Toward an Integrated Spatial Decision Support System to Improve Coastal Erosion Risk Assessment: Modeling and Representation of Risk Zones

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Key words: Coastal Erosion Risk Assessment, Multidimensional Decision Support System, SOLAP, Uncertainty, Fuzzy Object

SUMMARY

Coastal Erosion is a complex spatial dynamic phenomenon that threatens the coastal regions around the word and has a significant impact on social, economical and environmental aspects of people livings in these regions. Hence, coastal erosion risk assessment techniques require integrating several sources of data to provide a coherent and complete vision of potential risk regarding the phenomenon under study. This includes assessing possible damage on environmental, economical and social features as well as human-life losses. This fundamental information can then be analyzed at a higher hierarchical level to choose appropriate actions and strategies to protect the region, its environment, the people and their assets in an optimal way. Coastal regions are generally used by diverse habitats under authority of various organizations and stakeholders in local, provincial, and governmental levels. The main challenge arises when each organization prefers to take its own criteria and its own sources of data to assess the risk. The data and the criteria are often in conflict and it becomes difficult to provide a coherent vision of the overall risk as well as to support an efficient decision-making process. In addition, the way to represent risk zones is a challenging issue due to the complex hierarchical nature of risk as well as the existence of uncertainty. This complicates the adequate communication of risk values and their consequences to stakeholders and authorities. Therefore, an integrated information system is needed to manage the combination of several criteria, time periods and scales of information as well as the existence of uncertainty at different levels. Geographical Information System (GIS) are conventionally used for such purpose since they allow integrating the spatial and non-spatial data. However, on-the- fly multidimensional analysis of risk is only marginally supported by today's GIS and efficiency can only be achieved by integrating Business Intelligence (BI) concepts for spatial data exploration. In this paper we propose developing a Spatial Decision Support System (SDSS) that combines both GIS and BI capabilities to improve coastal erosion risk assessment. In particular, we propose to use Spatial On-Line Analytical Processing (SOLAP) Paradigm and Fuzzy Set Theory to improve the representation and analysis of coastal risk coastal infrastructures such as roads, buildings, plants, and people that are vulnerable to erosion.

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1. INTRODUCTION

The growing concern about potential coastal risk associated with natural phenomena such as erosion and human activities along the coast have created increasing interest in coastal risk assessment which is a critical and essential part of any decision-making process. It offers fundamental information for managing and ranking possible actions and strategies within any *Integrated Coastal Zone Management* (ICZM) plan treating environmental, social, and economical aspects.

Estimating risk involves identifying *Hazard* (the event produces risk), *Target* (element at risk) and *Vulnerability* of element at risk (the degree of intrinsic susceptibility of the features) (Varnes 1984; Blong, 1996; Cutter 1996; Cutter et al. 2003; Boruff et al. 2005; Blaikie, et al. 1994; Daudé et al. 2009). Risk assessment techniques require integrating a great amount of data from several sources to provide a coherent vision of potential risk regarding mentioned components. Moreover, coastal regions are under authority of different organizations in local, provincial and federal governments. Each organization often has its own source of data and its own criteria to assess the risk associated with erosion. Typically, these data and criteria are in conflict, which prevents the elaboration of a coherent vision of the coastal risk for decision makers from the different organizations. By the way, the common objective of all these organizations is to access to a fast and intuitive solution to report and summaries the degree of risk to take actions rapidly in the emergency cases. Beside that existence of uncertainty in different level of risk assessment and inherent fuzzy nature of risk necessitate modeling and representing of risk zones through a more flexible approach rather than a polygon-based with well-defined boundary.

However, the risk assessment process is not as straightforward as one might imagine. Dealing such analysis is the main challenge of decision makers who are involved in any step of ICZM plan by allowing fast synthesis, fast summarizing, easy comparisons and multi-level querying for efficient decision making purposes. In this regard, the main objective of this research is in to develop an integrated multidimensional tool to improve coastal erosion risk assessment and representation. *Spatial Online Analytical Processing* (SOLAP) is used as platform to accommodate the multidimensional aspect of risk assessment. *Fuzzy Set Theory* is proposed to improve the representation of risk zones due to inherent nature of risk and existence of uncertainty in different level. The proposed approach can be then applied to several types of objects in coastal area such as roads, buildings, plants, and people that are vulnerable to erosion. In addition, the interactions between those features and their corresponding risk at different levels are considered in the proposed multidimensional system.

The content of this paper is organized as follows: the second section is considered in present related works and described the problems. The proposed methodology and solution to develop a SDSS based on geospatial intelligence paradigm and representing risk zones are presented in the section three. Conclusions and guidelines for future investigations are presented in the last part.

2. PROBLEM DESCRIPTION AND PROPOSED APPROACH

Coastal Erosion Risk has inherently complex, multidimensional and continues nature, which involves the combination of several criteria, time periods and scales of information as well as the existence of uncertainty at different levels. Numerous frameworks and methods have already been developed for coastal erosion risk assessment (IPCC 2007; UNEP 2002; UNFCCC 1999; NOAA 2003; Mai and Leinbermann 2002). These approaches are mostly scale dependent that are developed for one spatial scale and are not suitable to be used for multi-scale analysis purposes. Based on regular or irregular analysis segment, most of these approaches are considered a homogenous distribution of vulnerable index for each segment as well as attributing the risk degree. However, coastal regions are occupied by diverse communities and are managed by different organizations such as fisheries, natural resources, agriculture, transport, and municipalities with local, provincial and federal authorities. These organizations have their own sources of data and criteria that may result in different and conflicting risk values and may consequently lead to inconsistent and inefficient decisions to prevent potential damages. Hence, a comprehensive tool for multi-scale representation of risk, not only in various spatial and temporal resolutions, but also in different levels of abstraction in thematic characteristics of risk for any aggregation or detailed information levels is crucial to sustainable development perspective of coastal regions. Proposed approach

*Geographical Information Systems (*GIS) provide a wide range of advantages from visualization, analysis, and integration of spatial and non-spatial data to support of decision making processes. However, GIS are limited when it comes to performing complex multi-scale, multi-epoch, and multi-theme spatiotemporal queries. Current advances in *Decision Support Systems* (DSS) and their integration with GIS provide interesting solutions for efficient risk assessment processes. Of particular interest are those advances coming from the field of Business Intelligence (BI), where a category of *Spatial Decision Support Systems (*SDSS) called SOLAP technology (Bédard et al. 1997) has been developed. SOLAP has been designed specifically to overcome the previously listed limitations of GIS and to allow rapid ad hoc multi-scale, multi-epoch, and multi-theme information retrieval and to perform complex querying by simply clicking on the desired level of information detail for given regions, epochs and themes (Inmon 2002).

The main dimension of uncertainty in coastal risk assessment is originating from risk zones representation. In addition, the fuzzy nature of coastal erosion along the coast due to the polyline-based approach of coastal erosion rate calculation introduces more vagueness to the risk assessment procedure. Furthermore, risk has hierarchical characteristics due to the inherent needs and interests of different participants working for different organizational levels. In this regard, risk zones are complex objects with uncertain boundaries resulting from the fact that their definitions are vague and multi-scale. The flexibility of *Fuzzy Set Theory* (has originally been proposed by Zadeh (1965)) to express risk value, consistent with human reasoning, together with possibility of dealing with uncertainties suggests that it is an efficient solution for spatial representation and communication of the risk (Darbra et al. 2008).

3. METHODOLOGY AND ACHIEVEMENTS

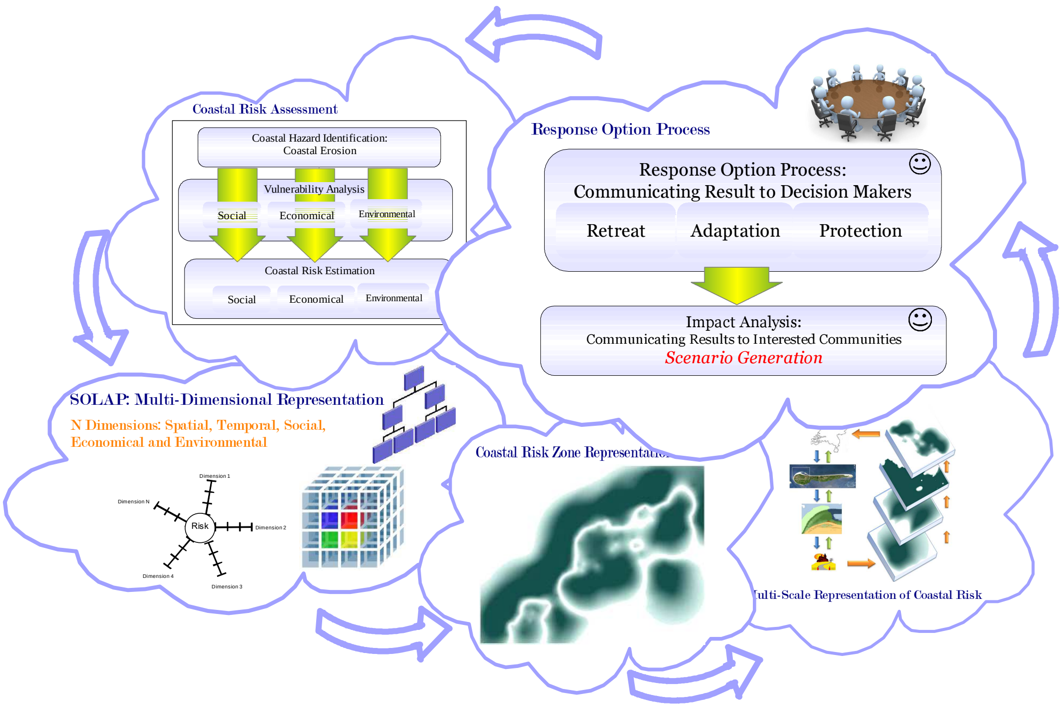

Fig. 1: A Scheme of Spatial Decison Support System for Coastal Erosion Risk Assessment

Fig. 1 illustrates a scheme of the SDSS for coastal erosion risk assessment. The system includes three main steps:

1. Risk analysis through geospatial intelligence paradigm,
2. Multi-Scale fuzzy representation of risk zones, and
3. Decision making board (response option process) through generating potential scenario for any possible action and its influence on the whole system.

The following section is focused on the first and the second parts of the system. The third part of system is out of scope of the current paper.

3.1 Development of Spatial Decision Support System Based on Geospatial Intelligence Paradigm

Bring in mind that risk assessment procedure is based on defining segment (regular or irregular) subject to potential hazards (Cutter et al. 2003), the segments may have different shapes and sizes. The area and shapes of these units may vary from a specific infrastructure to a very small cadastral parcel, municipality, state, or even a country. For each unit a vulnerability index and, subsequently, a degree of risk are assigned (IPCC 2007; Cutter et al. 2003; Gornitz et al. 1991). Vulnerability indexes are defined according to the vulnerable physical, social, and economic features within hazardous spatial units (Abuodha and Woodroffe 2006; Gornitz et al. 1991; Thieler and Hammer-Klos 1999; Shaw et al. 1998; Xhardé 2007; Boruff et al. 2005). The risk degree is computed by a cross measuring of hazard rate and vulnerability index by applying the Eq. 1 (Boruff et al. 2005, Cutter et al. 2003).

$$R(T,t) = H(T,t) \times \sum_{i}^{N} Rank(v(i)) \times \omega_{i}(T,t) \quad \text{Eq. 1}$$

where $R(T,t)$ is the risk of coastal erosion associated with target T at a given time t, $H(T, t)$ is the erosion rate affecting the target T at a given time t, $Rank(V(i))$ is the rank score (degree of susceptibility) of vulnerable feature, and $\omega_i(T,t)$ is the importance of this feature as weigtht for target T at a given time t. The risk level is expressed by values between 1 and 5 where 1 corresponds to very low and 5 to very high levels of risk.

Our previous work (Jadidi et al. 2012) is focused more on an analytical approach to develop the spatial multidimensional conceptual model for coastal erosion risk assessment. The analytical approach includes four main steps that consist of performing needs analysis, accomplishing data inventory, defining coastal erosion risk parameters (hazards, targets, and vulnerability index), and designing a spatial multidimensional conceptual model (dimensions of analysis, measures to calculate, and SOLAP implementation model).

There are several possibilities for building datacube within the SOLAP system that are *Relational OLAP (ROLAP)* , *Multidimensional OLAP (MOLAP)* or a combination of both *Hybrid OLAP (HOLAP)* (Imhoff et al. 2003). Most users do not have to care about distinctions since they are the implementation techniques. Alternatively, one may also use specialized SQL servers that support SQL queries over star/snowflake/constellation schemas (Bédard and Han 2009). Regading to diversity of SDSS users, one may prefer to read the data directly from the warehouse as a simple data exploration tool or to have its own data server. In this paper, Hybrid OLAP (HOLAP) approach is proposed to develop the adapted SDSS for risk assessment. HOLAP stores part of the data in a relational database and the other part in multidimensional arrays. A high-user end interface is provided by SOLAP (see Fig. 2) which leads to select the desired dimension and the level of details through datacube either for navigating different forms of data visualisation within Map4Decision. SOLAP also permits the decision makers of different organizations to consult and employ the same system (database and server) to navigate through the spatial and descriptive information. The navigation can be performed on different levels of granularity by basic operations such as spatial drill-down to go to finer granularity within a theme, spatial roll-up or drill-up to go to coarser granularity, spatial drill-across to show other information at the same level of granularity, and spatial slice and dice.

For more details, see (Rivest et al. 2005).

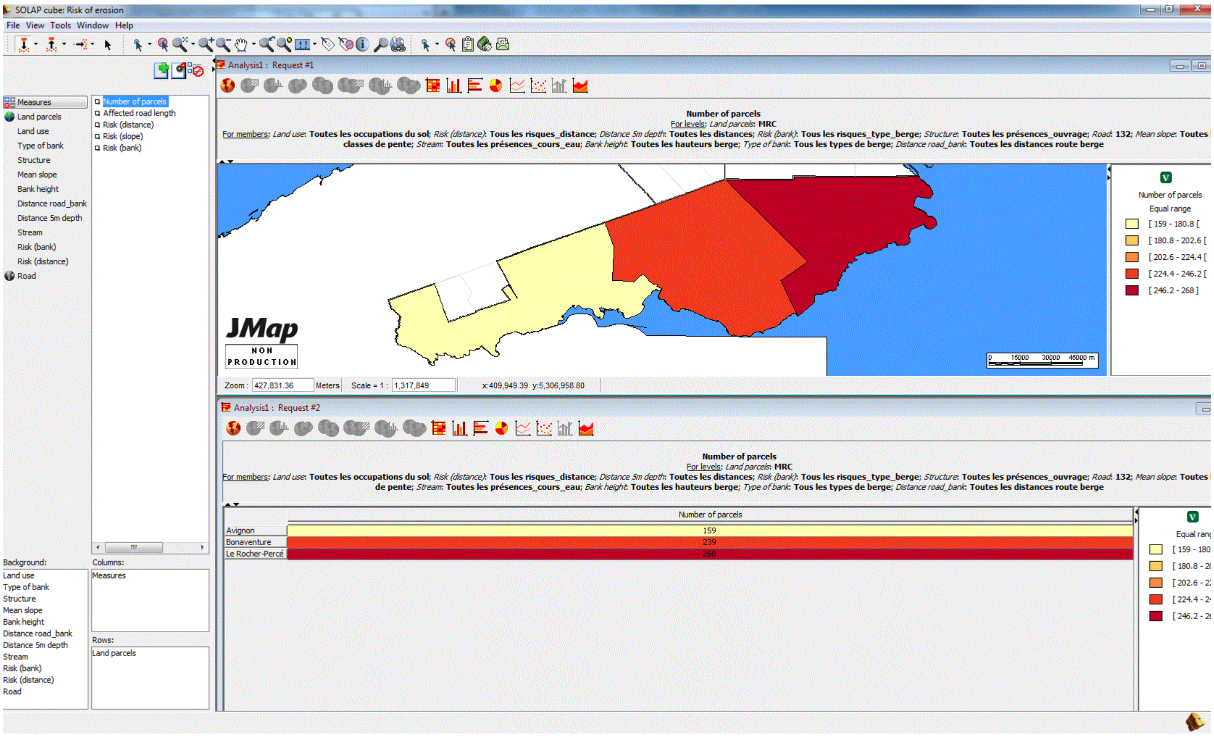

Fig. 2: An Example of SOLAP interface for users via Map4Decison software.

3.2 Fuzzy Approach for Coastal Risk Zone Representation

This paper proposes an algorithmic approach based on *Fuzzy Set Theory* to deal with the problem of ill-defined boundaries of risk zones which include:

1. Estimate coastal erosion rate,
2. Define the risk analysis unit,
3. Define fuzzy membership function and the rules,
4. Detect the risk zones as fuzzy objects and implement fuzzy operation to create a multi-scale representation.

The common indicator for coastal erosion identification is coastline change (Genz et al, 2007). The shoreline change is determined using a probabilistic approach, such as linear regression (Genz et al, 2007), a simulation-based technique (Uricchio et al. 2004), or is derived from *Digital Terrain Models* (DTM) obtained in different epochs (Limber et al. 2007). The coastal erosion rate can be calculated by the transecting a perpendicular line as profile along these lines to calculate the difference between different epochs. Based on erosion rate, the region is classified on 5 categories as very low, low, mean, high and very high rate of erosion. Next, the vulnerable object layers e.g. road network, houses, people density, and etc. are loaded in ARCGIS10 to have a significant perception of the distribution of vulnerable objects and variation of erosion. Regarding to the distribution of vulnerable objects and erosion rate classes, we define the segment of the risk analysis. The size and shape of the segment are always challenging issue in this stage. We inspired from traditional way of regular gridding, though we are more sensible about the distribution of the vulnerable objects. The vulnerability index is then attributed for each segment and a trapezoidal membership function is assigned to each segment (*IF...THEN...* rules). *Fuzzy Set Theory* uses membership functions and linguistic parameters to express vagueness in uncertainty issues. Instead of determining the exact boundary of a segment as in an ordinary set, a fuzzy set allows no sharply defined boundaries because of the generalization of a characteristic function to a membership function. Initially, all input variable are converted to a fuzzy variable using membership functions- a process known as *Fuzzification*. The shape of the membership function e.g. a simple vector, S-function, triangular, trapezoid is optimized through successive observations and may differ depending on the application and the need to capture different levels of uncertainty. Then, *Fuzzy Object Aggregation* approaches (union $\oplus$, intersection $\otimes$ and difference Θ) are applied to lead to a multi-scale representation of risk zones. Due to limited time, no concrete results are provided in this paper. The research is followed and continued and the final implementation on a concrete example will be presented in future works.

4. CONCLUSION

An understanding of risk and the application of risk assessment methodology is essential to be able to efficiently and effectively making decision and taking right actions and strategies. This paper presented a fast and efficient SDSS tool for coastal erosion risk assessment by privileging the geospatial intelligence paradigm. The proposed multidimensional database properly accommodates the mentioned challenges of risk assessment and decision making procedure. Furthermore, we tried to improve the representation of risk zones due to inherent complex and dynamic nature of risk itself and existence of uncertainty by translating them into fuzzy object. Moreover, the fuzzy concept guides directly to reduce the problem of ill-defined boundary of risk zones and existence of uncertainty in different level. However, more investigation in implementation of the idea of fuzzy concept through multidimensional databases and multi-scale representation are suggested in the future works.

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REFERENCES

Abuodha, P.A., and Woodroffe, C.D., 2006, International Assessments of the Vulnerability of the Coastal Zone to Climate Change, Including an Australian Perspective, Australian Greenhouse Office , Department of the Environment and Heritage, September 2006, 75p.

Bédard, Y., Larrivée, S., Proulx, M.J., Létourneau, F., Caron, P.Y., (1997), Étude de l'état actuel et des besoins de R&D relativement aux architectures et technologies des data warehouses appliquées aux données spatiales. Research Report for National Defence. Quebec City, Laval University.

Bédard, Y., Han J., (2009), Fundamentals of Spatial Data Warehousing for Geographic Knowledge Discovery. Geographic Data Mining and Knowledge Discovery. H. J. Miller J.H., Taylor & Francis: 46-66.

Blaikie, P., Cannon, T., Davis, I., Wisner, B., (1994), At Risk Natural Hazards, People's Vulnerability and

Disaster, London and New York.
Blong, R., 1996, Volcanic Hazards Risk Assessment, pp. 675-698 in R. Scarpa and R.I. Tilling (eds.), Monitoring and Mitigation of Volcano Hazards, Springer-Verlag Berlin Heidelberg New York.
Boruff, B.J., Emrich, C., Cutter, SL., 2005, Erosion Hazard Vulnerability of US Coastal Counties, Journal of Coastal Research, 21(5), 932-942.
Cutter, S.L., 1996, Vulnerability to environmental hazards, Progress in Human Geography, 20(4), 529–539.
Cutter, S.L., Boruff, B.J., and Shirley, W.L., 2003, Indicators of social vulnerability to environmental hazards, Social Science Quarterly, 84(1), 242–261.
Darbra R.M., Eljarrat E., Barcelo D., 2008, How to measure uncertainties in environmental risk assessment, Trends in Analytical Chemistry, 27 (4).
Daudé E., P. D., Dubos-Paillard E.,Gaillard D., Eliot E., Langlois P., Propeck-Zimmermamnn E., and Saint-Gérand T., (2009). Spatial risks and complex systems : methodological perspectives. From System Complexity to Emergent Properties Understanding Complex Systems. Aziz-Alaoui M. A. and Bertelle C., Springer.
Genz A.S., F. C. H., Dunn R.A., Frazer L.N., and Rooney J.J., (2007). "The Predictive Accuracy of Shoreline Change Rate Methods and Alongshore Beach Variation on Maui, Hawaii." Journal of Coastal Research 23(1): 87-105.
Gornitz V.M., White T.W. and Cushman R.M., (1991). Vulnerability of the US to future sea level rise. 7th Symposium on Coastal and Ocean Management, American Society of Civil Engineers.
Imhoff, C., Gallemo, N., and. Geiger J. G, 2003, Mastering Data Warehouse Design: Relational and Dimensional Techniques. John Wiley, 456 pages.
Inmon WH, 2002, Building the data warehouse, 3rd edition, John Wiley & Sons.
IPCC, 2007, IPCC Fourth Assessment Report: Climate Change 2007, Working Group I Report: The Physical Science Basis, http://www.ipcc.ch/ipccreports/ar4-wg1.htm
Jadidi A.M., Mostafavi M.A., Bédard Y., Long B., and Grenier E., 2011, "A Multidimensional Conceptual Model for Comprehensive Coastal Erosion Risk Assessment Based on Geospatial Intelligence Paradigm", Journal of Coastal Conservation and Management, Submitted.
Limber, P.W., List, J.H., Warren, J.W., Farris, A.S., and Weber, K.M., 2007, Using topographic lidar data to delineate the North Carolina shoreline, Proceedings of Coastal Sediments '07, American Society of Civil Engineers, 14p.
Mai S., and Liebermann N., (2002). A decision support system for an optimal design of sea dikes with respect to risk. 5th International Conference on Hydroinformatics, Cardiff, United Kingdom.
National Oceanic & Atmospheric Administration, NOAA, 2003, Science of Tsunami Hazards, 21(1).
Rivest S., Bédard Y., Marchand P., 2001, Toward Better Support For Spatial Decision Making: Defining the Characteristics of Spatial On-Line Analytical Processing (SOLAP), Geomatica, 55(4), 539 -555.
Rivest, S., Y. Bédard, M.-J. Proulx, M. Nadeau, F. Hubert & J. Pastor, (2005). "SOLAP: Merging Business Intelligence with Geospatial Technology for Interactive Spatio-Temporal Exploration and Analysis of Data." Journal of International Society for Photogrammetry and Remote Sensing (ISPRS) "Advances in spatio-temporal analysis and representation 60(1): 17-33.
Shaw J., T. R. B., Solomon S., Christian H.A., Forbes, D.L., (1998). "Potential Impacts of Global Sea-Level Rise on Canadian Coasts." Canadian Geographer 42(4): 365-379.
Thieler, E.R. and Hammer-klose, E.S., (1999). National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the US Atlantic Coast, Woods Hole, MA: United States Geological Survey (USGS).
UNEP (2002). Risk awareness and assessment. Living with Risk, ISDR, UN, WMO and Asian Disaster Reduction Centre. Geneva: 39-78.
UNFCCC (1999). Compendium of Decision Tools to Evaluate Strategies for Adaptation to Climate Change. United Nations Framework Convention on Climate Change. Bonn, Germany.
Uricchio V.F., Giordano R., Lopez N., (2004). "A fuzzy knowledge-based decision support system for groundwater pollution risk evaluation." Journal of Environmental Management 73: 189-197.
Varnes, D.J., 1984. Commission on Landslides and Other Mass-Movements-IAEG Landslide Hazard Zonation: A Review of Principles and Practices, UNESCO Press, Paris.

Xhardé R., 2007, Application des techniques aéroportées vidéographiques et lidar à l'étude des risques naturels en milieu côtier, PhD thesis, INRS-ETE, Quebec, Canada.
Zadeh, L.A., 1965, Fuzzy sets, Information and Control, 8 (1965), 338-53.

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Amaneh Jadidi Mardkheh is a Ph.D. Candidate at Geomatics Dept. in Laval University, Canada. She has a B.Sc. degree in Civil-Survey Engineering from IUST, Iran and a M.Sc. degree in Seismology Engineering from University of Joseph Fourier, France and Rose School, Italy as part of "Erasmus-Mundus" program. She joint Centre for Research in Geomatics (CRG) since Sept 2008. She is also representative of student in direction board of Canadian Institute of Geomatics (CIG)-Champlain Section. Her research interests include geospatial business intelligence, spatiotemporal modeling and representation; geospatial data quality, Fuzzy set theory as well as risk analysis in the context of multidimensional system.

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