SUSTAINABLE LAND-USE PLANNING SUPPORT BY GIS-BASED EVALUATION OF LANDSCAPE FUNCTIONS AND POTENTIALS

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ABSTRACT:

The paper presents an example of the application of the landscape functions and natural potentials methodology to the environmental assessment in the upland area of Pradnik and Dlubnia rivers catchments, south Poland. The aim of the research was to propose evaluation methodology applied in GIS environment and based on available digital (or easy for digitalization) spatial data. The study proved that evaluation of landscape functions and natural potentials is as a useful tool in land-use decision support process. Proposed assessment methods can be implemented not only in the investigated area, but also in similar areas in the South of Poland.

1. INTRODUCTION

Sustainable land-use planning should be based on many factors – environmental (ecological), economical, societal, etc. Many different methods for evaluation of land-use environmental determinants can be found in literature. One of the approaches is based on the concept of landscape (natural, environmental) functions and its potentials.

The term 'landscape potential' was introduced and developed by German geographers (Neef 1966, Hasse 1978) to characterize possible use of the environment by human society. Hasse (1978) proposed to assess the capabilities of the area by evaluation of so-called partial natural potentials: biotic yield potential, water availability potential, waste removal potential, biotic regulation potential, geoenergetic potential, building potential and recreation potential. During further development, landscape functions (related to the landscape system itself) were added (e.g. ability to buffer disturbances or to create flora and fauna habitats) (Marks et al. 1992).

Similar approach was developed in the Netherlands, where functions of nature were defined by De Groot (1992) as "the capacity of natural processes and components to provide goods and performances which satisfy human demands directly or indirectly. He proposed four categories of natural functions: regulation functions, carrier functions, production functions and information functions. Other classifications of landscape function can be found in Bastian and Röder (2002).
Numerous methods of land evaluation have been developed based on the mentioned concepts, especially in Germany where they were introduced into practice and proved useful in land-use planning context (Krönert et al. 2001, Bastian and Röder 2002). In Poland this kind of approach was used by Kistowski (1995) and Pietrzak (1998). They proposed assessment procedures for glacial landscapes.

In the presented work the methodology based on landscape functions and potentials assessment is applied in upland region of Poland. The aim was to test its applicability as a tool supporting land-use decisions. We wanted to propose evaluation methodology applied in GIS environment and based on available digital (or easy for digitalization) spatial data.

2. STUDY AREA AND DATASET

2.1 Study area

The watersheds of Pradnik and Dlubnia rivers (Malopolska region, Poland) were initially chosen as the study area. They comprise of a variety of different landscapes – rural, suburban and heavily urbanized. The majority of this area is protected as Ojców National Park, three landscape parks and their buffer zones. On the other hand lower parts of the watersheds lie in the borders of the city of Krakow – one of the biggest cities in Poland. This area was excluded from the study, because of different assessment methods needed to evaluate its landscape functions and potentials.

The study area consists of two parts – the west one belongs to Krakowska Upland and the east one to Malopolska Upland. Loess soils prevail in the entire area with some rendzinas and sand soils. Alluvial soils in river valleys are very similar to loess soils. The soils of Malopolska Upland are among the most fertile soils in Poland. Unfortunately they are in danger of erosion by water.

2.2 Dataset

Different kinds of data were used during the study: Digital Atlas of Krakow Voivodship (KAWK), Sozological Map of Poland (digital version), scanned topographical maps, satellite images, meteorological data and hydrogeological maps.

KAWK was created in the late 1990s in the UST Department of Photogrammetry and Remote Sensing Informatics (now Dep. of Geoinformation, Photogrammetry and Remote Sensing of Environment) (Florek et al. 2000). It is a spatial database consisting of layers related to environmental and socio-economical information. For this study the most important ones were land-use/land cover, soils, Digital Terrain Model, hydrology, geomorphology, and hydrogeology. KAWK was realized in Intergraph MGE format in Coordinate System 1942. Data accuracy and level of details is appropriate for scales of 1:50000 – 1:100000.

Sozological Map of Poland is prepared in scale of 1:50000. Database layers (MapInfo format) may be grouped in five classes: 1) protection of environment; 2) threats of environment and its degradation; 3) measures to prevent degradation of environment; 4) restoration of environment; 5) waste lands. Based on its layers it is possible to create land-use/land cover map as well.

Following satellite images were available (registration dates in brackets) together with their orbital data: Landsat 5 TM (19 Aug. 2000), Landsat 7 ETM+ (5 Jul. 2000), IRS LISS (2 Jun. 2000), IRS PAN (28 May 2000), IRS PAN (30 Aug. 2000), ASTER (7 Jun. 2001), ASTER (5 Apr. 2002). All images had geometric and radiometric corrections applied by producers.

Meteorological data used were in form of monthly precipitation sums measured in 53 gauges by IMGW in the period of 1975 to 1995. Only 15 of them were located inside the study area or in its close proximity.

3. DATA PROCESSING

The study was conducted using Idrisi32 software. All necessary KAWK and Sozological Map layers were converted into appropriate format, imported into chosen system and rasterized with 30 m pixel.

3.1 Satellite images orthorectification

For orthorectification of satellite images PCI OrthoEngine Satellite Edition ver. 7.0 was used. Ground Control Points and Check Points coordinates were acquired from topographical maps and DTM. Parametrical method was used for all images except IRS LISS. In this case orbital data were corrupted so RPC method based on GCPs was used. Orthophotomaps were generated using the nearest neighbor resampling method.

3.2 Precipitation data

From 53 precipitation measurement stations in available dataset only 31 were working incessantly twenty years. In 12 points it was possible to fill in measurement series based on correlations with other data points. Many different methods are used in hydrology for interpolation of precipitation based on point measurements, e.g. Thiessen polygons, inverse distance interpolation or isohyets. New approaches like spline functions or geostatistical methods have become introduced recently, outperforming other methods in comparison tests (e.g. Goovaerts 2000). In the presented study, two methods of interpolation available in Idrisi32 software were compared – inverse distance interpolator and ordinary kriging. All 43 points were used for interpolation of precipitation values, but because of very limited number of data points in the study area (15) we decided not to choose any control points but to apply the cross validation technique. In this technique, one of the measurement points is temporally removed from data population and interpolation is based on remaining ones. The removed point is used as a control point – the precipitation value measured in the point is compared with the interpolation result. The procedure is repeated for all data points and deviations are used to compare the applied interpolation methods. Cross validation was done with Gstat software (Pebesma and Wesseling 1998) before interpolation, based on 15 points located in study area or its proximity. Ordinary kriging with spherical model of variogram gave the lowest values of all three measures used for comparison – absolute errors, root-mean square errors and relative errors. This method was used to interpolate precipitation maps for further research.

3.3 Land-use map

Two sources of land-use/land cover information were present in the dataset – KAWK and Sozological Map. Unfortunately, none of them was up-to-date, despite the fact that they were made quite recently. Many differences were detected during their comparison with satellite images – mainly new or cut down forest areas and changes of arable lands into grasslands or fallow lands. We decided to create new land-use/ land cover map for the study purposes.

A hybrid solution, integration of cartographic data (from existing digital datasets) and up-to-date satellite images, was chosen. Some authors claim such type of land-use map creation methodology as the most appropriate in Polish conditions (e.g. Jędrychowski et al. 1998). Road network and railway infrastructure layers were imported from KAWK and surface waters, parks and cemeteries from Sozological Map. Forests form Sozological Map were verified by photo interpretation of IRS PAN images and first principal component image created through PCA transformation of spectral bands of all images. The cut out areas were removed, new forests added and borders of existing ones updated if necessary. Photo interpretation of IRS PAN images was also used for updating of built-up areas imported from KAWK.

Remaining land-use categories (agriculture, pastures and meadows, orchards, fallow land) were recognized by satellite images classification. Different methods of unsupervised and supervised classification were tested for individual images, but none of them gave acceptable results. Because of that we decided to take an advantage of our data set multitemporality. Satisfactory results were achieved with Idrisi32 HYPERMIN module. It is a minimum-distance classifier (using standardized distances) intended for hyperspectral data and the maximum number of spectral bands which can be analyzed is 240. In our case we used all spectral bands from all images. Because of different registration terms different phenological phases were imaged causing differences in thematic content even in the same spectral range.

4. LANDSCAPE FUNCTIONS AND NATURAL POTENTIALS

When assessing landscape functions and natural potentials, we can rely on many published methods and approaches. As the evaluation depends also on the assessment scale and specific local conditions, no universally applicable method exists (Bastian and Röder 2002). Usually they have to be adapted to the specific purpose and conditions. Available data and time needed to make an assessment must be taken into consideration as well. On the other hand, published approaches may provide us with some principles and key factors for the assessment of particular functions and potentials.

The aim of the investigation determines the choice of evaluated landscape functions and natural potentials. As we wanted to test the applicability of this approach in local conditions, we decided to focus on those, which are the most often considered in the practice of landscape evaluation and landscape planning (Marks et al. 1992, Bastian and Röder 2002). The following functions have been chosen: water erosion resistance function, groundwater recharge function, soil filter and buffer functions, runoff regulation function, groundwater protection function, potential for recreation and biotic productivity potential. Assessment framework proposed by Marks et al. (1992) was chosen as the starting point. Applicability of the proposed evaluation methods for particular landscape functions and potentials in our research was analyzed in the context of investigated area, assessment scale and available data.

It should be stressed here that many approaches useful to analyze and assess particular landscape functions and natural potentials have been developed independently from this methodological concept. Evaluation methods proposed on the grounds of sciences like hydrology, hydrogeology, agriculture, etc., can be used for this purpose. We searched for methods which are internationally recognized or were proposed in Poland and applicable in the evaluated area.

There is not enough room in this paper to give the detailed description of all used assessment procedures. Water erosion resistance function and biotic productivity potential will be provided as examples. For other landscape functions only the outline of adopted approach will be presented.

4.1 Water erosion resistance function

The water erosion resistance function of the landscape can be defined as its "ability to withstand soil losses caused by human activities" (Bastian and Röder 2002). Marks et al. (1992) proposes to assess this function with the help of Universal Soil Loss Equation (Wischmeier and Smith 1978) adapted to German conditions by Schwertmann et al. (1987). In Poland widely recognized methodology for soil erosion assessment was proposed in 1990s by Józefaciuk and Józefaciuk (1992). In this approach the potential water erosion hazard is estimated on the basis of soil texture, slope classes and the amount of annual precipitation. Actual erosion risk can also be assessed when land use, size and shape of plots and tillage system are taken into consideration. In both cases the result is only qualitative – in form of erosion hazard classes (Jadczyszyn et al. 2003).

In our investigation we took the advantage of available spatial data and decided to assess the water erosion risk by application of spatially distributed approach. From many existing soil erosion models we chose RUSLE (Revised Universal Soil Loss Equation) (Renard et al. 1997), as it prove its usefulness in different environments and is not data-demanding.
Mean annual soil loss is calculated with the equation (1):

$$A = R\ K\ LS\ C\ P \quad (1)$$

where A = mean annual soil erosion rate ($t\ ha^{-1}\ y^{-1}$)
R = rainfall erosivity factor ($MJ\ mm\ ha^{-1}\ h^{-1}\ y^{-1}$)
K = soil erodibility factor ($t\ h\ MJ^{-1}\ mm^{-1}$)
LS = topographic factor (dimensionless)
C = crop management factor (dimensionless)
P = erosion control practice factor (dimensionless)

The RUSLE rainfall erosivity factor (R) was evaluated with the Modified Fournier Index (Arnoldus 1977) based on mean monthly precipitation data, interpolated from the meteorological stations measurements as described in Section 3.2. Equations (2) and (3) (Renard et al. 1997) were used to assess soil erodibility factor (K):

$$K = 0{,}0034 + 0{,}0405 \cdot \exp\left[-0{,}5\left(\frac{\log D_g + 1{,}659}{0{,}7101}\right)^2\right] \quad (2)$$

D_g is a function of soil texture, calculated as:

$$D_g = \exp(0.01 \cdot \sum f_i \cdot \ln \frac{d_i + d_{i-1}}{2}) \quad (3)$$

where d_i = maximum diameter for particle size class *i*
d_{i-1} = minimum diameter for particle size class *i*
f_i = the corresponding mass fraction

The topographic factor (LS) was calculated in USLE2D software (Desmet and Govers 1996b). In the algorithm applied (Desmet and Govers 1996a) a unit contributing area is used instead of upslope length. Based on our earlier investigations of different runoff routing algorithms available in this software on drainage network modeling (Drzewiecki and Mularz 2001) we chose the flux decomposition algorithm (Desmet and Govers 1996b). Developed areas were excluded from modeling. Values of crop management factor (C) for different land-use types were assessed upon literature data. Orthorectified IRS panchromatic image and Digital Terrain Model were used to assess the tillage direction (by photo interpretation) against a background of slope direction (contours). Based on this evaluation, erosion control practice factor (P) values were evaluated.

As RUSLE is not capable to differentiate between soil erosion and deposition areas, the latter should be excluded from modeling (Mitasova et al. 1996). The USPED (Unit Stream-Power Erosion/Deposition) model (Mitasova et al. 1998, Mitasova et al. 1999) was used for this purpose. In the model the sediment transport capacity T is assesses with equation (4):

$$T = A^m (\sin\beta)^n \quad (4)$$

where A = unit upslope contributing area ($m^2\ m^{-1}$)
β = slope angle
m, n = empirical coefficients

Its divergence (Equation 5) allows detecting the areas of erosion (where sediment transport capacity increases) and deposition (where it decreases).

$$\nabla T = d(T \cdot \cos\alpha)/dx + d(T \cdot \sin\alpha)/dy \quad (5)$$

where α = the aspect angle of the terrain surface

Algorithm based on Equation 5 was proposed by Mitasova et al. (1999) for ArcView and GRASS. We adapted this solution for Idrisi 32 software. For coefficients in Equation 4 we assigned values of m=1.4 and n=1.2, assuming that modeling refers to average conditions in long period (Mitasova et al. 2003). Six classes of water erosion resistance function were defined based on modeled soil losses, according to the criteria (annual soil losses per hectare) proposed by Marks et al. (1992). For areas where the USPED model predicted deposition, no erosion risk was assumed. No erosion risk (very high value of the function evaluated) was predicted for 36.3% and high or very high erosion hazard for 25.7% of the investigated area. Areas of high erosion resistance function (low erosion risk) prevail. However, the fact that as much as one third of all arable grounds was assessed to be in high erosion risk should worry.

4.2 Biotic productivity potential

Biotic productivity potential can be understood as "ability of a landscape to produce biomass by photosynthesis in a sustainable manner" (Bastian and Röder 2002). We restricted the evaluation of this potential to agricultural areas only. As an evaluation tool the index proposed by Koreleski (1988, 1992) was used:

$$PWgk = \sqrt{g \cdot k} \quad (6)$$

where g = soil score
k = climate score

The index is based on two low correlated features. Both parameters are scored from 0 to 100. The use of the geometric mean causes that the index value is determined by the lower score and in this way it follows the principle of a limiting factor. According to Koreleski (1992) climate assessment can be obtained from the vegetation period length. This, in turn can be evaluated in Krakow area by applying empirical equations (Hess 1969). The vegetation period length can be calculated from the height above see level, but different equations are valid for different slope aspects as well as concave and convex landforms. To facilitate the analysis of terrain forms we used our MGE Grid Analyst script written in GOAL according to algorithm proposed by Blaszczynski (1997).

Based on calculated PW_{gk} values five biotic productivity potential classes were identified. The ranges of index values for each class were determined on the basis of biomass production and crops yield reported for different PW_{gk} values by Koreleski (1992).

The evaluation results proved high quality of the agricultural areas in this part of Poland. Very high or high biotic productivity potential value was assigned to over 86 per cent of the investigated area. The lowest class has not occurred and only 0.9 per cent of the area was included in the low potential value class.

4.3 Other evaluated landscape functions and potentials

The groundwater recharge function of the landscape means that it possesses the ability to replenish the groundwater resources by infiltration. The water balance equation was used to assess this function. Infiltration component (groundwater recharge) was estimated based on relief energy, soil types, groundwater levels and surface sealing. Low groundwater recharge values prevail in the analyzed area. Higher values can be found in the upper part of Pradnik drainage basin. However, the most important area was identified in the isolated region in the middle part of Dlubnia watershed.

Filter and buffer functions of soils are connected with the ability of the soils to buffer and transform harmful pollutants. The evaluation results indicated that the soils in investigated area have generally high filter and buffer characteristics. However, these parameters are a little bit lower in the upper part of Pradnik river basin, having at the same time relatively higher groundwater recharge rates.

Runoff regulation function refers to water retention capacity of the landscape. Its assessment was based on the well-known SCS (Soil Conservation Service) methodology. For SCS method details see e.g. Ward and Elliot (1995).

We evaluated also the groundwater protection potential. The DRASTIC method (Aller et al. 1987) of the groundwater vulnerability assessment was applied for this purpose. In this widely adopted approach seven parameters are taken into consideration: depth to water, recharge, aquifer media, soil, topography, impact of vadose zone and conductivity in aquiferous layer. The assessment unveiled that the most endangered region is located at the Pradnik valley outlet where Quaternary groundwater level is not isolated and located close to the surface. The other areas, having low groundwater protection potential, cover large parts of the river valleys and the outcrops of Jurassic and Cretaceous formations.

The potential for recreation is defined as "the landscape's capability to realize material and esthetic qualities for human recreation" (Bastian and Röder 2002). Land-use and relief energy parameters were assessed according to the methodology proposed by Dubel (1997). The approach is based on the research which showed that people want to rest in the differentiated landscape. The most attractive areas are the land use borders, especially the borders of forests and waters. Both, waters and forests, are considered as the places most desirable for recreation. The attractiveness increases with varied topography (measured by relief energy), and decreases in proximity of urbanized areas. High and very high recreation potential values were assigned to over 25 per cent of the investigated area. The highest values are to be found in the upper part of Pradnik basin – the area of Ojców National Park and its protected buffer area.

4.4 Applicability for land-use recommendations

The spatial comparison of the assessment results and existing land-use pattern enabled identification of present and possible conflicts and created the basis for formulation of recommendations for adjusting land-use practices to natural predispositions. Some of them are quite obvious, like in case of upper part of the Pradnik basin. This area was highly rated in terms of groundwater recharge function but the filter

and buffer functions of soils have low values here. Fertilizers and other chemicals should be used with caution in such area.
Two kinds of GIS-based solutions to support land-use decision making were used:

1. simulation of landscape functions changes caused by different land-use scenarios;
2. land-use optimization.

In the first case, the attention was focused on changes caused by development of residential areas and transformation of arable lands into pastures or fallow lands. Land-use optimization possibilities were shown both, with regard to one chosen function and to a set of chosen functions and potentials. The former may be used to support crop and cultivation practice to keep erosion rates in acceptable limits. GIS model used allows calculating the values of crop management and erosion control practice factors for a particular area. Based on these values appropriate crops or erosion control practices can be chosen.

Optimization based on several landscape functions can be done in many different ways. In our research the decision tree method proposed by Bastian and Röder (1988) was tested. Their approach allows adjusting the type of agriculture activity to the assessed landscape functions and natural potentials. Decision rules were adjusted to the local conditions.

5. CONCLUSIONS AND PROSPECTS

Presented research proved that evaluation of landscape functions and natural potentials is as a useful tool in land-use decision support process. Proposed assessment methods can be implemented not only in the investigated area, but also in similar areas in the South of Poland. The methodology is based on digital spatial data available in Poland. The assessment was realized in GIS environment. Numerous advantages of such approach were already described in literature. Nevertheless, it should be stressed here that available in GIS tools for spatial modeling of natural processes and phenomena creates new possibilities for the assessment of landscape functions and natural potentials. In our case, some of them could even not be evaluated without GIS unless different approach was chosen. Moreover, GIS tools enable us to simulate the influence of spatial decisions and land-use changes on landscape functions. In this way, land-use planners can evaluate the environmental the impact of different scenarios. Finally, through the possibility of optimization, GIS facilitates decisions about proper ways of land-use utilization. Of course, the optimization results have to be treated cautiously and carefully evaluated before the implementation.
Further research will concentrate on application of landscape functions and natural potentials evaluation approach to the assessment of landscape changes form 1960s to the present days. Some of the models and assessment methods will be improved as the study is based on data having higher spatial resolution. The research project is titled "Multitemporal remote sensing imagery based evaluation of spatial changes of land-use and landscape functions to support landscape planning activities".

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