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A Spatial Planning Tool for the Evaluation of the Effect of Hydrological and Land-use Changes on Ecosystem Services

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Abstract: Policy makers have to select effective planning strategies regarding ecosystem services management using the best information that science and technology can provide them. It has been demonstrated that spatial indicators have the power of bringing together necessary data to inform policy makers. Furthermore, spatial indicators provide a starting point for decision-making. The ultimate objective of this study is to develop a decision support tool that can be used by policy makers to assess the impact of their integrated natural resources management (INRM) strategies on selected ecosystem services. This study proposes a spatial planning tool to present spatial indicators to track changes in ecosystem services provision by considering the mutual interaction between hydrological and land-use changes. The results of modelling scenarios from the coupling of a hydrological model (SWIM) and a land-use model (SITE) have been used to derive spatial indicators. These spatial indicators quantify dynamic changes of landscape patterns related to ecosystem services provision. The approach used has been applied to a case study dealing with INRM in the Drakensberg area, South Africa. The spatial indicators were selected specifically to show the consequences of action or inaction by humans for human well-being and ecosystems by measuring the efficacy of spatial management measures we take on the spatial configuration of the landscape. In the future, a web-based indicator atlas will be implemented, based on the same open source technology. The spatial planning tool displays spatial indicators of the changes in ecosystem services provision over time as a function of land-use and hydrological dynamics, represented in GIS layers produced by the models. The proposed tool is valuable in a decision making process, because it provides a better way of communicating complex model results to the public and stakeholders, informing them how socio-economic development and planning measures will affect the ecosystem services in their region.

Keywords: Ecosystem services; spatial indicators; decision support system; QGIS; integrated natural resource management.

1. INTRODUCTION

In the 2005 publication of the millennium ecosystem assessment, ecosystem services (ES) are defined as benefits (resources and process) that people obtain from ecosystems (Millenium Assessment, 2005). Anthropogenic actions have always had a certain impact on the provision of ecosystem services. The spatial planning strategies tend to focus more on the socio-economic component of spatial development, while their impact on ecosystems services is less considered. The reason of that lower interest may be that policy makers lack a Decision Support System (DSS), which will help them to assess the impact of possible scenarios. Evaluating the ecosystem and planning of the environment requires spatial information (Geneletti, 2004). This study proposes an approach that provides an easy way to communicate not only the state of their environment, but also the effect of different management scenarios in time by using spatial indicators.

Figure 1 shows the framework of the proposed approach, where during the INRM, policy makers need information and criteria to assess the effect of their spatial planning strategies on ES. The ideal assessment channel (Figure 1) is to use model simulations of natural processes and components that provide ES in combination with the socio-economic scenarios proposed by policy makers. However, most of the modelling systems used are complex and lack transparency and user-friendliness. Therefore, people involved in making and administrating policies are subject to constraints of interpretation of information (Oxley et al., 2004). The practical assessment channel (Figure 1) will use spatial indicators that represent the actual properties of land-use patterns that can be a compared with a desired state. This is based on the fact that the configuration and the composition of land-use patterns greatly influence the quality of ES (Portela and Rademacher, 2001). The main role of spatial indicators in this approach is to assist the comprehension of the interaction between management policies and ES by providing a clear representation of model results to policy makers.

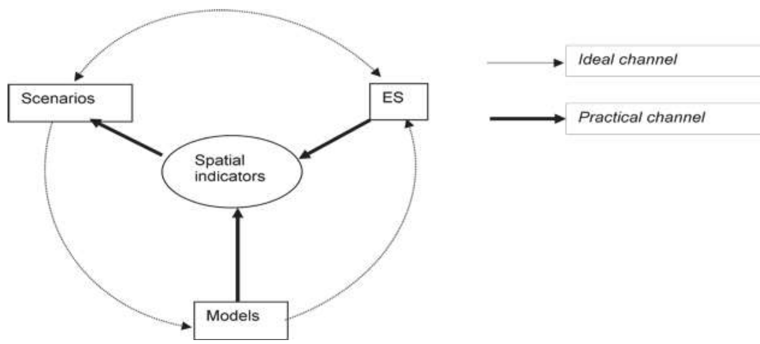


Figure 1. Channels of ES evaluation in a decision support framework.

The spatial indicators are used to predict changes in spatial arrangement of land use in the study area and therefore, evaluate the relevance of these changes with regards to the required landscape arrangement to achieve the desired target ES status at a determined point in the future. The desired state is characterized by the ability of the catchment to produce ecosystem services (Link, 2002) at the level that is in agreement with targets of national policies and international standards.

This research is incorporated in a conceptual framework of an integrated spatial decision support system proposed in the frame of the EU FP7 AfroMaison project in the uThukela catchment (Figure 2). The DSS proposed in that framework considers the fact that land use and water resources dynamically interact in a catchment and that the changes in location or magnitude of land use, and water resources or their respective components will affect each other, and that all these changes will affect the ES. The coupling of land-use and hydrological models, running them simultaneously and exchanging their inputs and outputs can provide a more realistic representation of the interactions between land-use and water resources compared to using separate models (Yalew et al., 2012). The spatial indicators explain the variability of landscape patterns by giving a meaningful and interpretable access to results of the spatial metrics that quantify changes of landscape properties in time.

The objective of this study is to develop a tool that informs policy makers about the impact of their INRM scenarios on ecosystem services through visualisation of spatial indicators. A QGIS plugin has been designed that visualises spatial indicators derived from the modelling scenarios in a graphical user interface integrated into QGIS.

2. CASE STUDY AND PROBLEM STATEMENT

The approach to evaluate the effect of land-use changes and hydrological changes on the ES by using spatial indicators has been applied to the uThukela catchment in the province of KwaZulu-Natal, South Africa (Figure 2) for some spatial indicators. The catchment is located along the northern areas of the Drakensberg Mountains that form the border between Lesotho and South Africa. According to the 2007 community survey (Catacutan, 2012), the size of the catchment is estimated at 29 036 km², it extends latitudinal from 27.41° to 29.40° S and longitudinally from 28.96° to 31.44° E. In 2007 there were 714 909 people living in the uThukela District Municipality, which covers a substantial part of the studied catchment.

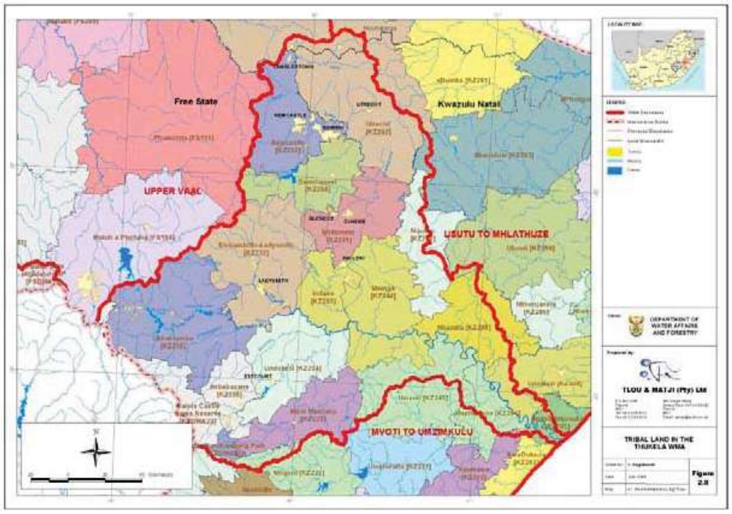


Figure 2. Location of the uThukela catchment. Source: (DWAF, 2004).

In the uThukela District Municipality, agricultural land use takes 13% of the land cover and this is because approximately 70% of the district is rural. Other major land use are stock farming, including beef and dairy cattle bush land (18.3%) and grassland (55.8%) areas, which altogether cover 74.1% of the land. Settlements (including urban and rural settlements) cover 3.5% of the land (Catacutan, 2012). Reduced availability of land for agriculture due to population growth may lead to food shortages. In addition, there is a challenge of soil erosion driven by the expansion of human settlements and increase of livestock, which causes deforestation and overgrazing, respectively. In those areas the land suitable for agriculture is threatened to decline by sheet erosion. Even though water is locally not a scarce resource, access to water resources is crucial when considering socio-economic development that is governed by INRM. The spatial indicators (Table 1) implemented show the consequences of decisions taken by policy makers regarding INRM scenarios on ES that are relevant in the study area. The ecosystem services have been selected by consulting stakeholders in the study area. The spatial indicators have been selected by the authors as examples that are related to the ES.

Table 1. Spatial indicators used to evaluate ES status.

No	**Ecosystem service**	**Spatial indicators**
1	Crop production	**Area** of agriculture
2	Fodder production	**Area** of grassland
		Patch size of grassland
		Grassland **cohesion**
3	accessibility to water	**Distance** from built up areas to water sources
4	Erosion control	**Patch size** of grassland
		Patch size of forest
		Forest **cohesion**
		Grassland **cohesion**
		Weighted Wetness **index**

3. METHODOLOGY

The approach to evaluate the trend of changes in ES provision by using spatial indicators consists of retrieving information about spatial patterns from model results. Spatial indicators describe dynamically the landscape patterns, and they give a meaning to spatial metrics. In the US Environmental Sciences Program (2014), spatial metrics are defined as “measurement of a component or components within the landscape, which is used to characterize composition and spatial configuration of the component within the landscape (e.g. forest size, fragmentation, proximity to other land-cover types).

3.1 Input data for the spatial tool

To compute the spatial metrics that describe spatial patterns after hydrological and land-use changes in the catchment, results of the coupled models were used. The outputs from the coupled hydrological (SWIM) and land-use (SITE) models are several years of simulation and they are provided as temporal series of Arc/Info ASCII Grid files. The input data are converted to the PCRaster mapstack format. This was needed in order to use the PCRaster Python library for the calculation of the spatial metrics. The input data was provided at a resolution of 500km X 500km.

3.2 Calculation of spatial metrics

For the quantification of landscape structures and landscape patterns, numerous mathematical indices have been developed. Spatial metrics can be categorized in two types (McGarigal et al., 2012):

1. Spatial *structural metrics* that measure physical composition and configuration of the landscape without reference to ecological process. This category is divided in two types of spatial metrics (McGarigal et al., 2012):
    I. Landscape composition metrics that quantify landscape features associated to patch complexity (e.g. patch size, patch density, etc), abundance of each class in the land-use map (e.g. area of cropland).
    II. Landscape configuration metrics describing arrangement of patches, connectivity (e.g. patch cohesion), position (e.g. distance from one landscape class to another), and orientation in the landscape.
2. Spatial *functional metrics* that measure landscape patterns with relevance to process under consideration (McGarigal et al., 2012). An example is the "weighted wetness index," where every land-use patch contributes to the spatial metric calculation, with different values depending on the wetness weight assigned to each land use.

In this study, the calculation of spatial metrics is mainly patch based. Forman and Godron (1981) defined patch as a non-linear surface area differing in appearance from its surrounding. If this definition is translated into a computer algorithm that uses landscapes discretized in raster cells, the patch represents a contiguous group of cells with the same value (Turner et al., 2001). In this study, the eight-neighbour rule has been used, where cells of the same value are grouped if they are within the immediate 8-cell neighbourhood of each other (Figure 3). The calculation of spatial metrics was applied to specific land cover, which spatial distribution or physical character within the landscape would give basis information to track the trend of ES generated from land use associated to them. The calculation of spatial metrics has been implemented in the Python programming language using the PCRaster library (PCRaster 2014). The fact that PCRaster offers comprehensive structuring for dynamic modelling (Van Deursen, 1995) was exploited to match the concept of dynamic assessment of this study. Some examples of spatial metrics used in this study are presented below.

Mean Patch Size (MPS)

The MPS presents the average patch size in a relevant landscape class at the landscape level (Figure 3):

$$\mathrm{MPS} = a/n$$

where n is the number of patches and *a* [ha] is area of the land cover class.

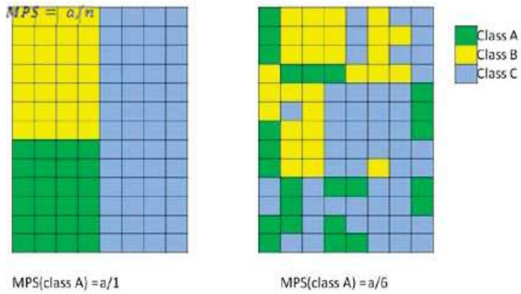


Figure 3. Example demonstrating Mean patch size using the 8 cell rule.

The different MPS for the two maps represent the fragmentation of the “Green” class. The results of this spatial metric can be translated in a spatial indicator, e.g. cluster size of grassland or forest, and it can be used to assess if the desired size of fragmentation is reached or not.

Average distance from settlements to water sources.

This spatial metric represents the 'openness'. For each cell belonging to the land-cover class of interest, and for each direction, the calculation determines the distance from a settlement cell to the next water resources cell (Figure 4). The calculated distances are averaged for the study area.

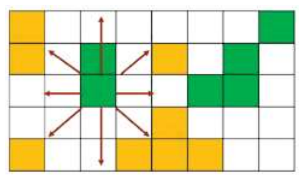


Figure 4. Average distance between settlements and water resources.

This spatial indicator can be used by policy makers to assess the dynamic changes of average distance from built up areas to areas with water resources. This information helps to understand the status and changes of water accessibility in the landscape.

3.3 Visualization of spatial indicators

A QGIS plugin was developed using Python programming language. It carries out not only the calculation of spatial metrics but also allows the visualization of spatial indicators. The plugin can dynamically display spatial indicators as series of maps and displays the graph of yearly maximum values of indicators. The graphs are produced using the Matplotlib Python library (Hunter, 2007).

4. RESULTS

15 years of simulation results were obtained from the coupled SITE and SWIM models. Spatial indicators show that the area of agriculture varies between 274000 and 278000 ha, from 2006 to 2020. In Figure 5, red and green colours indicate whether grassland patches meet the conditions required, e.g., 1.5 animal units per acre. The isolated patches that are coloured in red do not meet this condition, while the cohesive patches in green provide the desired fodder production.

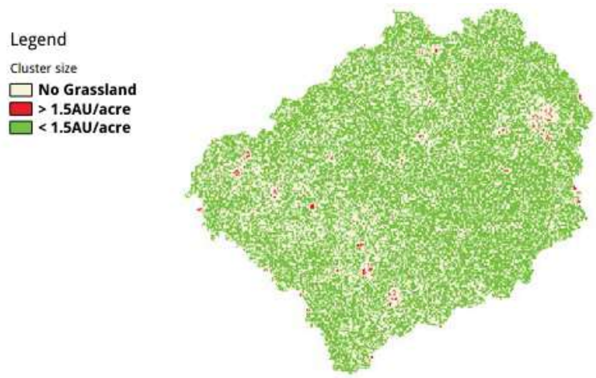
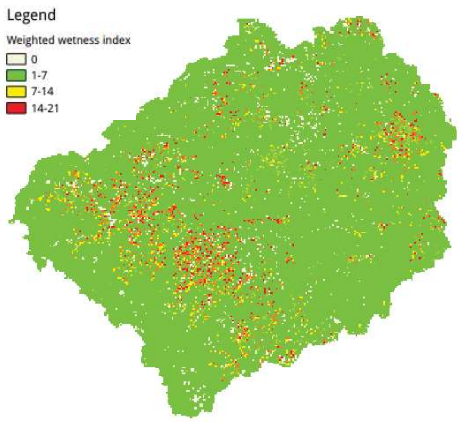


Figure 5. Cluster size of grassland.

The western part and the north-east of the catchment in red colour (Figure 6), have a high wetness index, and are likely to be more vulnerable to soil erosion than the other classes due to saturation of unstable slopes.



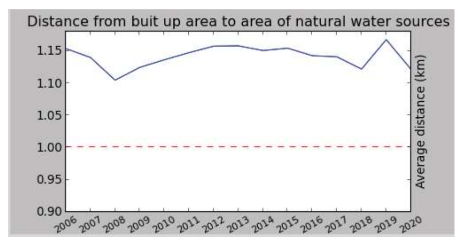


Figure 6. Weighted wetness index.

Figure 7. Distance from built up area to water resources.

The spatial indicator showing the average distance between built up areas and water sources shows a variability between 1.1 km and 1.16 km from 2006 to 2015 (Figure 7).

Figure 8 and 9 show the user interfaces of the implemented QGIS plugin for visualisation of spatial indicators.

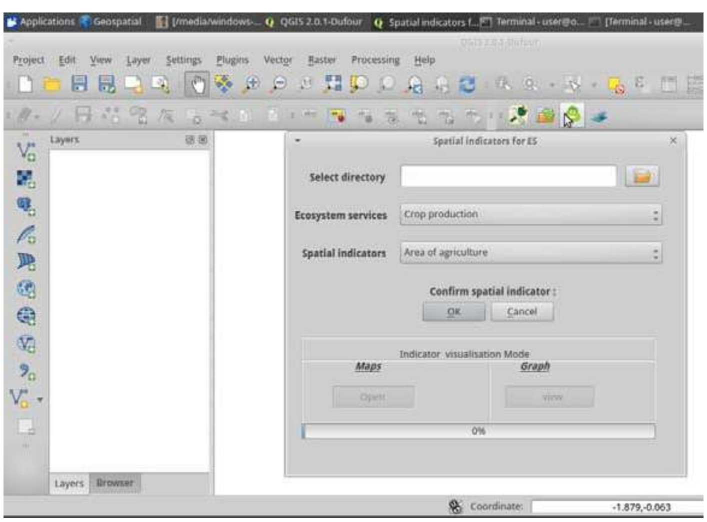


Figure 8. Dialogue of the QGIS plugin for the visualisation of spatial indicators

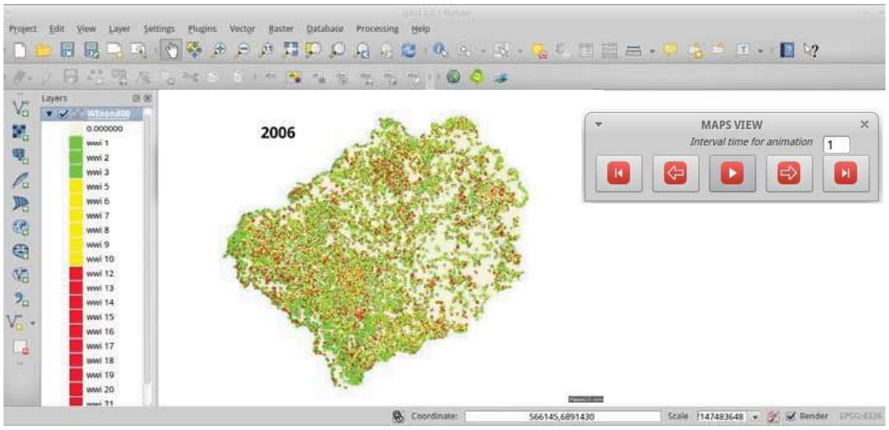


Figure 9. Animation dialogue of the QGIS plugin for visualisation of spatial indicators.

5. DISCUSSION

At the time of writing this paper, calibration of the coupled models was not yet done, and for that reason, quantitative results of spatial indicators do not reflect the reality as well as a calibrated model. However, this study demonstrates that spatial indicators can be derived from complex models and visualised using a user friendly open source tool. Together with end users appropriate indicators can be defined and used for assessing the impact of management strategies on ES status in the future in a spatially distributed manner both at the landscape scale and locally. The crop production status is evaluated by observing the trend of total area allocated to agriculture land use. The larger the area of agriculture, the more crop production can be expected because it is one of main factors involved in the generation of that ecosystem service. Water is considered inaccessible if it requires a travel of more than one kilometre to reach water source (Nkonya, 2010). The spatial tool allows the display of spatial indicators at local level, which enables the assessment of ES at the scale of a sub-catchment as well as within broader landscape context. This helps policy makers to understand the contribution of those sites in provision of ES of the whole catchment. The spatially explicit visualization can help policy makers to take a defensible decision on scenarios that are more effective in ecosystem sustainability management. This spatial tool does only inform to policy makers about the tendency of ES degradation or improvement. In a real context, measures to take for ES improvement or for ES sustainability are the responsibility of policy makers. Different ES may result in opposite benefits at optimizing an indicator, and this may result in worsening results of a spatial indicator that indicates the state of other ES (e.g. increase of crop production by increasing the agriculture area may reduce grassland size for fodder production). Policy makers have to evaluate the combination of spatial indicators to assess if their policy is appropriate to achieve multiple goals or if they have to set priorities in ensuring the sustainability of ES.

6. CONCLUSION AND RECOMMENDATIONS

The general objective of this study was to develop a decision support system that can be used to evaluate the impact of INRM policies on ecosystem services. Following the concept of this study, the spatial tool proposed in this study can elucidate the evolution of ES provision according to the properties of spatial patterns. In this study a QGIS plugin has been developed that uses the proposed approach. The plugin together with a Python library to calculate spatial metrics can be used at any spatial and temporal scale. The tool can be used by policy makers for spatial management and planning. The simplicity of the spatial tool and the choice for an open source platform will make it affordable for a large number of people involved in environment conservation and planning. In this study, few useful examples of spatial indicators related to issues in the study area have been presented. It is recommended to expand the list of possible spatial indicators, taking into account all ES relevant for the study area. The spatial metrics library is open source and can be extended with more metrics to calculate more spatial indicators. The quantification of ES was beyond the scope of this study. The spatial tool can be improved by incorporating the experience and expectations of the end users.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Catacutan, M., 2012. Rapid Assessment Report of AfroMaison project: Africa at a meso-scale: Adaptive and integrative tools and strategies for integrated natural resources management.

DWAF, 2004. Internal Strategic Perspective: Thukela Water Management Area.

Forman, R.T.T., Godron, M., 1981. Patches and Structural Components For A Landscape Ecology 733–740.

Geneletti, D., 2004. Using spatial indicators and value functions to assess ecosystem fragmentation caused by linear infrastructures. Int. J. Appl. Earth Obs. Geoinf. 5, 1–15.

Hunter, J.D., 2007. Matplotlib: A 2D graphics environment. Comput. Sci. Eng. 9, 90–95.

Link, J., 2002. What does ecosystem-based fisheries management mean? Fisheries 18–21.

McGarigal, K., SA Cushman, Ene, E., 2012. FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps [WWW Document]. URL http://www.umass.edu/landeco/research/fragstats/fragstats.html

Millenium Assessment, 2005. Ecosystems and human well-being, Millennium EcosystemAssessment. Washington, DC, Island Press.

Nkonya, L., 2010. Realizing the Human Right to Water in Tanzania. Hum. Rights Br. 17, 25–30.

Oxley, T., McIntosh, B., Winder, N., Mulligan, M., Engelen, G., 2004. Integrated modelling and decision-support tools: a Mediterranean example. Environ. Model. Softw. 19, 999–1010.

PCRaster, 2014. PCRaster | Software for environmental modelling [WWW Document]. URL http://pcraster.geo.uu.nl

Portela, R., Rademacher, I., 2001. A dynamic model of patterns of deforestation and their effect on the ability of the Brazilian Amazonia to provide ecosystem services. Ecol. Modell. 143, 115–146.

Turner, M.G., Gardner, R., O'Neill, R.V., 2001. Landscape Ecology in Theory and Practice: Pattern and Process. Springer.

US Environmental Sciences Program, 2014. GLB Methodology and Interpretation.

Van Deursen, W., 1995. Geographical Information Systems and Dynamic Models Development and application of a prototype spatial modelling language. NGS, Netherlands Geographical Studies.

Yalew, S., Teferi, E., Van Griensven, A., 2012. Land use change andss uitability assessment in the Upper Blue Nile Basin under water resources and socio-economic constraints: A drive towards a Decision Support System, in: Seppelt, R., Voinov, A.A., Lange, S., Bankamp, D. (Eds.), 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Sixth Biennial Meeting. International Environmental Modelling and Software Society (iEMSs).