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# Fuzzy logic based IEDSSs for environmental risk assessment and management

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**Abstract:** Environmental problems and the related adaptation strategies have grown in importance and complexity during the last years. The large amount of data and information that needs to be handled and integrated requires specific methodologies and tools. Several research and application activities are undergoing worldwide for the development of Decision Support Systems (DSSs) that allow management of multiple and different data in order to aid decision-making. In this paper the following DSSs using fuzzy models based Artificial Intelligence to address environmental problems will be presented. SYRIADE is a Spatial DSS for Regional Risk Assessment of degraded land supporting the inventory and assessment of contaminated sites and mining waste sites at regional scale. DESYRE addresses the main phases of contaminated sites' remediation process, e.g. analysis of social and economic benefits and constraints, site characterization, risk assessment, selection of best available technologies, analysis of residual risk and comparison of different remediation scenarios. MODELKEY is a GIS-based DSS that supports the EU Water Framework Directive (WFD) implementation by allowing the environmental quality evaluation of fluvial ecosystems and the prioritization of hot spots along the river basin. Finally, the CMCC DSS supports the identification and prioritization of climate change impacts and risks on coastal zones, in order to guide the definition of appropriate adaptations strategies.

***Keywords**:* Decision support systems, fuzzy logic, artificial intelligence, environment, GIS.

## 1. INTRODUCTION

There is a growing desire to develop effective and efficient computational methods and tools that facilitate environmental analysis, evaluation and problem solving. Environmental problems of interest may include concerns as apparently dissimilar as revitalization of contaminated land, evaluation of the impacts of climate change and effective management of inland and coastal waters. The approach to effective problem solving in both of these examples can involve the development of what are commonly called Decision Support Systems (DSSs).
A DSS is a system for helping to choose among alternative actions. There are many DSS application areas, possible approaches to making decisions, and levels at which decisions can be supported. A DSS might support decision-making for a specific problem or type of problems. DSSs for environmental problems and, more specifically, for risk assessment and management, are always related to complex problems where physical status of environment

as well monitoring and modelling data and decision maker's preferences need to be accounted simultaneously. To solve such multifaceted problems the use of Artificial Intelligence based models is a widely adopted solution as stated by Haupt et al. [2008].
The research field of artificial intelligence range from simple classification tools to complex neural networks, it involves many different approaches such as fuzzy logic and Bayesian networks. One of the most used techniques in environmental risk based DSSs is the adoption of fuzzy logic based Multi-criteria decision analysis (MCDA) (see Figueira [2005] and Linkov [2004]). MCDA includes a large class of methods for the evaluation and ranking or selection of different alternatives that considers all the aspects of a decision problem involving many actors (Giove [2009]). Basically MCDA consists in the application of aggregation and weight operators to the different criteria and decision maker's preferences. MCDA for environmental problems has its better application when its aggregation and weight issues are faced by the use of fuzzy logic techniques. Fuzzy logic, presented by Zadeh [1965], is a form of multi-valued logic which relates to fuzzy set theory in contrast with classical set theory, in order to deal with approximate reasoning. Fuzzy logic is particularly adapt for environmental problems because of the high level of uncertainty and approximation. Many other techniques exists to deal with uncertainty, the most widely used are Monte Carlo methods, Bayesian networks and Probabilistic models. All of them are based on known probability density functions (PDFs). Specifically, in Monte Carlo methods random events are iterated repeatedly in order to infer the final result, Bayesian networks are systems based on knowledge about conditional probabilities between the variables, and in Probabilistic models PDFs are interrelated by system of equations in order to define the final results.
Building DSSs like the ones presented and discussed in this article by the use of one of the aforementioned probabilistic methods would have involved the definition of many PDFs and the presence of a sufficient amount of data to perform a statistical analysis. Nevertheless, both these preconditions are not satisfiable in environmental analysis because of the nature of the data and the presence of subjective uncertainty. For this reason, in the four mentioned DSSs fuzzy logic has been chose to deal with the peculiar type of uncertainty present in MCDA. MCDA algorithms take into account values selected by decision makers and experts, and are therefore affected by subjective uncertainty (see Lehn and Temme [1996] and de Siqueira and de Mello [2006]). This kind of uncertainty differs from probabilistic uncertainty because it is mainly related to human perceptions and thoughts.
Another aspect which must be taken into account in environmental risk assessment and management related DSSs is the spatial extent of the elements involved in the system. It is a matter of fact that environmental problems are strictly related to land type and shape but also to the presence of different types of matrices like ground water, superficial water, air and any environment related entity which may participate in hazardous scenario. To be able to deal with such spatial issues the use of Geographic Information Systems (GIS) is the most widely adopted solution. GISs are systems able to capture, store, analyze, manage, and presents spatial data. Basically a GIS framework is a system including a mapping software along with spatial based assessment tools which allow the inspection of relations between spatial objects (see Chang [2007]). Environmental risk assessment DSSs make widely use of GIS frameworks, in some cases the DSS functionalities are directly developed inside such frameworks because of the predominance of the spatial aspects of these problems.
In this paper four environmental DSSs for risk assessment based on MCDA and fuzzy logic techniques by the use of GIS frameworks are presented in order to clarify the role and the strengths of such instruments in this type of problems. These DSSs are mainly related to risk assessment and management, they spread along different types of environmental problems and different types of technical solutions and are therefore an interesting set for this illustrative purpose.

## 2. THE SYRIADE DSS

The SYRIADE (Spatial decision support sYstem for Regional rIsk Assessment of DEgraded land) project is a project funded by EU Joint Research Center (JRC) in order to apply the EU Soil Thematic Strategy. The EU Soil Thematic Strategy concerns the

protection of soil by introducing a Risk-Based Land Management framework. It has been adopted by the European Commission in 2006 and states that European Member States shall be required to identify the contaminated sites in their national territory and, basing on a common definition and a common list of potentially polluting activities, establish a National Remediation Strategy. Accordingly, a Spatial decision support system was developed within the SYRIADE project which is intended to be an aid for national and regional authorities in the inventory and assessment of (potentially) contaminated sites and mining waste sites at regional scale.
The SYRADE DSS was implemented within a GIS platform and includes a set of tools which support the developed spatially resolved regional risk assessment methodology. The overall objective of the system is the ranking of potentially contaminated sites for priority of investigation, when no information on characterization and risk by site specific methodologies is available.
The SYRIADE DSS is based on MCDA where the alternatives to be ranked are the different risk values related to sources generating hazard. Risk is evaluated by the aggregation of criteria related to the different elements characterizing the risk scenario (source, pathway and target), normalized by the use of fuzzy membership functions. Because risk is not linearly related its defining criteria, a non linear aggregator have been used. The adopted aggregation function is the Choquet integral which is able, by the use of a mapping between criteria values and scores established by environmental experts, to mimic such non linear behaviour and supply a complete ordered ranking of the alternatives. The Choquet integral is a discrete fuzzy integral introduced by Choquet [1953], it generalizes additive operators, such as the OWA or the weighted mean, and is perfectly suitable in situations where adversarial and synergic effects are present between the criteria to be aggregated.
The SYRIADE methodology has been applied to Upper Silesia region in Poland which was selected since it is an acknowledged hot spot area in the context of environmental impacts from multi-source environmental contaminants from industrial activities. The application to the selected case study proved to be reliable and consistent with the environmental experts expected results. The regional targets and their relevant attributes were identified and spatially characterized. Moreover, the application of MCDA methodologies allows to take into account both relations between criteria and expert’s judgments, and the Choquet integral allows to parameterize non monotonic measures defined by the experts involved in the project.

## 3. THE DESYRE DSS

DESYRE (Decision Support sYstem for the REqualification of contaminated sites) is a project funded by the Italian Ministry of Science & Technology (MIUR) aimed at performing integrated management of contaminated mega-sites. The project comprises the creation of a Decision Support System, called the DESYRE DSS, which supports decision makers during the main phases of the remediation process, more precisely in the analysis of socio-economic benefits and constraints, in the site characterization, in risk assessment, in the selection of the best available technologies, in the creation of sets of technologies to be applied, in the analysis of the residual risk and finally in the comparison of different remediation scenarios. The DESYRE DSS is a GIS-based intelligent system which makes use of Multi-criteria decision analysis and fuzzy logic techniques to fulfil its goals.
The DESYRE DSS is a modular system composed by six interconnected modules each corresponding to a different step inside the remediation process. Although every module has its peculiar characteristics they are all based on spatial analysis tools. A geo-database has been designed to contain both the environmental and socio-economic characteristics of the land of concern. The socio-economic data are assessed by the application of a fuzzy logic analysis which generate a tool designed for decision makers that compares different land use options and outlines possible scenarios linked to alternative uses of the considered site. Within the risk assessment module the application of an original risk assessment methodology provides the estimation of risk spatial distribution. A risk-based partition of the site of concern, based on risks related to contaminants in soil and groundwater, is supplied to aid the definition of the remediation technologies plan. Selection and comparison of suitable remediation technologies and creation of technology sets are

obtained by the use of a Multi-Criteria Decision Analysis algorithm guided by environmental experts insights.
The DESYRE DSS has been adopted to study two differently scaled mega-sites within the Porto Marghera inland (Venice, Italy). The application of the methodology to sites of different dimension have proved that the methodology is robust enough to be seamlessly applied to different scale of analysis Among the future developments of the software, the improvement of the socio-economic module and the adoption of a MCDA methodology for the integration of the DESYRE results are considered of high interest. As far as the socio-economic module is concerned, its constraints should be lessen in order to made it more adaptable to different socio-economic contexts, while in the case of the MCDA methodology, it should allow users to integrate the results of the different modules in order to facilitate comparisons between scenarios.

## 4. THE MODELKEY DSS

MODELKEY (Models for assessing and forecasting the impact of environmental key pollutants on freshwater and marine ecosystems and biodiversity) is an Integrated Project with 26 partners from 14 European countries, funded by the European Commission within the Sixth Framework Programme in order to support the implementation of the European Water Framework Directive (WFD).
The WFD aims at achieving a 'good' ecological status in all European surface waters by 2015 and to this end asks water managers for carrying out various monitoring, assessment and management tasks. In order to classify the ecological status of water bodies a set of heterogeneous information and data on biological, chemical, physico-chemical, hydromorphological and ecotoxicological quality elements need to be gathered and integrated. Moreover socio-economic information have to be taken into account in economically analysing water uses and in setting up realistic and achievable management objectives.
The MODELKEY project methodology is based on the implementation of an Integrated Risk Assessment (IRA) methodology based on a Weight of Evidence (WoE) approach ( Burton [2002]). The methodology has been implemented within an environmental DSS developed inside the uDig GIS framework. The mathematical infrastructure realizing the WoE approach is based on a complex Fuzzy Inference System (FIS) which elaborates environmental and socio-economic status of fluvial ecosystems. Inside the system the Choquet integral has been widely adopted to mimic the non linear relations between the heterogeneous criteria taken into account. Moreover a prioritization procedure aiming at identifying hot spots along the river basin through integration of both environmental and socio-economic information is included in the DSS. This prioritization ranking is obtained by the use of a weight matrix which allows the simultaneous interpolation of many environmental and socio-economic indicators.
The MODELKEY DSS has been applied to three different river basins representing three typical situations along the European inland. The three selected case studies are the Elbe river in Czech Republic and Germany, the Scheldt crossing France, Belgium and Netherlands and the Llobregat river located in Spain. End-users and stakeholders related to the three river basins have been also involved in the evaluation of the results obtained by the DSS applications. Risk-based and GIS-based functionality has been highly appreciated. Output produced by applying both procedures (integrated risk and prioritisation) at basin scale are shown on dedicated GIS maps that can be easily compared. At site-specific scale intermediate results can be explored through dedicated visualisation tools. Moreover the inclusion of the Fuzzy approach that provides status evaluations based on probability distributions on WFD status classes taking into account uncertainty has been considered scientifically sound and effective for management and communication purposes.

## 5. THE CMCC DSS

The CMCC DSS is funded by the Euro-Mediterranean Centre for Climate Change (CMCC, www.cmcc.it), a national (Italian) research centre devoted to the study of climate change and its impacts, focusing on the Mediterranean region. The main aim of the CMCC-DSS is the integrated assessment of climate change impacts and risks on coastal zones at the regional scale, in order to support the definition of appropriate adaptation strategies. Accordingly, the CMCC-DSS may be considered a useful tool for the implementation of Integrated Coastal Zone Management (ICZM) in Europe and in the Mediterranean. ICZM is a dynamic multidisciplinary process based on an ecosystem approach that aims at protect and preserve the ecological, economic, social and cultural systems of the coastal zone, taking into account also a long time perspective that should consider climate change as major driving force (COM [2002]).

The CMCC-DSS is based on a conceptual framework that integrates tools and methodologies for the identification of potential climate change impacts and the assessment of bio-physical and socio-economic coastal vulnerability, in order to rank relative risks in the considered region. The framework structure is composed of 3 main phases: the Scenarios Construction phase which is aimed at the definition of future climate scenarios for the examined case study area at the regional scale, the Integrated impact and risk assessment phase which is aimed at the prioritization of impacts, targets and affected areas at the regional scale, and the Risk and impact management phase which is devoted to support the definition of adaptation strategies for the reduction of risks and impacts in the coastal zone, according to ICZM principles.

The core of the CMCC-DSS is a Regional Risk Assessment methodology (RRA) that is based on MultiCriteria Decision Analysis (MCDA) in order to estimate the relative risks in the considered region, compare different impacts and stressors, rank targets and exposure units at risk and select those risks that need to be investigated more thoroughly.

The main output of the RRA is the development of GIS-based Risk maps. Risk mapping is obtained through the integration of Hazard maps representing the exposure to climatic changes against which a system operates (e.g. inundation level) and Vulnerability maps representing the spatial distribution of environmental and socio-economic vulnerability factors.

The RRA methodology and the CMCC-DSS were applied to a case study region represented by the coastal area of the Northern Adriatic Sea (Italy). The application to the case study included the use of downscaled climate, circulation and morphodynamic models for the analysis of inundation, storm surge and coastal erosion processes, and of biogeochemical, trophic and fate and transport models, in order to assess climate change impacts on water quality. Moreover it includes the analysis of site-specific physical, ecological and socio-economic characteristics of the territory (e.g. coastal topography, geomorphology, presence and distribution of vegetation cover, location of artificial protection) and of local vulnerable receptors (e.g. beaches and dunes, wetlands, protected areas). Experts and decision-makers opinion take place, directly or indirectly, in every step of the RRA process (i.e. from hazard characterization to vulnerability assessment and risk ranking) and is particularly important for the selection of the aggregation functions and for the assignation of weights and scores to risk assessment parameters.

## 6. DISCUSSION AND CONCLUSIONS

The complexity and quantity of data related to environmental risk assessment and management processes requires the use of peculiar decision aid systems. Such systems are identified as Decision Support Systems which are the most widely used tools in this type of assessments. Among the many typologies of DSSs this paper has presented a set of GIS based DSSs characterized by the use of Fuzzy logic techniques inside Multi-criteria Decision Analysis infrastructures.

All of the presented systems are useful tools for decision makers as they supply a standardized framework which guides them along the decisional process. Decision makers' preferences and experts' judgments are taken into account in the calculations made by the decision algorithms. This is a crucial aspect in order for results to adhere to the decision makers' insights. Another important advantage related to these systems is the use of fuzzy logic which is able to deal with subjective uncertainty related to the values provided by decision makers and experts. Moreover, fuzzy memberships allow to present the obtained results in an effective way (e.g through pie charts displaying the different degrees of membership instead of just displaying the most probable value only ).

On the other hand, Fuzzy logic can also be a disadvantage for the systems. Fuzzy results, in fact, can be deceiving and, in some cases, taking a decision based on such evaluations can be a non trivial task. Moreover, the calibration of fuzzy logic based MCDA systems needs the assignment of thresholds and weights by decision makers and experts which can be as tedious as error prone.
The development of the presented DSSs have been challenging, mainly because of the use of geo-referenced data. In this respect, it is very important to chose the correct set of libraries and tools to be used since the beginning of the development process in order to avoid using non reliable or unstable technologies and end up with a non functioning product.
As far as the validation of the systems is concerned, three different aspects can be elicited: models, structure and results. Many of the presented systems make use of mathematical models which have been validated through experimental data. The structures of the DSSs have been examined by project involved end users (e.g. end users have tested different MODELKEY DSS prototypes and provided feedbacks by filling in dedicated questionnaires in order to improve subsequent software releases). Finally, as far as the validation of results is concerned, the results obtained by the application of the systems among the case studies have been assessed by case studies' experts in order to establish if final results were coherent with the actual situations.
To improve the reliability of these instruments, an assessment may be performed in order to examine uncertainty. To this end a sensitivity analysis should be performed which is supposed to give interesting information about precision and robustness.
Many enhancements can be done in order to increase the overall quality of the presented instruments. In particular, prediction modules should be included which, by the use of information regarding the present situation and the application of fuzzy logic based algorithms, should predict future scenarios. Also the spatial relations information should be more consistently introduced inside the fuzzy logic MCDA models toward the obtainment of results which are more strongly related to the underlying environment.

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