

Land management decisions in a carbonatic geo-environment

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Abstract. Land is the uppermost territorial unit of the earth's surface that is quasi-homogeneous in its physical, natural, and also anthropogenic properties. The fundamental component of land is lithosphere. The focus of this work is on a carbonatic geo-environment that is dominantly characterized by Mesozoic rock complexes, significant chemical weathering, and a set of landforms that are unique to this type of a geological structures. In general, optimal land management is a composite of land sharing and land sparing practices; however, in order to answer the question: 'What is a parcel of land best suited for?' often requires well-organized spatial data. In this work, we have focused on developing a model that would evaluate the suitability of a carbonatic geo-environment for land management practices. Due to the potential hazards of some sinkhole infested areas, the risk of natural hazards must be first evaluated. In addition, the level of hazards depends on population pressure and the intensity of human impact on this particular environment. In this research, we have applied the principles of geostatistics to evaluate the probabilities for sinkhole hazards as well as fuzzy logic to evaluate the suitability of land sharing and land sparing management.

1. Introduction

Since the dawn of Homo Sapiens on this planet, approximately 100-200K BP, the interaction between humans and their land base has become increasingly more dynamic; as a result, new methods and procedures for land management have gradually been developed in order to cut down on expense and promote more sustainability. In the United States, nature conservation expenses have reached 80 billion USD annually, which is about five times lower than the actual need [1]. In the United Kingdom, the environmental land management costs already amounted to 2 billion GBP several years ago; most of this funding was dedicated to the conservation of biodiversity and mitigation of global warming [2]. The Institute for European Environmental Policy (IEEP) have estimated that the costs associated with environmentally benefitting land management will be 34 billion euros per year in 2020. In addition, the cost of keeping up environmentally sensitive farms, physical infrastructures, and various trainings is going to add nine billion euros, which raises the total cost to 43 billion euros per year with a margin of error +/- 8.5 billion [3]. These estimates include many practices associated with agriculture and forestry, i.e. about 18 billion euros of investments per year into arable land, and an additional ten billion per year for grassland management as well as the creation of woods and forests, etc.

Land management practices are frequently grouped into two categories: land sharing and land sparing practices [4]. In the first category, the land is shared by both people and the natural wildlife, resembling a rather symbiotic life style; in contrast, land sparing practices leave the land undisturbed to wildlife and natural processes. Due to the preservation of endemic flora, fauna, and the source of



clean drinking water, the land sparing practices are more appropriate for some portion of carbonatic environment. In addition, the risk factors for humans are sometimes significantly higher due to the collapse of underground cavities. In an ideal case, the implementation of conjunctive land sparing and land sharing management practices appear to be the most effective from an economic point of view [4]. Examples of conjunctive land management in carbonatic geo-environment can be seen in a typical tourist environment where carbonate rocks usually create attractions (such as caves); the same land is used for tourism and the conservation of the original biosphere as well as its own special geological forms with their own wild life, i.e., such as species that have adapted to living without sunlight. The successful land management practices in a carbonate geo-environment require the assessment of potential risks associated with this land and its particular complex natural and human characteristics.

The world urbanization process has rapidly increased, and in some countries, it has almost climbed to 90%. The management of urban forestry, soils, air as well as industrial and historical complexes is a great challenge to society. Highly populated countries such as China face land management challenges that are associated with the development of megacities [5]. In this work, we will focus on data from the Ste. Genevieve and St. Louis limestones with high content of calcite mineral in Tennessee where urban areas and partially traditional agricultural land come together. The area also indicates some hazardous geo-environmental characteristics due to the infestation of sinkholes.

2. Model building

The purpose of this work is to build a two-step model that provides information about suitability of land for management practices. In the first block, indicator kriging method was used to assess the probability of hazards from collapsing sinkholes. In the second block, a fuzzy logic and GIS overlay are used to produce a land management propensity model (LAMP) that provides fundamental information about the potential of land for future development. The basis for this model is the three layers of information: a) probability of land hazards, b) the density of the population and c) landuse/landcover types. Technically, LAMP can be viewed as a set of models that use spatial data to evaluate a variety of land management aspects with the purpose to provide information on land management from different points of view. The fuzzy logic in GIS is an effective tool to evaluate the suitability question.

2.1 Hazard assessment

Sinkhole collapse is a hazard that occurs in carbonate areas when the structural roof of a void loses support and collapses. There are several parameters that lead to sinkhole collapse. For example, [6] identified the impact of four groups of parameters causing doline collapse: lithology, hydrology, topography and vegetation. In the Ebro Valley in Spain, six variables out of 27 were selected for model development [7].

For this model, two sinkhole morphometric parameters were identified in the field that are good indicators for sinkhole collapse: long to short sinkhole axes with a ratio equal and less than 1.8, and the angle of long sinkhole axis within 40-50, 70-80, or 320-330 degrees of azimuth [8]. The indicator kriging method (IK) was carried out to interpolate these parameters and produce a joint hazard probability map. In the first step, two indicators were created for each sinkhole geo-located by a vector of geographical coordinate's \mathbf{u}_α :

$$i_1(\mathbf{u}_\alpha) = \begin{cases} 1 & \text{if } L/W \leq 1.8 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

$$i_2(\mathbf{u}_\alpha) = \begin{cases} 1 & \text{if azimuth} \in [40,50] \cup [70,80] \cup [320,330] \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

The spatial connectivity of these two sets of indicators was then quantified and modelled using the indicator variogram:

$$\gamma_I(h) = \frac{1}{2N(h)} \sum_{\alpha=1}^{N(h)} [i_k(\mathbf{u}_\alpha) - i_k(\mathbf{u}_\alpha + \mathbf{h})]^2 \quad k=1,2 \quad (3)$$

where the indicator value of i_k (length-width ratio or alignment of long axis given in degrees of azimuth) at location \mathbf{u}_α is paired with another indicator value a lag distance \mathbf{h} away. Last, the probability for the occurrence of each event was estimated at the nodes of a 200 m spacing grid by applying ordinary kriging to indicators (2) and (3). The IK estimate at node \mathbf{u}_0 was written as:

$$\hat{i}_k(\mathbf{u}_0) = \sum_{\alpha=1}^{n(\mathbf{u}_0)} \lambda_\alpha i_k(\mathbf{u}_\alpha) \quad (4)$$

where λ_α are kriging weights that are solutions of the following system of linear equations:

$$\begin{cases} \sum_{\beta=1}^{n(\mathbf{u}_0)} \lambda_\beta C_I(\mathbf{u}_\alpha - \mathbf{u}_\beta) + \mu(\mathbf{u}_0) = C_I(\mathbf{u}_\alpha - \mathbf{u}_0) \\ \sum_{\beta=1}^{n(\mathbf{u}_0)} \lambda_\beta = 1 \end{cases} \quad \alpha = 1, \dots, n(\mathbf{u}_0) \quad (5)$$

The assessment of hazards in a carbonatic environment based on natural processes is incomplete without population data and land use practices. If people are absent in a hazardous region, then the natural hazard itself is not harmful, yet it can still be harmful to animals or wildlife. In order to account for these variables, the 2010 National Census data and kernel density function were used to produce a population density raster layer with a 200 ft. resolution and State Plane coordinate system. The impact on the wild life and conservation was evaluated using the National Land Cover Database with a total of 15 classes found within the study area [9].

2.2. GIS fuzzy overlay

The fuzzy overlay is a frequently used method for suitability analysis. It combines fuzzy membership raster data. In the first step, the original data are transformed to a fuzzy membership based on its relationship to a specific set such as population density. These transformed values (from 0.0 to 1.0) define the possibility of a point or pixel to be in a specific set. The full membership receives the value 1, while the weak membership will be close to 0. In addition, fuzzy logic is a useful approach in regard to the imperfection of attribute values that do not have strict binary characters. Most of the variables in earth sciences are continuous rather than strictly defined categories. In other words, there is a natural transition zone between two different categories where variable properties change continuously from one type to another. For example, soil texture categories often change continuously from sandy soils to silty soils, or forest types from a hardwood to coniferous forest. These changes in nature occur slowly from one type to another with many transitional stages. Fuzzy logic accounts for this “fuzziness” of the earth’s natural-physical boundaries.

From the group of fuzzy overlays, the gamma overlay was selected due to its property to combine the fuzzy Sum and fuzzy Product characteristics. The three previous layers, a) probability of hazard as predicted by indicator kriging, b) population density, and c) landcover data were used to produce the LAMP model. The landcover data was also assigned a new weighting system that was based on the estimated residence time people spent in a specific landcover type. The weight for open water, woody wetlands, barren rock is the lowest (equal to one); shrub/scrub and forests is two; grassland, cultivated crop land, pastures is three; low intensity developed land and open land is four; and medium and high intensity land is five. The gamma fuzzy overlay was performed in a GIS environment to combine all three transformed raster data using the following equation:

$$\mu(x) = (\text{Fuzzy Sum})^\gamma * (\text{Fuzzy Product})^{1-\gamma} \quad (6)$$

where ‘ μ ’ is the LAMP index and the ‘ γ ’ value was determined to be 0.9; as it appears to be the optimal value between the fuzzy Sum and fuzzy Product for this dataset. The fuzzy Product decreases the final values while the fuzzy Sum increases the importance of values with high membership characteristics. Therefore, in the decision-making process regarding land management practices, the high membership values in the LAMP model warn managers regarding the safety of people and activities in this particular area.

3. Results

The results from indicator kriging that led to the evaluation of the spatial distribution of sinkhole collapse probabilities is presented in figure 1 (left). The spatial distribution model originated through a “joint” (combined) probability: $p = \text{prob} \{a_1 \cap a_2\}$ which is the probability that the two events $a_1 =$ “length-to-width” sinkhole ratio is at or below the critical value of 1.8 and $a_2 =$ “the long axis orientation” runs parallel to one of the three systematic joints sets occurring simultaneously. Hence, this joint probability was obtained by multiplying the two estimated probabilities of the two separate events that were estimated by indicator kriging. As figure 1 (left) indicates, the darker regions with a higher combined probability occur in a circular shape, mostly in the southwestern part running from Interstate Highway 24 in the southwest to the Montgomery County eastern boundary in the northeast.

Most of the current land management in this area focuses on land sharing activities between pastures and agriculture crops on one hand and the wildlife and conservation on the other. The higher risk also continued along the Red River where parks and reservations such as the Port Royal State Park with a high historical significance are located. The area marked as “C” is especially worth noticing; it indicates that the intersection area is highly prone to sinkhole collapse. The right side of figure 1 shows the results of the fuzzy overlay.

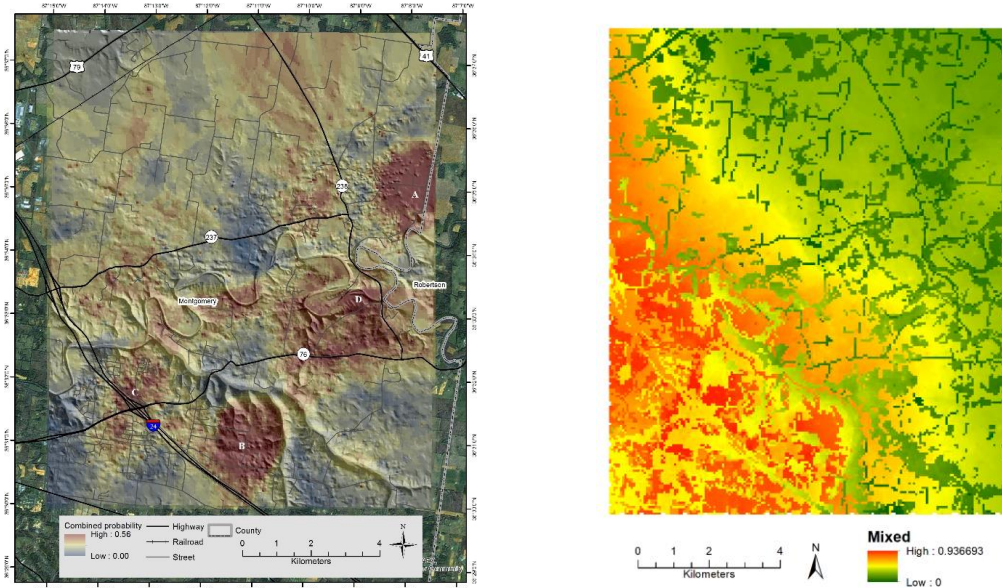


Figure 1. Spatial models indicating sinkhole collapse probabilities (left) and LAMP model (right).

In order to evaluate this area properly, one must consider the population density and the type of landuse. Therefore, some of the highly probable areas for sinkhole collapse disappeared in the LAMP model, especially the area marked with the letter “A.” There is also no imminent potential threat to people based on the estimated residence time. Hence, the potential collapse of sinkholes can be hazardous only if a high number of people reside in this area and/or other properties that are located in this type of land. In our opinion, this part of land is suitable for land sparing practices. On the other hand, the combination of low (blue) sinkhole collapse probability values from the left map and low hazard potential (green) values from the right map of the same figure can be considered for further development. Therefore, in order to make sound decisions about the future of this land, the LAMP

model, together with the potentiality for sinkhole collapse model provide valuable information for the land decision-making process.

4. Conclusion

Land is our prime resource. Due to an increasing population and economic developments, land is becoming more expensive and the land management processes more complex. There are six major criteria that must be considered regarding future land management: 1) the production of food to satisfy even the most populated areas in the world, 2) the conservation of the natural environment, 3) urban development, 4) the detoxification of polluted regions, 5) economic and technological advancements and 6) safety factors that guarantee life without conflict or threat. The idea of sustainable development is closely related to the goals of land management. This study focuses on developing a new perspective on land management; it inspires better solutions for future decisions regarding the management of land resources and land space for human development. In spite of a great complexity of socio-economic, demographic, and conservation problems, the fundamental question is very simple: How are we going to survive on this planet and “What can this land offer?” These are basically the same questions humans have been asking themselves since the beginning of our existence. The purpose of developing the LAMP model is to produce a tool for planners, developers, practitioners, local governments and public offices for making informed decisions about the future of land and its components: natural-physical and anthropogenic. The LAMP model also provides information about the risks or vulnerability factors. People make decisions to live in places where natural hazards are of a genuine concern (e.g. active tectonic zones) or where wild elements pose a significant hazard or even where people become a hazard to endangered species.

We demonstrated the development of the LAMP model on the example of the Red and Cumberland Rivers in Tennessee where three major criteria were considered: 1) the propensity to existing land hazards, 2) a high population density, 3) and the amount of time people are spending in hazardous areas. As can be seen in figure 1 (right), the LAMP index, which is close to the 0.9 value is mostly in the southwestern corner of the study area where all of the three mentioned criteria have a high probability of occurring; on the other hand, values near zero occur in the northeastern area.. Some of this region has the potential for implementing land sparing management practices; it is a safe area where wild life and land aesthetics can be developed. Therefore, each value in the LAMP model is an impetus for corresponding land management decisions and practices. The areas with high values (near one) are suitable for conjunctive land sharing and land sparing practices, while the low coefficient values near zero are attractive for land sparing management. Therefore, land management practices must be well-planned and geared towards people and their needs.

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