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Decision support tool for the evaluation of landscapes

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ABSTRACT

This paper presents a full SDSS for landscape – its design, algorithmization and practical implementation. The created system allows simultaneous analysis and evaluation of landscape from the perspective of ecological stability, erosion susceptibility, retention capacity and the economic value. The presented system implements products ArcView GIS 3.x, EMDS 2.0 and NetWeaver 1.1. The system implements four methods which are generally accepted for the given analyses and which have been algorithmized and applied in the GIS environment many times. Ecological stability is assessed using the basic coefficients of ecological stability. The susceptibility of soil to water erosion is determined by the RUSLE method. Retention capacity is determined based on the Runoff Curve Number Method and the economic value of the landscape draws on the modified Hessen method. The result includes a filled knowledge base, an algorithmized decision-making scheme for the landscape segment assessment and an optimized data model. The practical solution is applied to the model area of the Trkmanka catchment area.

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1. Introduction

Land management decisions are becoming increasingly important nowadays. Growing populations and consumerism are putting pressure on natural resources and biodiversity Moreover, public awareness of land management and sustainability issues is growing in many sectors, including spatial planning, and is placing greater expectations on managers to balance competing values. Consequently, the responsibilities involved in land management are becoming more complex. The theory on decision deals with the problem of the manner of arriving at an optimized decision based on existing alternatives (Seip and Wenstøp, 2007). Usually, there is no simple guide to deriving a solution, and every decision entails a certain amount of risk. In the present-day situation of increasing anthropogenic pressure on the environment, one of the important themes is the problem of resource allocation. However, a qualified decision concerning resources requires seeking, assembling and verifying reliable information. At many decision-making levels, such information is hardly obtainable as it is difficult to combine often conflicting opinions (Prato, 1999). Today, the land represents as a very limited resource; it is, therefore, important to recognize its potential and optimize its usage (Malczewski, 2006). Due to the complexity of the requirements and the large number of criteria (environmental, economic, sociological, and natural), it is necessary to use multi-object planning techniques and multi-criteria analysis (Chakhar and Martel, 2003; Feick and Hall, 2004; Yalcin and Akyurek, 2004). The rapid process of urbanization brings along the need for effective spatial planning with emphasis on the construction of urban infrastructure for housing, work and various supportive activities of the population (Laaribi et al., 1996). Pursuant to the high number of specific criteria (geotechnical, environmental, constructional, municipal, etc.) that must be concentrated into this planning, the application of multi-criteria analysis method may have significant impacts on the planning quality, speed and cost (McKinney and Cai, 2002; Sugumaran and DeGroote, 2011). An effective approach using the instruments of geospatial analysis methods (GIS) and multi-criteria system analyses will allow spatial planning to solve the problems associated with landscape planning in somewhat easier and faster ways (Pechanec et al., 2011). Related topics – where the instruments of decision-making systems are also applied – include the identification of plots with natural and technological prerequisites for development (Malczewski, 2006). Creating an optimal model for land assessment, which indicates the cost operation of investments and compliance with the provisions and objectives of urban development in accordance with international conventions is further demanded (Pechanec and Brus, 2012). Decision-making strategies may also become useful in evaluating other natural phenomena, such as floods, landslides, hurricanes, volcanic activity, etc. (Ponjavic and Ferhatbegović, 2010).

2. Material and methods

2.1. Definition of SDSS

Nowadays spatial planning processes increase in importance and complexity. Moreover stakeholders require more transparency in decision processes. These are often complex problems with large datasets, a high degree of uncertainty (Báčová et al., 2013; Brus et al., 2013), and

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multiple stakeholders with conflicting interests and viewpoints. From this reason there is a need to formalize and rationalize decisions with available scientific information (Bonczek et al., 2014). Decision support systems (DSS) are interactive computer-based systems designed to support decision-making activities. DSS uses knowledge and theory from diverse areas such as database research, artificial intelligence, decision theory, economics, cognitive science, management science, mathematical modeling, and others. Spatial Decision Support Systems (SDSS) represent a special type of information systems. According to Sugumaran and DeGroote (2011) SDSS provide a spatial extension of Decision Support Systems (DSS), or rather an integration of GIS and DSS. SDSS are therefore usually regarded as a computer-based information system designed to assist in decision-making while solving problems which are difficult to formulate and structure, and in cases when a fully automated system cannot be applied. SDSS are closely related to knowledge-based and expert systems. A typical SDSS contains three generic components: a database management system and geographical database, a model-based management system and model base, and a dialogue generation system (Malczewski and Rinner, 2015). Chen et al. (2010) note that these systems have to be applied to complex spatial problems which are difficult to structure or can only be partly structured, rendering the decision-maker unable to define a problem or set objectives fully.

SDSS as a spatial extension of DSS have further four characteristic features:

- provide a mechanisms for spatial data input,
- enable representation of spatial relations and structures,
- encompass analytical tools for spatial and geographical analyses,
- allow the creation of spatial outputs, including maps (Sugumaran and DeGroote, 2011).

2.2. Software and data

The presented system implements products ArcView GIS 3.x, EMDS 2.0 and NetWeaver 1.1.

Ecosystem Management Decision Support (EMDS) integrates logical formalism justified on the basis of knowledge base in the GIS environment so that it provides support for decisions on evaluation and assessment of landscape from ecological point of view. The EMDS decision-making pattern is based on a knowledge base that uses fuzzy logic, network architecture and object-based approach (Reynolds, 1999). When it is interconnected with ArcGIS we get a full SDSS product (Prato, 1999). An older version of EMDS 2.0 was used to enable full application of raster data together with a compatible GIS product by Esri–ArcView GIS 3x.

NetWeaver development system that is designated for creation of knowledge base. NetWeaver knowledge bases use an object-based approach, which makes them very modular, therefore, they are easily created and maintained. NetWeaver enabled the design and creation of the evaluation network and the assessment module of EMDS then analyzed the individual landscape segments (Reynolds, 1999). All data are in shapefile format. Contour lines and streams are lines and the rest are polygons. To valuate landscape segments in the SDSS, the first stage requires input data processing to retrieve other characteristics which enter to the valuation network. The extent of input data needs to be adjusted relative to the extent of analyzed area, and based on the conversion tables of individual methods and corresponding mathematical relations the required attributes must be added to the input data. Data pre-processing can be performed in any GIS.

2.3. Study area

The study area for testing of SDSS tool is represented by the catchment area of the Trkmanka stream, a left-bank tributary of the Dyje River. The area is situated in South Moravia of the Czech Republic. The catchment area covers approximately 380 km^2. The elongated area stretches from the north-east to south-west. Detailed description of study area can be found in Pechanec and Kilianová (2011).

2.4. Implemented methods of landscape condition analysis

The created systems allow the simultaneous analysis and evaluation of landscape from the perspective of ecological stability, erosion susceptibility, retention capacity and the economic value of the landscape. The system implements four methods which are generally accepted for the given analyses and which have been algorithmized and applied in the GIS environment. These factors were chosen based on expert decisions, availability of data sources and verification of results by field surveys. Combining these methods to one spatial decision system brings new synthetized results. Ecological stability is assessed using the basic coefficients of ecological stability, the susceptibility of soil to water erosion is determined by the RUSLE method, retention capacity is determined based on the Runoff Curve Number Method and the economic value of the landscape draws on the modified Hessen method.

The *coefficient of ecological stability* based on proportional representation of individual forms of land use can be calculated in several ways and according to different authors. The coefficient of ecological stability thus described provides information on the stability/instability of territorial units (Machar, 2012). The calculation of ecological stability in GIS is described e.g. Romportl et al. (2013).

Water erosion is manifestation of the destructive impact of water and wind on the soil surface. To determine the water erosion susceptibility of farmland and assess the efficiency of the proposed erosion control measures, the Universal Soil Loss Equation by Wischmeier and Smith (1978) is used. An extended method of erosion modeling is called RUSLE – Revised Universal Soil Loss Equation. The equation determines the susceptibility of farmland to water erosion. The calculated value represents the amount of soil which might be removed from the plot in sheet erosion, yet it does not take into account soil deposition on the plot itself or areas lying below it. The value of soil loss tolerance helps to determine the level of erosion susceptibility of a given plot and is defined as the maximum amount of soil erosion at which sufficient soil fertility may be indefinitely and economically sustained (Fernandez et al., 2003).

Water retention capacity of a landscape is ability of landscape to hold water and thus reduce the surface runoff from the area. To calculate the runoff loss from a catchment, the Runoff Curve Number (CN) method is applied. It is designed to determine the direct runoff volume and peak discharge from a proposed excess rainfall of selected frequency in unobserved profiles, particularly in catchments or their parts which are subject to farming. It is a simple model with relatively accessible inputs, it is sufficiently accurate and applicable for determining the direct runoff. Determination of water retention capacity of the landscape in GIS using the CN method is described, e.g. Chow et al. (1998), Maidment and Djokic (2000). The calculation itself is based on the assumption that the ratio of runoff to rainfall equals the ratio of the actual water retention during runoff to the potential maximum retention.

Economic assessment of the landscape draws on a modified Hessen biotope assessment method adjusted to the conditions of the Czech Republic (Seják and Dejmal, 2003). For SDSS purposes, the data processing as well as the assessment itself takes place in a GIS environment and is based on implementing a method which enables partial automation, simplification and acceleration of landscape assessment procedures in the GIS environment. Its key characteristic is a two-level assessment which encompasses an expert relative assessment of the environmental characteristics of given types of landscape (in points) and assigning specific financial sums to individual points. The method assesses biotope types according to standard typology used in the Czech Republic. The assessment of biotope type is followed by individual assessment of specific biotopes. Corrections of point values use a coefficient determined on the basis of six auxiliary criteria (Cudlín et al., 2005).

3. Results and discussion

The designed system enables a multi-disciplinary view of a landscape being assessed from the four given viewpoints by the chosen methodologies. Thanks to the documented methodologies for data preparation, development of particular dependency networks and assessment procedure in EMDS, the SDSS tool can be also used for other areas of interest. Landscape analysis (valuation) through an expert system based on the EMDS environment consists of several parts, represented particularly by the algorithmized decision-making scheme for landscape segment valuation, i.e., by the proposed valuation network in NetWeaver. Simultaneously, a landscape knowledge base is established and filled. The latter process consists of interconnecting the valuation network with input landscape data by means of network datalinks. To ensure interconnection with input data, an optimized data model must be designed together with a series of reclassification tables which allow users to adjust data into a required optimized data structure. The last step involves valuation of landscape segments by the designed network in the assessment system and displaying results in shapefile and grid formats in EMDS. The valuation is performed over the Esri shapefile data format. The SDSS tool is beneficial for these two aspects: a) determining all 4 relations from minimum consistent data at the same time and b) formalized marking of reclassifying, assigning coefficients and ascribing weights to the factors.

Landscape valuation using the proposed valuation networks is verified on the Kobylí, Rakvice and Ždánice model sites by sampled field surveys where potential situation was compared with real situation. These localities were also subject of continuous previous research. According to the coefficient of ecological stability according to Míchal, the model sites of Kobylí and Rakvice were classified as sites subject to above-average use with visibly disturbed natural structures, where basic ecological functions must be constantly substituted by technical interference. The coefficient of ecological stability according to Miklós can be determined more accurately, as the method distinguishes the ecological significance of individual land use categories. Yet, the classification of results is identical to that of the Kobylí and Rakvice model sites, which are both assessed as instable areas. The Ždánice model site is considered a site of limited stability. Water erosion susceptibility was calculated using the RUSLE equation. Results are available only for the Kobylí and Ždánice model sites. Results for Rakvice could not be calculated due to the limited availability of good-quality data for the area. Retention capacity was determined indirectly by calculating the direct runoff volume by the Runoff Curve Number method. CN calculations revealed that upon the proposed rainfall of 12 mm, the direct runoff value most frequently amounts to zero. The highest runoff values are monitored in places of built-up sites and roads. Runoff is affected also by the hydrologic soil group, upon good conditions there is zero runoff but poor conditions do not display the same values.

Landscape value was calculated using the modified Hessen method in a GIS environment. Segment price expresses the average costs required for increasing the value of 1 m^2 by 1 ecological point.

More highly valued landscape segments, falling into the category of 701 and above CZK/m^2, cover 42% of the study area, although they encompass only three, yet vast segments in the center of the evaluated site.

4. Discussion

The results are distorted due to the variable quality of the available input data. The contour lines in the Rakvice model site, for instance, are broken in many places (the area is flat, auxiliary contours are not continuous) and the constructed digital model therefore does not fully correspond to reality, which in turn affects the LS factor in the RUSLE calculation. In addition, the only partial input data has been verified by field examination. Land use reclassification for the purposes of each method was performed several times, e.g. reclassification of land use categories to correspond with the assigned CN table or assigning ecological significance to the individual land use categories. The reclassification was performed with due consideration, yet a different classification may be possible as well, which will affect the resulting values. However, users can adjust these land use categories according to methods given in the text. Economic valuation of the landscape using the modified Hessen method can be determined only through the first, simpler method. The second method lacks sufficient input data in the biotope mapping layer, as the data usually comes from mapper's notes which are not always available.

A more accurate result would be obtained, for instance, if the vegetation cover and management factor were replaced by current land use data obtained from a field survey, which would divide the area into several values. Similarly, partial changes may be incorporated for example by replacing the existing shapefile of constant values of RUSLE factors with an input layer with several values.

5. Conclusion

The presented work makes a contribution to applied environmental geo-information science. It studies the possibilities of GIS application in the process of landscape analysis, particularly with respect to GIS as a spatial planning support tool. Landscape as a highly limited resource requires the recognition of its potential and optimization of its use. The complexity of requirements and a high number of criteria (environmental, economic and sociological) require the implementation of spatial analysis methods and multi-criteria system analyses over spatial data to ensure efficient spatial planning. These situations have been proved by many authors (Bagstad et al., 2013; De Groot et al., 2010; Gorsevski et al., 2013; Groot et al., 2007; Hermann et al., 2014).

The paper presents a synthesis of the existing knowledge in the form of a newly created and tested landscape-oriented decision support system. It enables a multi-disciplinary approach to the landscape which is assessed from four different perspectives according to the methods selected. These assessments may be conducted using a limited amount of generally available data (land use, biotope assessment according to the NATURA 2000 method, the ecological soil unit classification layer, forest typology and contour lines) which is gradually adjusted to the required structure and assessed using the assessment system in EMDS. This system has been successfully applied in many other studies (Hessburg et al., 2013; Segura et al., 2014). Landscape analysis (valuation) through an expert system based on the EMDS environment consists of several parts, represented particularly by the algorithmized decision-making scheme for landscape segment valuation, i.e. by the proposed valuation network in NetWeaver. Simultaneously, a landscape knowledge base is established and filled. The latter process consists of interconnecting the valuation network with input landscape data by means of network datalinks. The benefit of the created system is twofold: i) all four relations are computed from a minimum number of coincident data and in a single moment of time and ii) it provides a formalized outline of how reclassifications are performed, how coefficients are assigned and what factor weights are applied.

The current trend is to develop integrated modeling systems that serve as decision support tools in the search for optimum processes of environmental management (Huang and Chang, 2003). There are a number of practically tested models of various scales (local, regional, global) and various complexities, whose integration would make utilization of data streams from various sources (stationary on-line monitoring, satellite observation or digital image analysis) more effective. It may be assumed that future development will focus on expert SDSS which will utilize not only databases and data streams but also expert knowledge and estimates. Overview can be found in Reynolds and Hessburg (2014). Not all parameters are available, the results of practical SDSS application are to be validated and mathematical models are to be further developed and improved. Mere isolated modeling outputs which do not take into consideration the wider context and therefore also data uncertainty or the stochastic nature of the modeled processes are not adequate from the perspective of decision-making processes (Günther, 1998).

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