hazard and the vulnerabilities. Alternate loss-based definitions of risk that are frequently applied in the banking and insurance industries are less well suited to natural disaster management because they tend to emphasize financial recovery after a hazard as the only basis for action. Risk management based on economic loss-control can consequently obscure the benefits of early warning systems and risk reduction actions such as evacuation from the path of the hazard. The hazard-vulnerability approach also allows non-economic losses and humanitarian considerations such as the number of displaced people to be taken into account in quantifying risk.

Determination of the level of risk posed by any specific hazard requires an understanding of complex spatial and temporal interactions among multiple datasets. These interactions may even involve the analysis of unprecedented events. It is unreasonable to expect individuals involved in disaster response management to analyze these complex interactions under emergency conditions without major omissions or errors. The preparedness phase therefore represents the best opportunity for effective risk analysis. In this phase, there is no specific event to prepare for; consequently, a range of possible events must be analyzed to establish baseline profiles for both hazards and vulnerabilities, to which future events can be compared (INGC et al., 2003).

SDI in Hazard Characterizations

A baseline hazard profile is a series of realizations of hazard events of varying severity that is generated for preparedness planning. These event realizations are usually classified based on one particular attribute of the hazard. For example, cyclones are classified based on intensity attributes such as the maximum sustained wind speed (Saffir-Simpson Scale) while earthquakes are usually classified using the Richter Scale which measures the energy emitted by the vibrations. Floods are classified based on frequency of occurrence, while droughts are typically classified in terms of duration and magnitude.

Note that these severity classifications are adopted more for the convenience of the agencies responsible for monitoring the hazard than for those estimating their impacts. Primary hazard data producers are primarily interested in improving their understanding of the dynamics of the hazard in terms of its genesis, propagation and disintegration. They are considered to have characterized the hazard successfully if they are able to accurately forecast its spatial location and intensity. There are a few exceptional cases in which hazards are classified based on impact. An example is the Fujita Tornado classification scale in which a tornado is classified based on field surveys of the damage after it passes over a man-made structure. The limitation of such classification systems is that hazard severity information is not available during the early warning phase as severity can only be estimated after the event. For this reason, impact-based classification systems are only used for monitoring hazards for which pre-impact severity estimation technologies have not yet been implemented. For other hazards, a single physical attribute of the hazard is the basis for severity classification. An example of a single attribute classification system used for cyclones is shown in Figure 2. Inferences on impacts of the hazard from severity classifications alone are incomplete as they refer solely to potential wind damage and not to coastal damage from storm surge, inland flooding or the spatial and temporal distribution of damage.

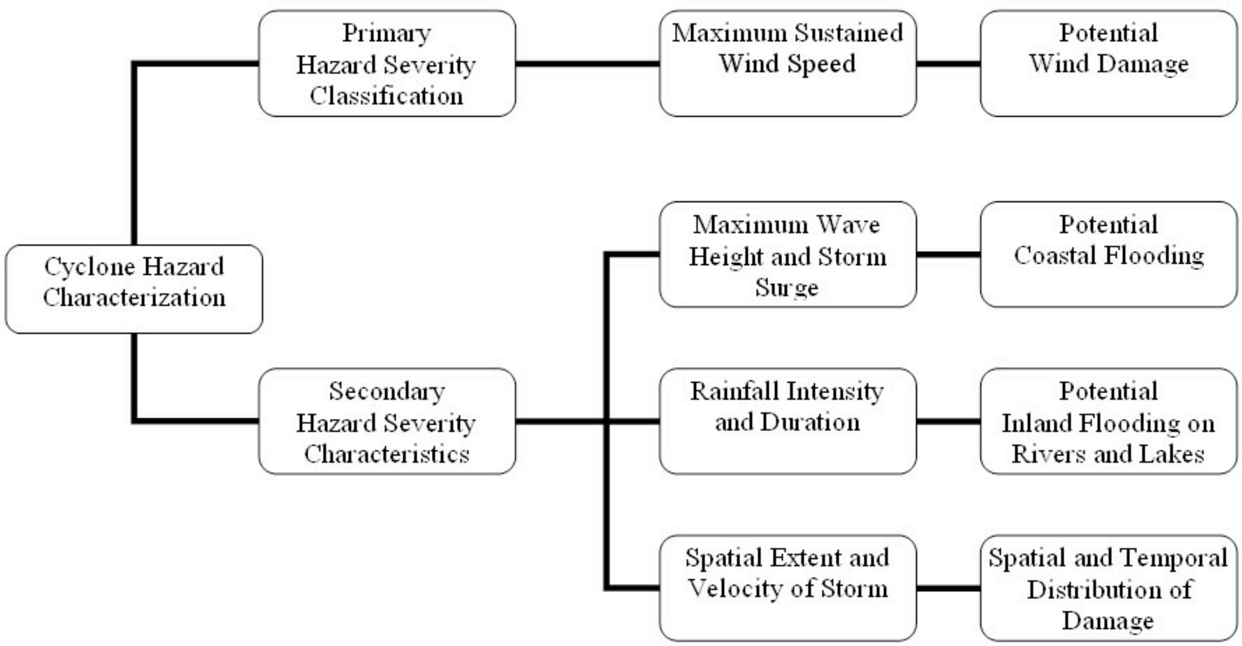

Figure 2 Single Attribute Classification System for Cyclones

A secondary layer of data producers is required to assess the impacts of the hazard on the natural and built environments. The secondary hazard data producers consist of agencies that are responsible for the monitoring of natural resources such as forests, rivers, and lakes, as well as physical infrastructure such as dams, levees, and canals. Information from these impact assessments should be presented in a form that allows disaster managers to make quantitative determinations of actions needed to minimize vulnerability to the hazard. For example, given forecasting information on an approaching cyclone from a meteorological agency, the hydrological agency should be able to supply disaster managers with forecasts of inundation extent. Without such information, the disaster manager is forced to relate cyclone wind speeds to the number of individuals who would be flooded out of their houses when no scientific, discernible relationship exists between the two variables.

In Mozambique, a dual classification approach has been adopted in which severity is characterized using a traditional numbering system (categories 1 to 5) based on maximum sustained wind speed while imminence is communicated through a color coding system with blue, yellow or red indicating less than 48, 24 or 6 hours to landfall, respectively. Warnings based on this system are generated by the national meteorological agency. Separate flood warnings are generated by the water management agencies which similarly characterize flood severity based on expected depth of water and imminence based on expected time of arrival of peak flows. The importance of such multistage warnings is demonstrated by the TRMM-based satellite rainfall fields from Cyclone Eline over Mozambique. The first image in Figure 3 shows the cyclone making landfall on February 22nd while the second image shows the cyclone being degraded to a tropical storm with the decline it's maximum sustained winds on the 23rd. However, the last image shows that the most severe rainfall actually occurred on February 24th, after the downgrading of the storm. The rainfall pattern emphasizes the need to incorporate both primary and secondary severity characteristics into response planning, impact analysis and decision making.

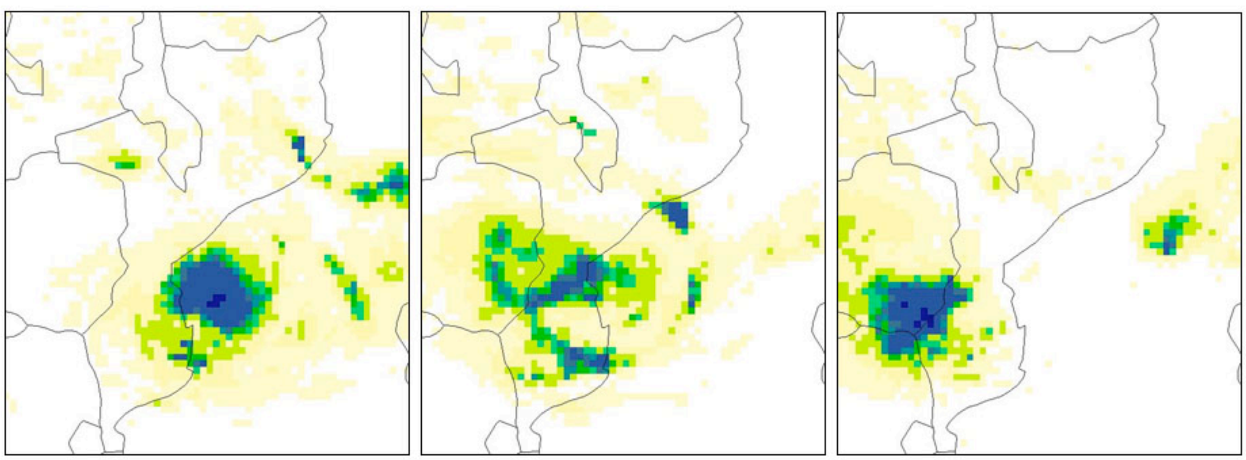

Figure 3. TRMM-based Satellite Rainfall Fields from Cyclone Eline

Disaster managers are the primary users of meteorological and water hazard characterizations. They must design and implement hazard response plans to translate hazard analyses into response actions to be taken by secondary data users, who consist of at-risk communities of individuals, businesses and other organizations such as government agencies. The translation of hazard characterizations into recommended actions requires an understanding of the vulnerability of at-risk communities to the hazard. A detailed description of the vulnerability assessment process and the role of spatial data infrastructure is the subject of the next section.

SDI in Vulnerability Assessments

Two hazards of equal severity that pass over areas of similar geomorphology will not necessarily cause equal damage or elicit similar responses. Differences in physical infrastructure and in socio-economic factors determine vulnerability to a hazard (Wisner et al., 2004), and these must be taken into account in response planning. Vulnerability is a dynamic factor that can change significantly in a very short time. In the Mozambique floods of 2000, the residents of the Lower Limpopo Valley were rendered more vulnerable to Cyclone Eline than they would otherwise have been because of damage to their flood monitoring infrastructure caused by another cyclone less than a month earlier (Christie and Hanlon, 2001). The value of a well developed and up-to-date spatial data infrastructure quickly becomes apparent in vulnerability assessment, even during the preparedness phase.

Let us begin by examining the data needed to address the physical infrastructure variable in the vulnerability equation. At the most basic level, a determination has to be made of the names, locations, and sizes of population centers. National census data are often a good source of this information but the data have to be compiled in geospatial format to allow for integration into the vulnerability analysis. The next step is to identify the location and status of infrastructure used to monitor potential hazards to population centers. This information typically comes from the various agencies responsible for monitoring meteorological, hydrologic, oceanic and subsurface events such as earthquakes and volcanoes. In the United States, meteorological and oceanic infrastructure is maintained by the National Oceanic and Atmospheric Administration (NOAA), while infrastructure for monitoring hydrologic and subsurface events is maintained by the USGS. If the location and condition of these monitoring systems is part of SDI, then vulnerabilities arising out of malfunctions of the monitoring infrastructure can be assessed in near real time.

Next, the condition of physical infrastructure such as roads, residential housing and commercial buildings within these urban areas must be assessed to evaluate their vulnerability to the hazard. Information on the condition of individual structures is often maintained by Federal, State and local agencies responsible for issuing building permits and maintaining structures such as roads and bridges. Again, the value of linking local, state and national SDI becomes apparent. If databases are dynamically linked and updated, it is possible to make an assessment of how many, or even which specific structures could be vulnerable to a particular hazard. New constructed or demolished structures and roads under repair could be taken into account in such an assessment. It also becomes possible to determine which structures can serve as temporary shelters during an emergency. Similarly, assessment of industrial facilities that could pose a secondary hazard to population centers or the natural environment would be performed to identify vulnerabilities associated with secondary hazards such gas leaks, oil spills, or other chemical releases.

The determination of socio-economic vulnerability likewise requires a number of data inputs. A national land use data layer is the most basic input to this analysis. It allows hazard zones to be subdivided by economic activities such as agriculture, forestry, mining, recreational, transportation, industrial, commercial and residential (INGC et al., 2003). Economic data identifying the human, material, and energy resource inputs for these activities and the resulting production figures allow for the quantification of economic vulnerability. These vulnerabilities may also be cyclical in nature with seasonal or interannual patterns of variation (Patwardhan and Sharma, 2005). For example, within agricultural land uses, a hailstorm occurring before the initiation of planting or after the harvest will have a much smaller economic impact than one that occurs in the middle of the growing season. These variations in vulnerability can be captured by seasonal crop calendars. Other land uses such as tourism may likewise have seasonal patterns which can be easily represented in a database as part of the vulnerability information to allow for the assessment of economic disruptions.

Other economic indices such as per capita income, unemployment rate, per capita motor vehicle ownership and proportion of residents that have personal property and commercial insurance are all important indicators of the ability of the population to recover after the event (Kumar and Newport, 2005). Some of these data are captured in census tabulations or annual tax returns and could also be incorporated into the SDI. The ability to recover, also termed resilience, is an important parameter for response planning. It is often closely linked to the willingness of populations to leave their possessions behind should an evacuation become necessary. Resilient communities are more willing to abandon their primary residence because of their ability to replace damaged property using personal income reserves, personal or business credit, or risk management tools such as insurance. They are also more likely to have access to personal transportation during the evacuation. By contrast, communities with low resilience are unlikely to want to evacuate their residence and may require additional personnel to encourage, assist and if necessary, enforce such evacuation. They are also more likely to require public transportation, food and accommodation, and provision should be made to meet these needs in the disaster response plan. Figure 4 shows a summary of the main data inputs for hazard and vulnerability assessments.

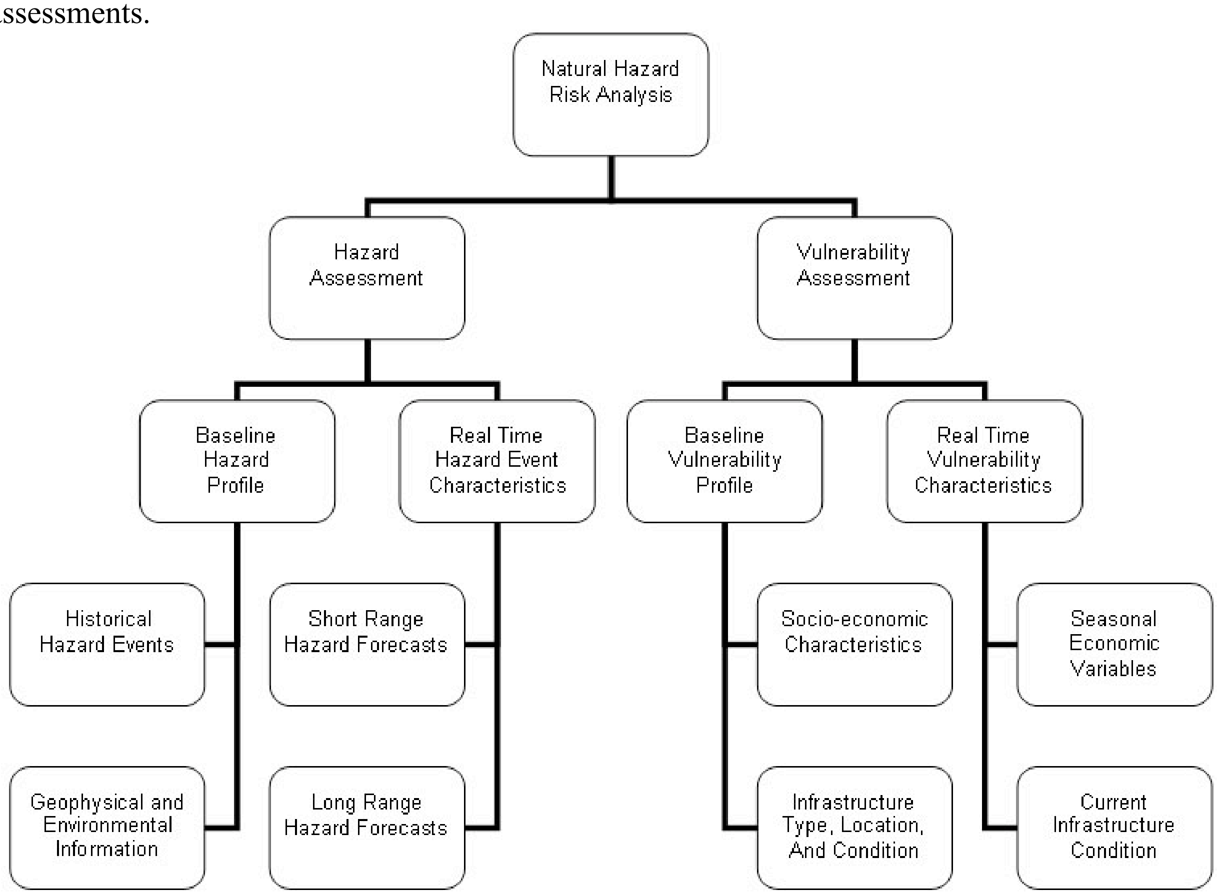

Figure 4 Data Inputs to Risk Assessment for Natural Hazards

SDI in Preparedness and Response Planning

Given the assessments of hazards and vulnerabilities, disaster managers must recommend a set of actions to end users in at-risk communities that will minimize risk to the community as a whole. The disaster managers may recommend that residents stay at home, congregate at more secure locations, or evacuate the risk zone completely. A combination of measures may be adopted based on stated individual vulnerability criteria. In making these decisions, the disaster manager is often faced with a large number of geospatial variables and may even require the use of complex decision analysis models (Levy et al., 2005) to integrate the data and arrive at the appropriate decision. Individual end users are motivated to action (or inaction) by both their personal perception of the magnitude of risk and their need to preserve and protect their personal welfare. Perception can be influenced by a variety of factors including age, gender, health, and social-economic condition (Brilly and Polic, 2005). Differences between objective risk analysis and subjective risk perception means that not all actions recommended by disaster managers will be adhered to by end users. Disaster managers must therefore estimate the likelihood of compliance and make provision for it in response planning through measures to improve compliance or provide additional assistance to non-compliant groups. Measures to improve compliance could include increased emphasis on preparedness training, insurance plans and improved warning dissemination. For those hazard events in which evacuations are necessary, provision of security, coordination of transportation, location of accommodation centers, and assurance of food, water, health care, and other humanitarian supplies can be important determinants of compliance (Gall, 2004).

Disaster managers must also plan and coordinate their own response efforts. One study of the Mozambique floods of 2000, for example, identified over 65 non-governmental organizations and 10 government agencies involved in the response (Moore et al., 2003). Figure 5 shows the extensive process that has been established for planning and coordinating response activities among these key institutions in Mozambique and the southern Africa region. At the beginning of each rainy season, the agrometeorological and water sectors of the respective countries initiate the process with a forum to generate regional consensus of both prevailing climatic conditions and forecasts for the upcoming season. After negotiation to reconcile differences, a consensus outlook is generated and distributed to the various agrometeorological and hydrological sectors in each country. Within Mozambique, each of the application sectors is required to use the consensus forecasts to update disaster preparedness plans which are then integrated into a national contingency plan. This process has contributed to the development of an integrated national spatial data infrastructure as discrepancies in datasets used for contingency planning quickly become apparent (Asante and Verdin, 2005). Postseason assessment forums involving both regional and national hydrological, meteorological, agricultural and disaster management agencies are held each year. These forums revisit the seasonal climate outlooks and assess their validity. They also assess water resource, food security and vulnerability conditions as a basis for recommending additional response activities to address lingering climate-related problems from the previous season. Policy recommendations are made and submitted to the respective national and regional policy-making organs in southern Africa for implementation. Past policy recommendations have included requests for review of import/export regulations, requests for unified field assessments and regional disaster relief appeals. Other actions have included updating of agency contact lists and communication channels, the redesign of specific hazard monitoring products and requests for specific flow measuring gauges to be repaired or installed.

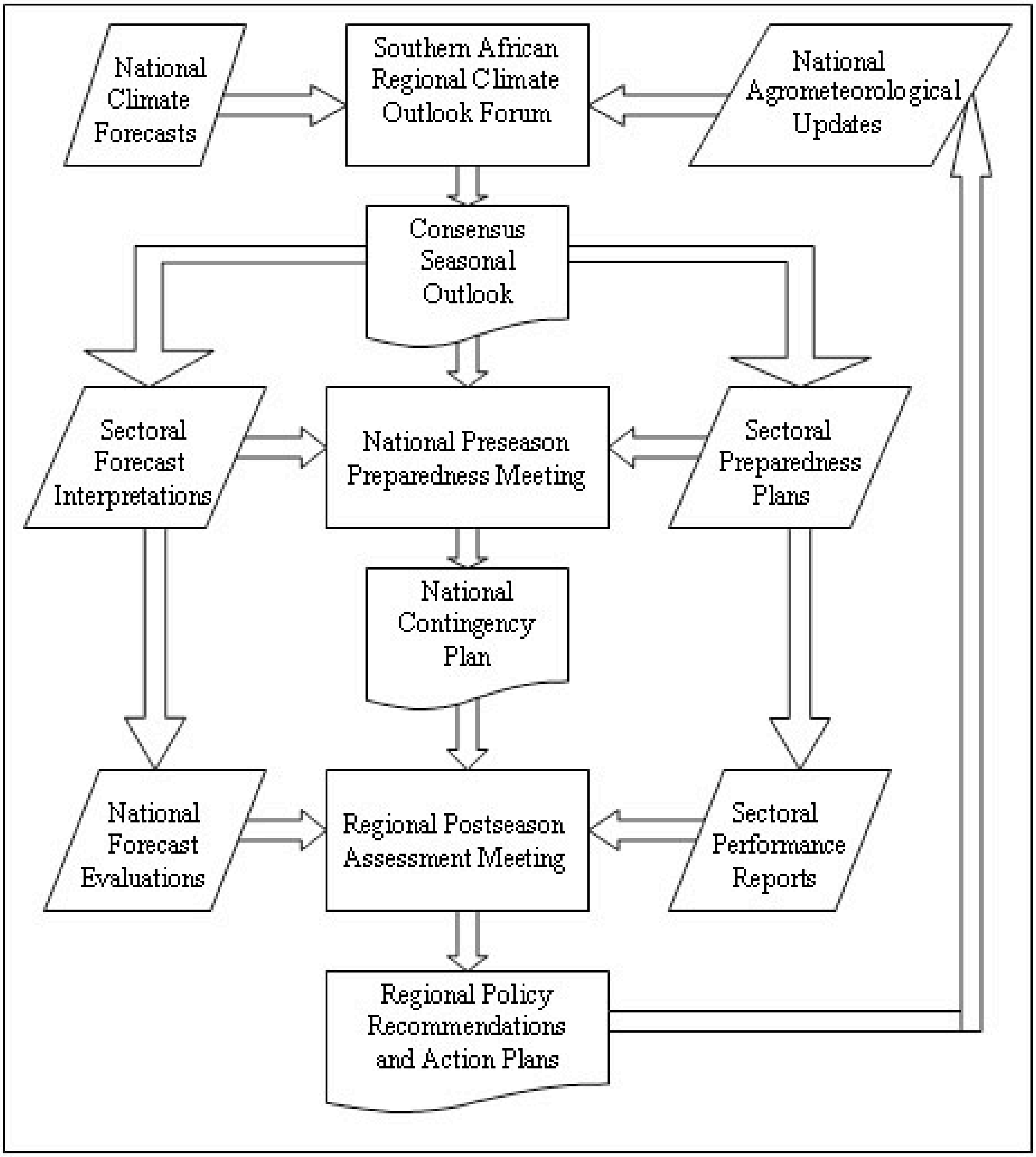

Figure5. Process Established for Planning and Coordinating Response Activities

Disaster response plans also help mitigate the physical and economic impacts of specific hazard events on communities in the hazard zone. For slow onset hazards such as drought, long range forecasts can be combined with real time model runs to provide early warning. Spatial data integration efforts can contribute to adoption of long range actions to manage risk. Financial risk management tools such as insurance, economic diversification and modified marketing may be adopted as coping strategies. At the local scale, modified water use policies, culling of livestock, or modification of planting cycles and crop types are examples of long range actions that may be taken as a result of such policy analysis. With rapid onset events such as floods, response actions are usually defined based on scenario analyses of *a priori* model runs. The focus of early warning systems shifts to communicating risk information to at-risk communities while response focuses on providing impact assessments to multi-sectoral disaster managers. Real time hazard information is the basis for determining which of the scenarios described in the disaster response plan should be put into effect. In Mozambique, the disaster preparedness and response atlas has proven to be a useful tool for communicating policy analysis associated with various disaster scenarios (INGC et al., 2003). End users are able to quickly make policy recommendations by relating real time hazard information to one of the hazard scenarios described in the atlas. However, the information within the atlas can quickly become outdated with changes to hazard profiles, population centers and other socio-economic activities.

The physical infrastructure components of SDI could play an important role in ensuring that end users have access to the most up-to-date versions of geospatial datasets, through the integration of web mapping technologies and service architecture. Existing online geospatial data search services such as the USGS Earth Explorer (http://earthexplorer.usgs.gov), internet map servers such as Google Earth and data distribution services such the USGS National Map (http://nationalmap.gov/) are invaluable for transmitting real time imagery and baseline data to users (Mansourian et al., 2006). Map servers have enabled the rapid distribution of real time hazard information (Asante and Verdin, 2005). Satellite-based communication systems have also been used for transmitting information from computer models, socio-economic databases and field reports from central repositories to end users operating in the field during a disaster (Brandon, 2002). In the commercial sector, automated teller machines and point of sale units rely on service architecture for remote financial data access and transaction processing. However, there are few examples of integrated policy assessments that are generated by automatic processing of data available from geospatial data servers. The integration of service architecture and map server technology with satellite-based communication systems could bring about the integration of available geospatial data and field reports into a coherent picture of disasters in near real time, and would significantly increase opportunities for SDI to contribute directly to disaster response and to policy analysis in general.

SDI in Recovery and Reconstruction

Following the initial response to a natural disaster event, attention shifts to restoring livelihoods and economic activities to a semblance of pre-event levels. An important part of this recovery and reconstruction effort is the estimation of the extent of damage and the overall cost of the disaster. A detailed handbook on how to perform such assessments has been developed by the United Nations Economic Commission for Latin America and the Caribbean (ECLAC, 2003), based on experiences in dealing with natural disasters in that region. The publication outlines methods of estimating the cost of disruptions to livelihoods, housing and social services such as education, health, energy, water, sanitation, and transportation. Economic impacts in agriculture, trade, industry and tourism are estimated as well as costs associated with clean-up within both the built-up and natural environments. Damage assessments must also be performed to enable private individuals, businesses, and policy makers to make determinations of whether to repair, replace, or completely abandon damaged infrastructure. Many of the datasets used in the preparedness phase of disasters are applicable during the damage assessment component of the recovery phase.

The cost of long-term impacts on the environment, population distribution, and socio-economic dynamics of the region are also taken into account. These long-term costs underscore the disruptive nature of major disasters on both the physical and cultural landscapes. Recovery from environmental impacts such as beach erosion, salt water intrusion and sediment deposition can take several decades. These impacts, together with the psychological trauma from the event, may cause many individuals to move away permanently from an impacted region. Because of such changes, pre-event datasets may no longer be representative of post-event settlements and population distribution, socio-economic baselines, hazard baselines, and environmental conditions. During the Asian Tsunami of 2004, for example, mangrove forests served as a bio-shield, blunting the force of the tsunami as it propagated inland (Danielsen et al., 2005; Kathiresan and Rajendran, 2005). Many communities living behind the mangroves were spared the type of catastrophic impacts experienced by other coastal communities. However, many of the mangrove forests were also damaged by the tsunami, and the communities behind them are more vulnerable now than they were before the tsunami. New hazard and vulnerability profiles that reflect post-event conditions must therefore be developed after each major disaster. If a distributed, integrated SDI exists (or is developed as part of reconstruction efforts), then updates to population distribution, socio-economic, and environmental datasets that are produced by the different agencies involved in reconstruction work become available for preparedness planning as they are generated. Development of this kind of feedback mechanism provides an invaluable opportunity for knowledge gained from the management of a disaster to systematically contribute to planning for future disasters.

Conclusions

Management of natural disasters requires the analysis and integration of both hazard and vulnerability data that is produced by many different agencies at the Federal, State, and local levels. The southern African experience suggests that such data integration is best performed during the preparedness phase by teams representing both primary and secondary hazard data producers as well as end users who could be impacted by the natural disasters. Integrated products such as the "Atlas for Disaster Preparedness and Response in the Limpopo Basin", and national contingency plans are useful for communicating risk and initiating personal and communal preparedness activities. However, such integrated products can also become outdated as vulnerability and hazard profiles change. Only when data producers, disaster managers, and end users are linked through an integrated national spatial data infrastructure can changing risk profiles be updated in near real time to support effective decision making during natural disasters. An integrated national spatial data infrastructure must incorporate online databases, data processing, real time mapping capabilities and information collection and dissemination technologies. Recent natural disasters have served to illustrate that while the geospatial databases are well developed, the data integration and dissemination components are still lagging behind in many countries.

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