GIS-based analysis of geo-resources and geo-hazards for urban areas – the example of the northern periphery of Belo Horizonte (capital of Minas Gerais, Brazil)

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Monika Hofmann
Doutoranda
TU-Darmstadt
Institut für Angewandte Geowissenschaften
Schnittspahnstr - Darmstadt - Germany
mb.hofmann@gmx.de

Andreas Hoppe
Professor
TU-Darmstadt
Institut für Angewandte Geowissenschaften
Schnittspahnstr - Darmstadt - Germany
ahoppe@geo.tu-darmstadt.de

Joachim Karfunkel
Professor Associado
Universidade Federal de Minas Gerais - UFMG
Departamento de Geologia
Belo Horizonte - Minas Gerais - Brasil
jkarfunkel@yahoo.com

Allan Büchi
Mestrando
Universidade Federal de Minas Gerais - UFMG
Departamento de Geologia
Belo Horizonte - Minas Gerais - Brasil
allanbuchi@gmail.com

Abstract

Easily understandable thematic maps of geo-scientific parameters are important for land use decision making. If several parameters are relevant and have to be compared, it is important that they are consistent with each other, available at the same spatial range and detail and normed to a common data range. In the current study, geological and topographical data have been used to derive a set of 90 geo-scientific maps for an area of 400 km² in the northern part of the metropolitan area of Belo Horizonte. Each parameter has been transferred to a common data range between 0 and 1 using a Semantic Import Model strategy and afterwards combined to derive new parameters for soil hydrology and hydrogeology. From these, many intermediate geo-scientific parameters, maps of geo-resources (sand/gravel, carbonates, fertile soils) and geo-hazards (erosion, groundwater pollution) have been derived that they can be used as base information for a participatory and sustainable land use planning. The workflow is transparently stored in GIS-tools and can be modified and updated if new information is available.

Keywords: spatial analysis, multi-criteria decision making, soil properties, predictive mapping, geo-resources, geo-hazards, spatial decision support system, GIS, groundwater vulnerability.

1. Introduction

Easily understandable spatial information is essential for stakeholder participation in land use decisions. Maps of geo-potentials – i.e. resources and hazards related to geology - visualize knowledge that is otherwise difficult to describe and compare (Lehné *et al*. 2013). Spatial Decision Support Systems (SDSS) use this information by showing the best location according to different stakeholder groups' priorities. Hoppe *et al*. (2006), Marinoni and Hoppe (2006) and Lamelas *et al*. (2012) give examples of this concept for densely populated areas in Spain and Germany. In the current study, this concept is applied to a rapidly developing region in Brazil.

A typical workflow converts base information regarding geology and topography into normed thematic maps of risks and resources. These maps are multiplied by a weight factor depending on their estimated importance and then combined to a map showing the most suitable locations (Figure 1). The aim of the current project is to combine available information until the first result in Figure 1, i.e. normed factor maps of geo-resources and geo-hazards that can be the input for a SDSS.

The following requirements must be met for the maps:

- Consistent: input data needs to be checked for contradictions due to different scale and amount of detail

- Spatially continuous: parameters available only as point information need to be regionalized
- Comparable: transferred to a normed data range e.g. from 0 – 1
- Transparently documented and possible to update.

Taking into account the existing compendia of thematic maps for the area, translation and interpretation of already available data could not be the only focus of the project. Instead, a complete workflow from the analysis and enlargement of the existing database until the regionalization of new parameters was created. The result comprises over 90 thematic maps that have been published in a PhD thesis (Hofmann 2014) and can be downloaded including the GIS tools at http://tuprints.ulb.tu-darmstadt.de/4152/.

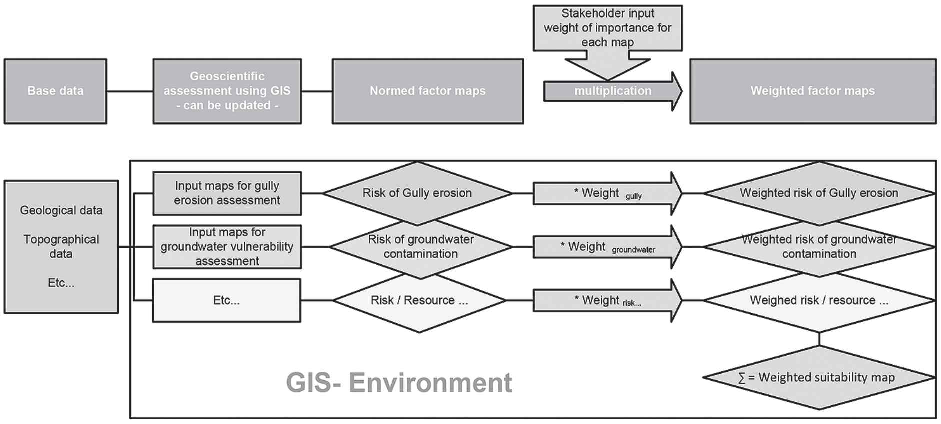

Figure 1
Principle of the weighted overlay for the generation of a suitability map. The weights can be generated using a ranking method (e.g. Saaty 1977) and add up to 1.

2. Materials and method

The study area comprises 400 km² in the northern periphery of Belo Horizonte, where urbanization proceeds rapidly following the construction of the highway MG 10 (Figure 2). The geological underground is composed of flat lying sequences of Late Proterozoic limestone – marl - pelite alternations of the Bambuí Group above Precambrian crystalline basement. The following units of the Bambuí Group can be found in the study area (from bottom to top): Carrancas Formation, Sete Lagoas Formation and Serra de Santa Helena Formation. The diamictites of the Carrancas Formation are documented only at a single outcrop, their spatial extent is not known. The base of the Sete Lagoas Formation consists of impure limestones (Pedro-Leopoldo Facies), which are overlain or interdigitated with pure, finely laminated limestone of the Lagoa Santa Facies (Schöll 1972, 1973). The meta-pelites of the Serra de Santa Helena Formation cover these limestones in large parts of the study area. Except for the Lagoa Santa Karst area (Kohler 1989, Kohler and Karfunkel 2002), the hilly landscape is covered by deep saprolites of weathered meta-pelites of the Serra de Santa Helena Formation and in the southern part also of weathered gneiss-granite basement. The city of Lagoa Santa

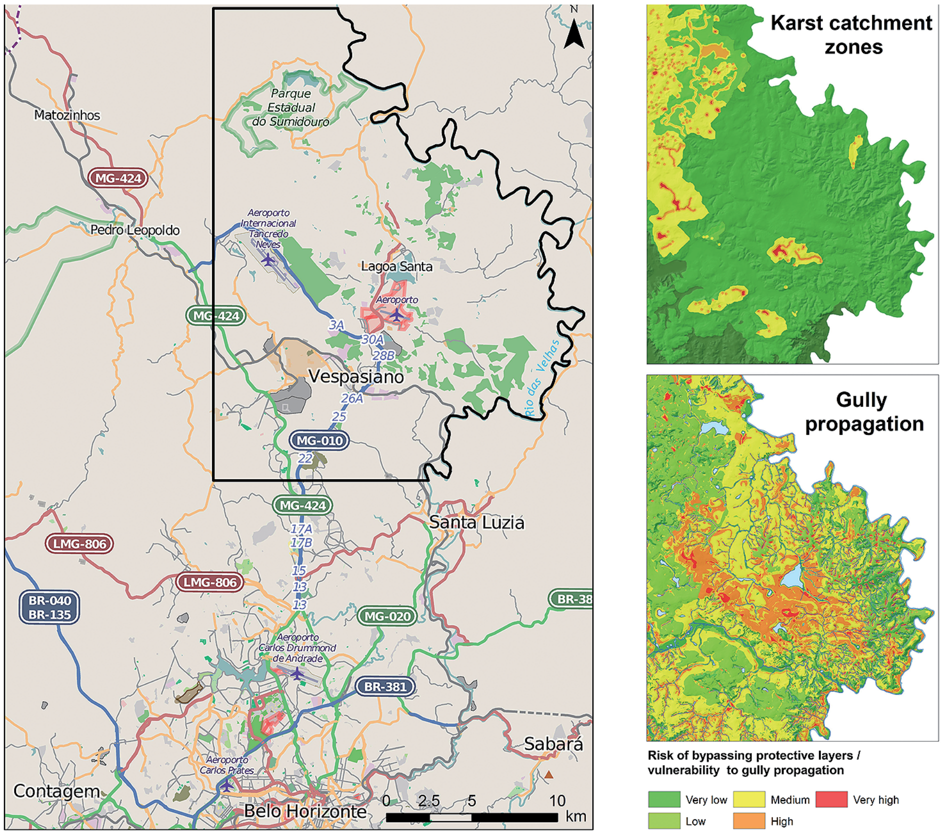

Figure 2
Location of the study area north of the state capital Belo Horizonte (source: Open Street maps) and two exemplary thematic maps regarding karst groundwater resource and vulnerability to gully propagation.

is built on meta-pelites around a triangular lake that is not connected to the karst system (Parizzi *et al.* 1998). The climate is tropical at high altitudes (650 – 920 m.a.s.l.) with humid warm summers, dry cool winters and an annual precipitation around 1300 mm.

In this area, the following geo-potentials play an important role for land use planning: In karstified terrain, a large unconfined groundwater reservoir exists that is highly vulnerable to pollution, especially since the most fertile soils are near doline bottoms. Limestone outcrops are potential locations for cement quarries and compete with the protection of the sensitive karst environment, which also hosts many archeological sites. Increased sealing following urbanization quickly changes the catchment hydrology and leads to a higher risk of inundation and linear erosion. Especially the deeply weathered hills on meta-pelites or granite basement are often cut by deep gullies. Since the urban area is only partly connected to sanitation systems, pollution of surface and subsurface water is a large issue. Exploitation of sand and gravel resources have left a very irregular relief in alluvial plains that restrict its further use.

Throughout the workflow of the project, the rate of data aggregation and thus the directly accessible information for non-experts rises from the base data and continues until the final thematic maps (Figure 3). Altogether, four levels (steps) of data and knowledge aggregation can be distinguished:

In Step 1, the available primary input data is collected and integrated into a digital spatial database. The most central information involves geological architecture, relief and hydrological soil properties. The input data with highest spatial detail is the topographic map 1 : 25 000.

In Step 2, a geology – soil – landscape model is developed. Geological maps are checked for consistency with relief features and updated to a scale of 1 : 25 000. Also the information about geomorphology and soil is updated using field studies and remote sensing data. The result is used to derive a conceptual model from geological architecture to landscape evolution and the typical distribution of hydrological soil properties.

In Step 3, information about the geological architecture from Step 2 is used to interpolate the thickness of each strata including an estimation of the weathering depth and the existence of covered karst features. The descriptive geology-soil-landscape model is transferred into regionalization rules for hydrologically relevant soil properties using a Semantic Import Model strategy (Figure 4, Hofmann *et al.* 2013). The output parameters comprise an estimation of the highly permeable red topsoil layer depth, hydrological soil class, degree of lateral flow, hydromorphic soils, effective field capacity, base saturation, soil erodibility, risk of near surface epikarst and weathering depth.

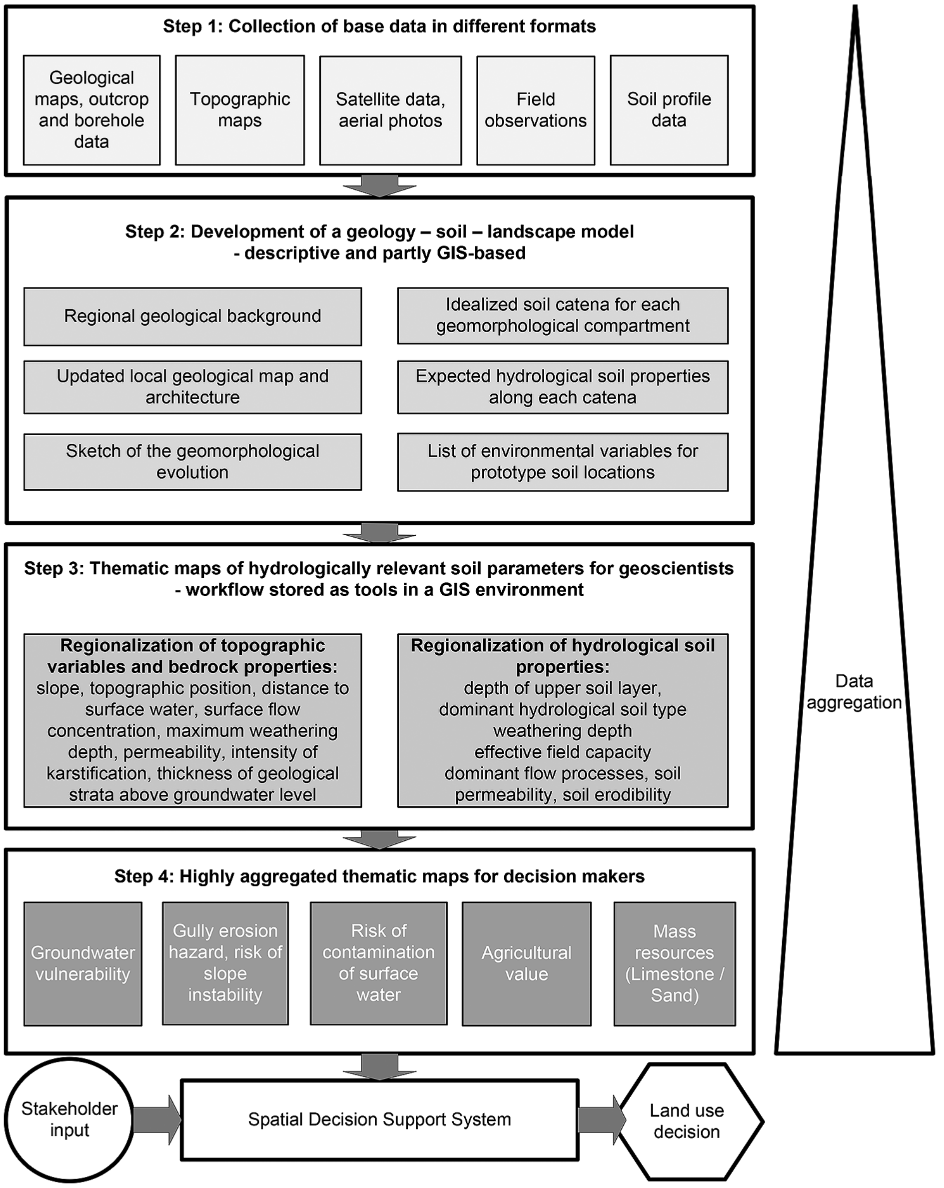

Figure 3
Workflow of the project
(modified after Hofmann *et al.* 2013).

In Step 4, the parameters derived in Step 3 are aggregated into thematic maps for decision makers regarding geo-hazards and geo-resources. These maps comprise groundwater vulnerability, gully erosion hazard, risk of contamination of surface water, agricultural value and the accessibility of mass resources.

Land use information, which is quickly changing, is incorporated at the latest possible stage in the workflow, especially during assessment of groundwater vulnerability and erosion hazard. In most other thematic maps, such as agricultural value or availability of limestone resources, land use is not included at all.

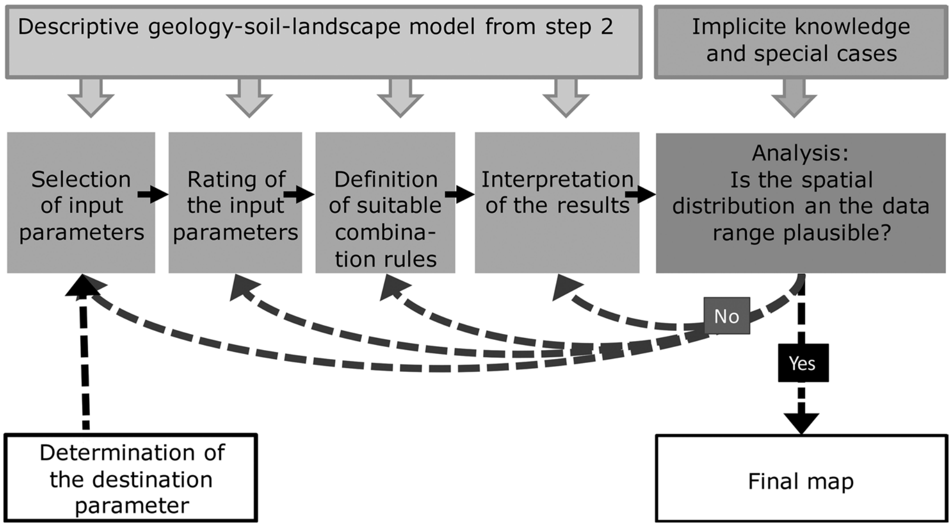

Figure 4
General workflow for regionalizing hydrological soil properties (step 3 in Figure 3).

A short overview of the methodology for Step 4 is given below, a detailed description can be found in Hofmann (2014):

- Limestone resources and their accessibility are estimated by the interpolated thickness of overburden and interpolated thickness of limestone layers above groundwater surface.
- Sand resources in the area are estimated based on sedimentary structures and a GIS-based volume calculation of the Quaternary sediments (Hofmann *et al*. 2009).
- Agricultural value is primarily related to parent material and relief position and restricted by erosion hazard along steep slopes.
- Groundwater vulnerability is estimated based on of the protection by overlying strata combined with the risk of bypassing these layers by lateral flow into karst ponors. This method has been specifically developed for a mix of a karst and non-karst environments (Goldscheider 2002, Goldscheider *et al*. 2000).
- The risk of gully erosion is divided into two sub-processes: The first subprocess focuses on concentrated surface flow or small landslides that can remove the protecting topsoil cover and may act as trigger. The second sub-process is gully propagation, for which the workflow is displayed in Figure 5. Here, the most important parameters are concentration of subsurface flow, depth of saprolite, location inside a headwater hollow and the existence of a temporary aquifer (Bacellar *et al*. 2005). For the final gully erosion hazard map (Figure 6), both subprocesses are combined. The effect of concentrated surface and subsurface flow is derived using a modified topographic threshold method based on drainage area and slope.
- The risk of surface water contamination by rain-wash is derived from the hydrological closeness to water courses. A precipitation-distribution map was not available for this assessment but could easily be integrated into the GIS-workflow.

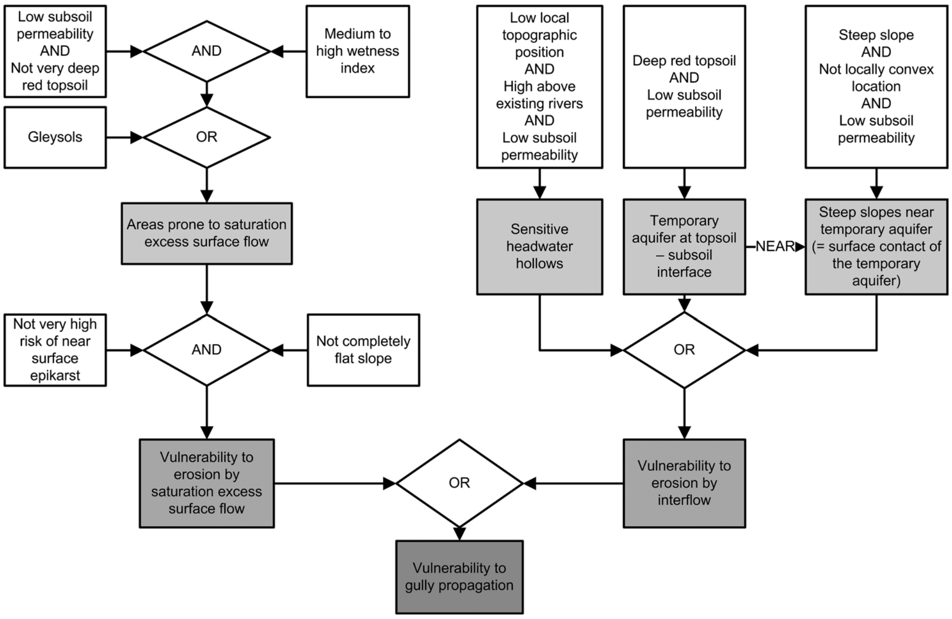

Figure 5
Sub-workflow
for the estimation of vulnerability
to gully propagation (Hofmann 2014).

3. Results and discussion

The maps of hydrological soil properties include relief information from the topographic map 1 : 25.000. Thus, they display a higher spatial detail than the previously available soil maps 1 : 50 000 (CPRM 1994, Shinzato and Lumbreras 1998). Although a high spatial resolution suggests higher accuracy, it has to be remembered that the rules of the workflow are necessarily general and do not comprehend local special situations. It is very difficult to compare the existing maps or use them for validation since the mapping units are different and often combine several soil types. Still, similar approaches have shown better results for mapping continuous soil parameters than extracting them from classical soil maps (Qi *et al*. 2006). One of the most often used intermediate parameters is the risk of near surface epikarst. This parameter is very difficult to estimate but central for the assessment of groundwater vulnerability, mass resources and erosion.

Following the methodology of Goldscheider *et al.* (2000), subsoil and saprolite are considered the most important protecting layers for the groundwater in this area. The assessment quality of their thickness depends largely on the correctness of the interpolated geological architecture, weathering depth and groundwater level. The degree of bypassing protective layers by lateral flow into karst ponors is highly sensitive to the correct identification of urban features generating surface runoff. The final groundwater vulnerability map shows highest vulnerability around karst outcrops. Also sealed areas in the catchment of sinking streams are assigned a high groundwater vulnerability class due to the risk of bypassing protecting layers via surface runoff into karst sinks. A better identification of areas with high surface runoff using current and high resolution land use data will probably increase the mapped groundwater vulnerability for the karst area.

Since the input parameters for the estimation of mass resources are associated with high insecurity, the resulting optimality values "thickness of overburden", "resource thickness" and "accessibility of limestone resources" also have to be interpreted with care. Nevertheless, it is difficult to achieve a higher data quality. The necessary effort is very high and requires many and well distributed drillholes in the study area.

The agricultural value shows soils with highest natural fertility in the karst area, especially near doline bottoms. Thus, the most favorable areas for agriculture are flat lowlands on carbonates.

The resulting gully erosion hazard map correctly identifies existing erosion features (Figure 6) but also shows areas that are probably vulnerable to gully propagation if concentrated overland flow is generated, e.g., by inadequate urbanization structures. Still, for a statistically sound evaluation of the method, more field studies are needed.

Risk of surface water contamination by rain-wash is only estimated by the downhill-distance to the next water course, independent of possible polluting sources. If a polluting source is identified, this map, together with a map of rainfall intensity distribution, yields information how quickly the pollutant can reach the next water course.

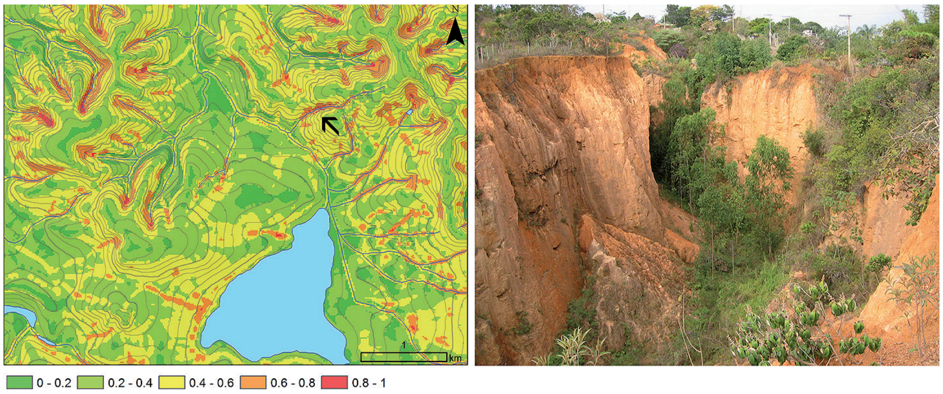

Figure 6
Detail of the gully erosion hazard map near Lagoa Santa (Hofmann 2014). The scale ranges from 0 (low risk) to 1 (very high risk). The arrow indicates the location of one of the largest gullies in the region (photo on the right).

4. Conclusion

For the current project, a structured workflow has been created, which resulted in over 90 consistent thematic maps out of a very heterogeneous database. These maps can be interpreted as a digital atlas of geo-potentials for the region around Lagoa Santa. They represent visualizations of complex topics that are understandable as single maps but yield more comprehensive information as a set. The relatively high number is due to the fact that most intermediate results of long workflows are also displayed as maps. This offers the possibility for a visual check of the integrity and plausibility of the calculations.

One of the major problems in the project was the scarce database that often required rough assumptions for the regionalization of parameters. Next to a field validation that checks the regionalization rules by systematic analysis, a classification of recent high resolution land use data would be an ideal supplement to the current work.

When accepting these uncertainties, the gain of information availability and its spatial display in the form of maps make this knowledge accessible to a larger group of stakeholders and thus favor its active incorporation in land use planning.

Using this atlas, new combinations of geo-scientific parameters can be created for specific projects. This overlay is done most easily in a GIS environment but it is also possible using the analogous print version of the maps, for example for a first overview or in discussion groups.

Also more complex models can use the database of the project, since gully erosion and floods seem to be the most strongly perceived geo-hazards in the region. A dynamic model of the catchment hydrology is needed. Such a model needs many spatially continuous data on soil hydrology that could be drawn from this project.

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