Integration of Earth observation and in-situ data for landscape change analysis. A case study of an area affected by a bauxite residue spill in Veszprem province, Hungary

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Abstract. Satellite imagery can provide consistent information measuring the extent and the impact of disasters; however, it might provide only limited information in the context of socio-economic aspects. The aim of the present research is to prospect the combination of two approaches – one that focuses on the physical state of the land surface – obtained through the land cover classification of satellite imagery – and another that describes socio-cultural aspects – mapping landscape perception using participatory GIS. The case study site is an area in Veszprem province, Hungary which was heavily affected by a caustic “red mud” spill caused by a dam failure of a bauxite sludge reservoir in October 2010. The remotely sensed data used are multi-temporal and multi-sensor images (including ASTER, GeoEye, IKONOS and MODIS) dating from before, during and after the accident. The land cover change detection analysis was performed based on an image classification using relatively new algorithms such as Support Vector Machine (SVM) and Random Forest (RF). The results were then compared. There could no significant differences be found between the results of SVM and RF classifiers. The extent of the spill and changes of the settlement structure in the village of Devecser could be mapped based on the classifications, though the comparison of results derived from different EO data in terms of spectral and spatial resolution posed a challenge. Findings in literature on ways of integrating these results with participatory GIS methods imply several methods for mapping social aspects are suitable to be used jointly and combined with the change detection maps. (Next to the incorporation of additional methods such as object based classification) the integration of qualitative ground truth may improve and explain the results of a landscape change analysis and provides additional information on local landscape change and processes present after a disaster occurs.

Keywords. land cover change analysis, classification, disaster management, participatory GIS

1. Introduction

The subject of this research is an analysis of landscape change in Veszprem province, Hungary which was heavily affected by a red sludge spill caused by a dam failure of a bauxite sludge reservoir situated adjacent to an aluminium factory in 2010. The objective is to analyse multi-temporal and multi-sensor remote sensing imagery and to find ways of combining them with spatial information collected on site (site visit, map-related inputs from residents (PGIS)) in a Geographic Information System (GIS) and to derive conclusions about the landscape change in the area.

1.1. Research questions:

The research questions formulated are therefore:
1.2. Context

The study area is located approximately 150 km southwest from Budapest. Between 14 and 35 km² of land ([1] p135) were covered in red mud, comprising several villages along river Torna (including Kolontar and Devecser) agricultural and woodland as well as a historic park that belongs to the Devecser Esterhazy castle. Ten people died during the flood which reached in some areas a height of two meters and numerous persons were injured.

Bauxite residue or red sludge is a by-product of aluminium production. Aluminium is extracted from bauxite which contains aluminium oxide and other metal oxides such as iron oxide (rust) that causes the red colour of the sludge. During the process the aluminium is extracted while other bauxite components remain, high temperatures and additions of caustic soda are used. As a result bauxite residue (or red sludge) is a waste-production of aluminium production with high alkalinity (pH 12-13) and can contain toxic trace elements. The alkalinity poses the main threat to humans and living organisms in general when exposed to the sludge.

In Ajka bauxite residue is stored in its liquid form within a reservoir bordered by dams. In direct contact its strong alkalinity destroys human and animal skin and causes severe damage to cell tissues, which results in the death of cells affected. The base does also have a lasting effect on pH values of soil and water (Though the alkalinity was neutralized by gypsum additions to the Torna river water). The toxic metals contained such as mercury, cadmium and lead may cause damage as they are deposited within the organism and change the structure and functioning of proteins. [1]

The soil structure and water balance and (supposedly) as a result also vegetation vigour was not only impaired by the sludge itself but also by clean-up efforts. The settlement structure was altered as the severity of the damage resulted in some cases in inevitable demolition of buildings while new houses were built elsewhere.

Fleck [2] describes the chemical state of soils collected on site six months after the incident and finds that pH sunk during this time but had not reached recommendable values for cultivation. For crop plants grown in soil affected by the red mud spill trace elements as Cadmium and Manganese were found in the plant tissue. Therefore it was recommended to further monitor soil conditions before agricultural cultivation can be reintroduced in affected areas.

There were no findings about effects of the pH values on plant biomass. Fleck therefore assumes salinity and alkalinity, that had been identified as the two major factors that impede plant growth, have been reduced greatly already half a year after the accident.

1.3. Disaster analysis and monitoring using remote sensing

The analysis of remote sensing imagery before during and after a natural disaster occurs, allows predicting and measuring the extent and the impact of the incident on the physical environment. Van Westen [3] states "Many disasters may affect large areas and no other tool than remote sensing would provide a matching spatial coverage."

Satellite imagery may provide information on a large scale and from multiple points in time. The acquisition of this kind of data by other means (e.g. surveying on site) would impose high labour input and could not be done within a comparable time span. Furthermore the homogeneity of an image taken with the speed of a camera shutter (or even if it was within several seconds or minutes) cannot be compared with the collection of data on ground that might take days weeks or even months and changes over time such as weather conditions may distort the results.
Even if an appropriate availability of imagery may not always be given and "[Whereas] the timing and spatial resolution of satellite sensors may not be appropriate for monitoring this [type of] disaster they may be useful for before and after analysis of the disaster site and for planning restoration of damaged areas." [4]

Therefore a way of describing the implications of a disaster is to perform a landscape change detection analysis. A "Digital change detection encompasses the quantification of temporal phenomena from multi-date imagery that is most commonly acquired by satellite-based multi-spectral sensors." [5] Landscape change may be detected by comparing two or several images of the same area from different points in time.

1.4. Field support – a wider approach

Site visits provide the analyst of remote sensing data with additional information of the place and contribute to the accuracy of a (supervised) image classification by defining training sites. Field support "relates to all those activities that are undertaken to support obtaining the most accurate information from the remotely sensed image data". [6]

In the present work we do claim field visits do offer the opportunity to explore not only the physical or tangible properties of the landscape but also social and cultural aspects.

Including public participation in all areas of landscape research has been strongly promoted by the European Landscape Convention (ELC) [7] and is therefore more and more present in various landscape disciplines’ research as well as in planning.

Meier and Bucher [8] say the concept of a landscape perceived every day (by local residents) is hardly comparable with the general scientific understanding. They suggest combining facets of the physical space and inner conceptions and images. As a method for understanding these conceptions they suggest reading traces. The principle of this method implies, one can extract information about present and past events, conditions and uses by interpreting the physical state of vegetation and other elements of the landscape, for example during a field visit.

Another approach describes integrating ground truth in the form of qualitative data using participatory methods and has been previously used, for example, in natural resource assessment in Senegal [9]. Likewise integrating observations such as (changes of) landscape values as perceived by lay people over time, acquired using participatory GIS methods (described e.g. by Brown and Raymond [10]) responds strongly to the appeal of the ELC.

Both of the above approaches include an aspect generally avoided in Remote Sensing: bias. Contrary to the objectivity aimed for in the classification of Earth Observation data they include personal conceptions and aspects as personal value and experience of the analyst as well as of the lay local population and use them as valuable sources of information.

2. Methods

2.1. Remote Sensing Data

The data used for image classification include one ASTER image dating from May 2007, one ASTER image from October 2010, a combination of one GeoEye and one IKONOS image from October 2010 and one GeoEye image from May 2012. All the images from October 2010 date shortly after the accident occurred and are therefore suitable to be used to map the extent of the flood within the study area.

The area covered by the high resolution image data does not include the entire area affected by the accident, but the majority. It encompasses the three villages most affected by the spill (Kolontár,
Devecser and Somlóvásárhely) as well as the origin of the flood, the bauxite residue reservoir and adjacent arable and woodland as well as industrial areas and water surfaces.

![Figure 1](image.jpg)

**Figure 1.** Extent of imagery used. The bauxite residue reservoir is marked in red, villages in black

The remote sensing data used for his research furthermore includes a time series of MODIS NDVI data used to explore the feasibility of the study.

### 2.1. Data quality and implications

The remotely sensed data used is diverse in the respect of sensors, resolution, coverage and acquisition time. From all images only the visual spectrum (VIS) and the near infrared (NIR) band was used. For the ASTER images this implies a total of three bands (green, red, NIR) were used with a spatial resolution of 15m. All other available ASTER bands are of a lower resolution (30 and 90m) and were therefore excluded from the analysis.

IKONOS and GeoEye data both include very similar bands from the visual spectrum (3 bands, blue, green, red) as well as a NIR band. These were all used for the image classification processing. The spatial resolution of the 2010 mosaic and the 2012 image were resampled to 2m in order to reach a compromise between the 4m IKONOS resolution and the 1.65 for GeoEye.

As the GeoEye/IKONOS mosaic dating from October 2010 showed substantial cloud cover, parts of this image could not be used for the analysis.

### 2.2. Methods

#### 2.2.1. Preliminary observations

Before developing a strategy to quantify and describe landscape change in the study area two measures were taken in order to reassure the feasibility of detecting landscape change in the study area and to provide proof land cover change was present in the area.

Therefore a time series of MODIS images showing NDVI values in a coarse resolution was created to highlight possible changes in vegetation vigour from September 2010 to September 2011.
Furthermore another MODIS time series showing NDVI values observed in the month of November for ten years (comparison November 2002-2011) was prepared in order to identify anomalies in 2010, one month after the accident occurred (in October 2010).

The second measure, which relates to the aim of an inclusion of peoples’ perception in the present research, was a site visit to the village of Devecser on October 26th 2012 and the description of a walk through the village, ‘traces’ of use found, as well as information provided by locals.

2.2.2. Image classification

2.2.2.1. Preprocessing

The GeoEye and IKONOS image from October 2010 were combined as well as two GeoEye image tiles from 2012. All images were then subset to the same extent and their spectral data was equalized to a digital number range of 0 to 255 in order to assure comparability.

NDVI was used as additional feature for ASTER data. Previous research has shown that the inclusion of NDVI is likely to contribute to the improvement of classification results [11].

2.2.2.2. Classification scheme

Based on the 2010 GeoEye/IKONOS mosaic a set of classes was defined that covers all land cover (LC) types included in the present image as well as of all other images to be analysed. The 2010 GeoEye/IKONOS image presumably showed all possible LC types as it included areas affected by the red sludge spill as well as unaffected areas. During the sampling and classification process a need for additional classes and classes unnecessary was identified and they were added or removed accordingly. Finally a set of classes was used as follows:

The LC classes included:
- Agriculture cropped
- Agriculture – contaminated and bauxite reservoir
- Agriculture bare soil
- Agriculture wet bare soil
- Built up/urban
- Forest
- Water surfaces

2.2.2.3. Sampling and training

Based on the defined classes a supervised maximum likelihood classification was performed on the 2010 GeoEye/IKONOS image. 100 random stratified points per class were then identified as samples.

For these sample points the spectral information of all four images was extracted to be used in with the sampling software (Land cover Validation Toolbox (BOKU) V1.2011[12]). The software uses Google Earth (GE) to display the location of the sample points on the high spatial resolution images and allows allocating a class to each point in a fast and efficient way. Furthermore information about the spatial homogeneity and confidence can be added for further differentiation of the training samples.

After samples with low homogeneity and/or confidence were removed the samples were separated into training and testing datasets in order to create and test classification models.

2.2.2.4. Classifiers

For the image classification two relatively new classifiers were used and compared: The Support Vector Machine (SVM) and Random Forest (RF) classifier.

The SVM classification was performed in Matlab using the LS-SVMlab Toolbox © 2010 KU-Leuven-ESAT-SCD [13] The RF classification was performed using “randomforest-matlab”- an implementation for Matlab [14][15].
The classification was first run on the testing data set before moving on to the classification of the entire images.

2.2.2.5. Post processing
After the classification was finished the images were spatially filtered and classes were recoded as necessary.

2.2.2.6. Accuracy assessment
The target overall accuracy of the classifications aimed for was between 80 and 85%.
This goal is based on a review of studies that showed for ASTER images accuracies of 70-92% have been reached ([16][17][18]).
For IKONOS varying results have been found from around 79.5-96.9%. GeoEye analysis outcomes are expected to be coinciding with the above values as spatial resolution and spectral bands are similar to IKONOS imagery [19][20]. Wilkinson [21] has shown in his research, achieved accuracies mentioned in a large set of articles published in Photogrammetric Engineering and Remote Sensing over fifteen years did not show significant differences between sensors of diverging spectral resolution.
The comparison of these publications does also imply that a higher spatial resolution compensates for fewer bands available. This is based on the observation of a tendency towards high resolution imagery containing fewer bands and may explain the stability of measured accuracies throughout the studies based on different remote sensing data.
In present accuracy assessment this assumption is not applicable as, in contrast to this general tendency, for the lower resolution imagery (ASTER) classification only three spectral bands are used while the higher resolution images (IKONOS, GeoEye) comprise four spectral bands each.
The high spectral resolution imagery was therefore expected to show higher accuracies.

2.2.3. Literature review: Integration of qualitative ground truth
In order to cover the social dimension and to find ways of integrating qualitative ground truth describing (lay) peoples’ perception and using participatory GIS methods a literature research was initiated including a broad range of international publications on the topic.

3. Results

3.1 Image classification and landscape change detection
The first analysis of MODIS data revealed a significant drop in NDVI levels after the disaster and a normalization of the values during the subsequent months, while the site visit in October 2012 showed land cover changes both within and outside the area affected, triggered by the disaster according to locals. Both preliminary results imply substantial land cover changes were present and provided sufficient evidence to justify further analyses of Earth Observation data.
The MODIS time series do also indicate that Flecks [2] observation of a normalization of the chemical state of the soil and a reduction of the main burden on plant growth: alkalinity after a period of six months has a positive impact on plant vigour.
The comparison of the two classifiers showed one advantage of the Random Forest (RF) classifier: the classification results did not include unclassified pixels. Apart from this the images showed little differences. The accuracies of the four images by class are shown in Table 1.
Table 1. Image classification accuracies.

<table>
<thead>
<tr>
<th>Image</th>
<th>SVM classifier</th>
<th>RF classifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTER 2007</td>
<td>89%</td>
<td>84.5%</td>
</tr>
<tr>
<td>ASTER 2010</td>
<td>75.5%</td>
<td>80.8%</td>
</tr>
<tr>
<td>IKONOS/GeoEye 2010</td>
<td>75.6%</td>
<td>74.4%</td>
</tr>
<tr>
<td>GeoEye 2012</td>
<td>91.9%</td>
<td>86.7%</td>
</tr>
</tbody>
</table>

As the Random Forest classifier does not result in unclassified pixels in contrast to the Support Vector Machine algorithm the RF images were used for creating change detection maps.

The classified images dating from October 2010 both show confusions between the classes ‘Bare soil’ and ‘Built up/urban’ – and therefore their accuracies are low - but they both showed a clear delineation of all other classes, the ‘Agriculture contaminated and bauxite reservoir’ class respectively despite some misclassified pixels. Therefore these two images were used to identify the area affected by the spill. A spectral analysis of bauxite residue in the form of red dust has previously also been successfully performed by Pascucci et al. [22].

The images dating to 2007 and 2012 were used for the preparation of a landscape change map. As they are both dating from the month of May they were more comparable than other possible image combinations (2007-2010 or 2010-2012).

Both images showed confusions between the classes ‘Bare soil’ and ‘Built up/urban’ though they were less significant as in the 2010 images. Therefore the change detected relating to these two classes is not reliable and may be validated by other means (site visit).
The change detection map showed changes in land cover in multiple areas of the image. As most of the land is agricultural and crop rotation might change from one year to the other as well as the timing of ploughing and periods of leaving the land fallow, it cannot be argued that the change of land cover relates to the accident. It can be assumed that some of the land affected is now fallow as remaining toxins impede plant growth and farmers are not likely to use this land for agricultural production any more. On the other hand the lack of cultivation may also have resulted in uncontrolled growth of vegetation elsewhere and therefore a higher level of plant vigour than normally present in May on arable land in this area.

Furthermore it is likely that the normalisation of soil pH values (as previous observations showed) does actually result in a normalisation of plant vigour, while remaining toxic trace elements do not have a comparably strong effect on plant growth.

![Figure 3. Landscape change map May 2007-May 2012. Areas that have changed are marked in white while persisting land cover is shown in colour. The most stable land cover classes are forest (dark green) and water (blue). The bauxite residue reservoir is shown in red. The transparent red area shows the extent of the spill from October 2010.](image)

A comparison and visual interpretation of the change of built up land and water surfaces between 2010 and 2012 (GeoEye/IKONOS images) in the area of the village of Devecser reveals new structures introduced on formerly unbuilt land in the Southern part of the settlement and water features introduced in a previously built up area North of the village centre in an area affected by the spill. This observation can be validated using the information collected in situ during the site visit.
3.2 Integration of qualitative ground truth – peoples’ perception

First results of a literature review on ways of integrating these results with participatory GIS methods that is currently being prepared imply several methods for mapping social aspects are suitable to be used jointly and combined with the change detection maps.

Public participation in general is more and more used within different disciplines. In planning it may range from informing the public to using local knowledge by approaching members of a community as consultants or even to planning strategies that involve prospective users of the planned space directly in the process of drafting solutions for spatial issues of all kinds concerning the community. [23]

Participatory GIS as a tool integrates methods of public participation in Geographic Information Systems (GIS). It makes use of GIS software to map and analyse various inputs from experts or lay people.

Dunn [24] notes “the growth of a more socially aware type of GIS which gives greater privilege and legitimacy to local or indigenous spatial knowledge” referring to the development of PGIS.

While the integration of quantitative spatial data using GIS can be considered common practice in processing EO data, the integration of participatory or qualitative spatially referenced data is not typical.

The literature review showed that in previous research several methods have been used that illustrate how spatially referenced data can be collected - though only few show how this data can be integrated with results from remote sensing analyses [9]. These methods are put in practice based on concepts that describe peoples’ perception and/or the relationship to their environment.

3.2.1 Concepts

Concepts found in literature include individual preference described by Witcher [25], the concept of place attachment and place dependence (Bogac [26]) and landscape values by Raymond and Brown [10] and there are numerous other concepts. Here only some examples shall be given to illustrate possible starting points for the methods described below.

Witcher stresses the dichotomy of GIS analysis of physical landscapes and landscape perception in the field of archaeology. He sees the public as consultants that help understand landscape change.
His concept of landscape perception relates to the definition of Meier and Bucher [8] mentioned earlier as one out of three concepts: landscape in its physical state, the image of the landscape and landscape dynamics. The second concept - the image of the landscape - describes the landscape as perceived in the context of memories, perception of all sense and aesthetics including individual and collective awareness.

Bogac describes how place attachment and place dependence changed for members of a Turkish Cypriot community that was involuntarily relocated when conflicts led to the division of the island in 1974. In sociology the concept of “place attachment” describes the (positive) bonds of an individual or group with their physical environment. Two aspects of place attachment are placed dependence and place identity. The first term describes functional attachment and is related to conditions that allow desired activities. The latter term relates to emotional bonds and meaning of a place [27].

Raymond and Browns’ approach includes the concept of place attachment and adds landscape values in order to receive an assessment of the space, identifying special or favourite places of local residents – thus places that locals allocate a certain quality to, in the respect of recreation for example and on the other hand development places were pointed out – areas that need to be improved.

3.2.2 Methods

The methods used by the authors mentioned above include interviews (all) observations (Witcher) drawing maps with residents (Bogac) and mapping places using stickers representing values (Raymond and Brown).

In the latter case this information was then transferred to a GIS were a hot spot analysis of point accumulations was performed.

3.2.3 Summary

The production of maps of peoples’ perception (e.g. by positioning stickers or other items on a map) is a method that can easily be transferred to other situations and later on be processed in a GIS along with other data. The non-verbal nature of this method may be beneficial if language barriers exist. Nonetheless initial interviews that include questions about general socio-demographics as well as interrogation related to the chosen concept such as place attachment and dependence have been used in all examples given above and can be seen as a crucial step.

The integration of PGIS methods therefore should be based on one or more concepts of perception and rely on one or several of the participatory mapping methods that require different ways of processing data ranging from simple map overlay to hot spot analyses.

For the present landscape change analysis mapping e.g. favourite places of local residents before and after the disaster occurred, their analysis in GIS e.g. using a hot spot analysis and a comparison with areas of land cover change identified on the EO images could be one option out of many to reach an integration of EO data and qualitative information collected on site using PGIS.

4. Conclusions

The land cover change analysis of the study area in Vezprem province affected by the red sludge spill did not show areas of change clearly to be defined. Nevertheless some areas of settlement change could be identified in and outside the area affected by the disaster. The extent of the flood could be clearly delineated based on its spectral profile using land cover classification.

These results pass more emphasis on to the possibility of an integration of qualitative ground truth that may improve and explain the results of a landscape change analysis and provides additional information on local landscape change and processes present after a disaster occurs.
Next to the incorporation of qualitative ground truth methods such as object based classification or object based image analysis (OBIA) are techniques that might allow to overcome the problem of diverse imagery and confusion of built up areas and bare soil as a major source of error in the present analysis.

E.g. Pu et al. [28] compared one pixel-based and on object-based Artificial Neural Network (ANN) classification of the same IKONOS image for urban land cover classification and found accuracies of the object-based classification being higher. They say the variability in land cover units or so called “salt and pepper effect” occurring in high resolution data classification can best be eliminated with this method.

Concluding from this finding in future research on the present study area one may make use of OBIA and might furthermore integrate more vegetation indices to enhance results.

The integration of qualitative ground truth that could only be described theoretically in the present work (due to the limited framework of a Masters’ thesis) may provide the basis for a development and application of a concept for including local peoples’ perception that may improve results in addition to the suggested methods of processing EO data.

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