Multicriteria GIS Modelling of Terrain Susceptibility to Gully Erosion, using the Example of the Island of Pag

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Introduction

- Multicriteria GIS data analysis (GIS-MCDA) is process of transforming and combining various spatial data for the purpose of obtaining new information.

- GIS-MCDA has application in numerous fields → urban planning, agriculture, forestry, mining, optimal site selection, natural hazards, etc.

- In geomorphological studies GIS-MCDA is used to determine the areas of different susceptibility for the appearance of certain morphological features and processes (e.g. gully erosion).

- Better understanding of spatial distribution of studied object or process.
Gully erosion importance

- Gully erosion is **threatening** the valuable soil sediments
- Specific Mediterranean grassland eco-system

Examples of **soil degradation and removal caused by gully erosion**

Local **sheep breeding depends on grassland areas**
Study location – Pag Island, Croatia

- Largest island in Northern Dalmatia archipelago (284 km²)
- Specific karst landscape → scarce vegetation cover
- Many active gullies (Lončar, 2009)
- Gully erosion → one of the most prominent denudation processes

Location of the study area
Characteristics of study area

- Mediterranean climate - between Csa and Cfa climatic zones (Köppen)
- The annual average amount of precipitation on the island of Pag is between 1050 mm and 1106 mm
- Bare landscape shaped by the influence of strong northern Bora wind

Specific bare karstic landscape
Aims of the study

I. **Modelling of gully erosion susceptibility of Pag Island**

   H1: Large parts of the Island are vulnerable to the gully erosion occurrence

II. **Determine the correlation between high susceptibility areas and existing active gullies**

   H2: High and very high susceptibility areas coincide with existing gullies

III. **Analyse the vulnerability of the settlements of Pag Island from gully erosion**

   H3: The immediate surroundings of many settlements is directly threatened by gully erosion
Data acquisition

I. DIGITAL ELEVATION MODEL (DEM)
   - DEM was made based on the height data collected by the photogrammetric restitution (DGU, 2017).
   - Ordinary kriging (OK) interpolation of 148,518 height points → 15 m spatial resolution of DEM (284 km²)
   - Optimal interpolation method chosen by cross-validation results → RMSE = 1,0279

II. Medium resolution satellite image
   - Sentinel 2 multispectral images → supervised classification (Erdas Imagine)

III. Soil maps (1:50 000)
   - Soil types are vectorized from basic soil maps at scale 1:50 000
Research methodology

GIS-MCDA WORKFLOW

1. Define the GIS-MCDA goal
2. Determination of criteria and constraints
3. Standardization of criteria
4. Calculation of the weight coefficients
5. Aggregating (model creation)
6. Model validation
I. Morphometric parameters

<table>
<thead>
<tr>
<th>SLOPE (SLO)</th>
<th>ASPECT (ASP)</th>
<th>PLANAR CURVATURE (PLAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main predisposing factor in the</td>
<td>Regulates the exposure of the</td>
<td>Affects the homogeneity of the surface</td>
</tr>
<tr>
<td>evolution of the slope relief</td>
<td>terrain to various climatic factors</td>
<td>runoff</td>
</tr>
<tr>
<td>Influences the intensity of the</td>
<td>Controls the vegetation cover</td>
<td>Concave slopes are causing the</td>
</tr>
<tr>
<td>gully erosion</td>
<td>development</td>
<td>convergence of runoff → higher</td>
</tr>
<tr>
<td>Optimal slope for gully erosion</td>
<td>Northern and north-eastern slopes</td>
<td>erosion potential (EP)</td>
</tr>
<tr>
<td>is 12°-32°</td>
<td>affected by Bora wind</td>
<td>Convex slopes are causing the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>divergence of runoff → lower EP</td>
</tr>
</tbody>
</table>

Data source:
15 m DEM

Horn method (1981.)

\[ N (º) = \sqrt{G^2 + H^2} \left( \frac{180}{\pi} \right) \]

Data source:
15 m DEM

Horn method (1981.)

\[ A = 180º - \arctan \left( \frac{H}{G} \right) + 90º \left( \frac{G}{|G|} \right) \]

Data source:
15 m DEM

Zeverbergen & Thorne (1987.)

\[ \omega = 2 \left( \frac{DH^2 + EG^2 + FGH}{G^2 + H^2} \right) \]
1. Morphometric parameters

**PROFILE CURVATURE (PROF)**

- Affects the speed of downslope surface runoff and occurrence of material removal
- Concave slopes are causing the slowdown of surface runoff $\rightarrow$ lower EP
- Convex slopes are causing acceleration of runoff $\rightarrow$ higher EP

**LENGHT-SLOPE FACTOR (LSF)**

- Measure of sediment transport capacity of surface runoff
- Applied in USLE and RUSLE equations for calculation of soil erosion
- Higher LSF $\rightarrow$ Higher erosion EP

**Data source:**
15 m DEM

*Zeverbergen & Thorne (1987.)*

\[
\phi = -2 \left( \frac{DG^2 + EH^2 + FGH}{(G^2 + H^2)} \right)
\]

*Zhang (2013.)*

\[
LSF = \left( \frac{A_s \times \text{spatial resolution (DEM)}}{22.13} \right)^{0.4} \times \left( \frac{\sin \beta}{0.0896} \right)^{1.3}
\]
II. Hydrologic parameters

STREAM POWER INDEX (SPI)
- Represents the measure of the erosive power of surface runoff
- Influences the intensity of gully erosion
- Higher SPI $\rightarrow$ higher EP

Data source: 15 m DEM

Moore (1981.)
SPI = $\ln(A_s \times \tan \beta)$

TERRAIN WETNESS INDEX (TWI)
- Measure of the potential humidity of a given terrain
- Allows the separation and differentiation of the saturated areas from unsaturated areas
- Higher TWI $\rightarrow$ lower EP

Data source: 15 m DEM

Moore (1981.)
TWI = $\ln\left(\frac{A_s}{\tan \beta}\right)$

Watershed (WAT)
- Erosion force of the surface runoff depends mostly on the surface of the catchment area
- Larger watershed $\rightarrow$ larger surface runoff $\rightarrow$ larger EP

Data source: 15 m DEM
III. Additional parameters

**LAND COVER (LC)**
- 9 land cover classes classified from satellite images
- Different vegetation and land-use types
- Bare rocks, grasslands, agriculture, forests, swamplands, etc.

**PEDOLOGY (PEDOL)**
- Different types of soil characterize different erosion resistance
- Soil characteristics are affecting the erosion intensity
- Connected with vegetation cover and land-use practice

**BOOLEAN (BLN)**
- Areas that are not suitable for gully erosion
- Differenced from satellite images
- Water bodies and urban areas

**Data source:**
- LAND COVER: 10 m Sentinel 2
- PEDOLOGY: Soil map (1:50 000)
- BOOLEAN: 10 m Sentinel 2
**Standardization, weight calculation and aggregation of criteria**

- **Standardization** of criteria is the basis for their mutual comparison (Malczewski, 2015)

- 10 predisposing criteria standardized to the scale (1 – 5), BLN criteria standardized to binary scale (0,1)

- Predisposing factors $\rightarrow$ lower values = lower importance

- **Weight coefficients** for each criteria were calculated by **analytical hierarchy process (AHP)**

  - AHP allows the calculation and validation of weight coefficients for each criteria

  - Validation is performed through the **consistency index (CI < 0,1)**

- Based on chosen criteria and their weight coefficients **four different models** were produced (Model 0, Model 1, Model 3, Model 4)
Output models of the GIS-MCDA

- Visual comparison of created models shows significant difference in distribution of susceptibility classes
- Models 0 and 1 are less good than other two models

**MODEL 0** → all criteria equally important

**MODEL 1** → SLO, ASP, PEDOL, LC most important

**MODEL 2** → PEDOL less important (poor data quality)

**MODEL 3** → morphometric parameters most important
Validation of created models

- Model validation performed through the creation of ROC curves

REFERENCE DATA

- Object-based Image Analysis (OBIA) → more than 100 gullies mapped
- Manual vectorization (DOF - 1:1000) → 10 reference gullies mapped
ROC curves validation

- **Model 3** is the most accurate model (AUC > 0.8 → very good quality model)

- ROC curves have confirmed the strong correlation between existing gullies and high susceptibility areas.

![ROC curves for 10 reference gullies](image1)

![ROC curves for 120 OBIA gullies](image2)
High and very high susceptibility areas are covering around 30% of total island area.

Low susceptibility areas are mostly related to flat, inner parts of the island.

Baren NE and E slopes of karst hills are most vulnerable to gully erosion.

Field surveys have additionally validate the accuracy of created model.
Settlement vulnerability analysis

- Buffer zone of 500 m around 25 settlements is analyzed.
- The most endangered settlement is Pag town. Recently built apartments are built in high gully erosion susceptibility areas.
- Several other settlements are endangered (Kolan, Lun, Metajna, etc.).
- Gully erosion can negatively affect further development and expansion of the settlements.

Gully erosion susceptibility within 500 m buffer around Pag city.
Conclusion

- Created gully erosion susceptibility model shows that large parts (30%) of the Pag Island are directly endangered.
- ROC curves have proven that high and very high susceptibility areas coincide with existing gullies.
- The immediate surroundings of many settlements is directly threatened by gully erosion, while most vulnerable settlement is Pag city.
- GIS-MCDA represents a key basis for planning and preparation for prevention of future negative effects of gully erosion.
Thank you for your attention

Any questions ???