

MODEL-BASED ESTIMATION OF IMPERVIOUS SURFACE BY APPLICATION OF SUPPORT VECTOR MACHINES

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ABSTRACT:

Due to its various negative consequences impervious surface is increasingly recognized as a key issue in assessing the sustainability of land use – particularly in urban environments. In Germany, a regional or state-wide method for an accurate, fast and cost-effective quantification and assessment of impervious surfaces is still missing. Thus, we researched into the characterization of impervious surfaces based on an automated analysis of Landsat-7 data by means of a model-based estimation with Support Vector Machines (SVM). The approach provides a semi-automated method to model the impervious surface via Landsat data based on an automated training procedure. Additionally, the technique facilitates the supplementation of vector-data in order to enable the consideration of small-scale infrastructure, the aggregation of the gathered information to user-defined spatial units and the combination with socio-economic data. The study area includes the entire region of the German federal state of Bavaria covering an area of 75.500 km². The analysis targets the degree of impervious surface for the total of residential, industrial and transport areas as well as the area of impervious surface per head. This information is referenced to various administrative and landscape-related units. The validation of the modeled degree of impervious surface based on the Landsat data shows a mean absolute error of 14 percent. The combination of the impervious surface raster and vector information on linear infrastructure such as roads and railways showed a difference of one percent from according reference information. The result of this study documents that the proposed approach is qualified for a highly automated and area-wide mapping of the degree of impervious surface.

1. INTRODUCTION

Most of the developed and emerging nations feature a constantly increasing loss of land resources due to rapidly growing settlements and transport infrastructure. This development is closely associated with various negative consequences for the environment but also for the municipal budgets. Nevertheless, in Germany a regional or state-wide method for the quantification and assessment of impervious surfaces in an accurate, fast and cost-effective way is still missing. Thus, we researched into the characterization of impervious surfaces based on an automated analysis of Landsat-7 data by means of a model-based estimation with Support Vector Machines (SVM) (Vapnik, 1995; Burges, 1998).

So far several approaches towards the characterization of impervious surfaces by means of remote sensing data and digital image analysis have been presented. Braun and Herold (2003) use the correlation between Normalized Difference Vegetation Index (NDVI) and degree of impervious surface to map imperviousness in the region of Bonn, Germany, based on ASTER data. Bauer et al. (2004) correlate information on the greenness derived by tasseled cap transformations of Landsat data with the degree of impervious surface in the Twin Cities, Minnesota. Cablk and Minor (2003) apply a principal component analysis and spatial morphologic operators to Ikonos data for assessments of the impervious surface in urban areas of the Lake Tahoe Basin. Heiden et al. (2003) and Herold et al. (2003) show the high potential of hyperspectral remote sensing systems for qualified analyses of urban surfaces, whereas Schiefer et al. (2006) classify segmented hyperspectral

data from urban areas using support vector machines. Nevertheless, most hyperspectral sensors are still restricted to airborne systems with limited capabilities for state-wide observations. Among a wide range of existing algorithms, sub-pixel classifiers suit very well for assessing the percentage of impervious area within a pixel. Several approaches based on spectral mixture analysis (SMA) (Lu and Weng, 2006), normalized SMA (Wu and Murray, 2003; Yuan and Bauer, 2007) or multiple endmember SMA (Powell et al., 2007) achieved remarkable results.

In the context of the presented study we implemented a stand-alone software which provides a semi-automated method to model the impervious surface based on automated training via SVM. Additionally, the software facilitates the supplementation of vector-data in order to include information on small-scale infrastructure, to aggregate the gathered data to user-defined spatial units and to combine the geo-information on imperviousness with socio-economic data.

The following section introduces the study area and data base, whereas the third chapter contains a description of the methodology. In chapter four the results of this study are discussed. Finally, the conclusions are drawn in section five.

2. DATA BASE AND STUDY AREA

The mapping of impervious surface in Bavaria is based on nine Landsat-7 ETM+ scenes acquired between 09th June 2000 and 24th September 2000 (path 193-195, row 25-27). The Landsat-7

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system records data in a spatial resolution of 30m for seven multispectral bands and 15m ground resolution in a panchromatic channel. The spatial footprint of a Landsat-7 scene covers around 180x180 kilometers whereas the revisit interval amounts to 16 days (USGS, 2007). The data sets used in this study are resampled to a geometric resolution of 25 meters in the multispectral bands and 12.5 meters in the panchromatic channel. The images are atmospherically corrected using the ATCOR-2/3 software (Richter, 2006) and radiometrically adjusted by means of a histogram match. Finally, the images are georectified to coordinates of Universal Transversal Mercator (UTM) and WGS 84.

The Landsat imagery is supplemented by vector data of the German Official Topographic Cartographic Information System (ATKIS). ATKIS is a nation-wide, digital geo-topographic information system in a uniform format (AdV, 2008). In our study we use ATKIS vector data of the Digital Landscape Model (DLM) in a scale of 1: 250.000 in order to focus the analysis on built-up areas (object category 2000) and infrastructure such as roads, railways and channels (object category 3000). After transferring this data to the coordinates of UTM WGS 84 certain object types such as underground and open cast mining, cavity and quarry (object types 2121, 2301) are removed. These regions cover large areas of bare soil or stone which can not be separated properly from impervious surface. Finally, the polygon themes of the categories 2000 and 3000 are merged to form the mask 'potentially impervious area', whereas line features – e.g., streets, railway tracks – were annotated with a type specific width and degree of imperviousness.

In order to afford the automated generation of training data for the modeling process via SVM (chapter three) we utilize a vector data set which provides information on the impervious surface for the municipality of Passau. This reference was created by digitizing impervious surfaces on the basis of orthorectified, aerial images acquired in the year 2000. This data set covers an area of 69 km². The pre-processing of the reference data includes the transformation to the coordinates of UTM WGS 84 and the aggregation to a one meter binary grid (impervious, not impervious).

The study site covers the entire area of Bavaria which represents the largest state in the Federal Republic of Germany. It comprises 12.5 million people distributed over more than 70,000 square kilometers. Bavaria is characterized by an immense diversity of landscapes such as the Alpine region, the foothills, the central massif in Eastern Bavaria and the region of Franconia and Swabia. Due to the European urban conglomerations of Munich and Nuremberg and other major cities like Augsburg, Ingolstadt, Regensburg or Wuerzburg, Bavaria is a growing centre of business and industry. This development generates an enormous pressure on Bavaria's natural resources. In 2005 the loss of natural and agricultural land due to growing settlements and transport infrastructure came up to 15 hectare per day. In total 766.500 hectare – or 11 percent of the state of Bavaria - were occupied by residential, industrial or infrastructural areas.

3. MODELING OF IMPERVIOUSNESS

The assessment of impervious surface includes three main steps: the modeling of impervious surface based on remote sensing data and SVM, the supplementation of this information by line

features providing additional data on small-scale infrastructure that can not be detected via satellite imagery and the aggregation of the combined impervious surface layer to user-defined spatial units such as administrative boundaries of municipalities. In this context the information on impervious surface can also be combined with statistical data, e.g., about the population, in order to define the impervious area per head. The estimation of the degree of impervious surface within each Landsat pixel is performed by means of a training area covering a region of 15x10km within the municipality of Passau. The reference information for the training area is provided by according reference data in form of a manually digitized map of impervious surfaces (see section 2). Based on this binary mask a regression model is calculated. Thereby, the support vector machine correlates the spectral information of all Landsat bands with the degree of impervious surface provided by reference data set. By applying the resulting model to the mosaic of nine Landsat images the degree of impervious surface can be assigned for the area of Bavaria.

In order to accelerate the analysis and – at the same time – improve the accuracy of the modeling, the analysis of the Landsat data is specifically focused on residential, industrial and transport areas. The information on the position and extent of the according regions is provided by the vector data of the German Official Topographic-Cartographic Information System (ATKIS). At the same time this vector data serves as a basis for the integration of linear infrastructure such as country roads or railway tracks which would not be detected properly with the Landsat data. Therefore, the impervious surface raster generated on the basis of the Landsat data is combined with ATKIS vector information on linear infrastructure such as roads and railways (object categories 3100 and 3200) (see Figure. 1). Thereby each category is assigned with a specific width and imperviousness.

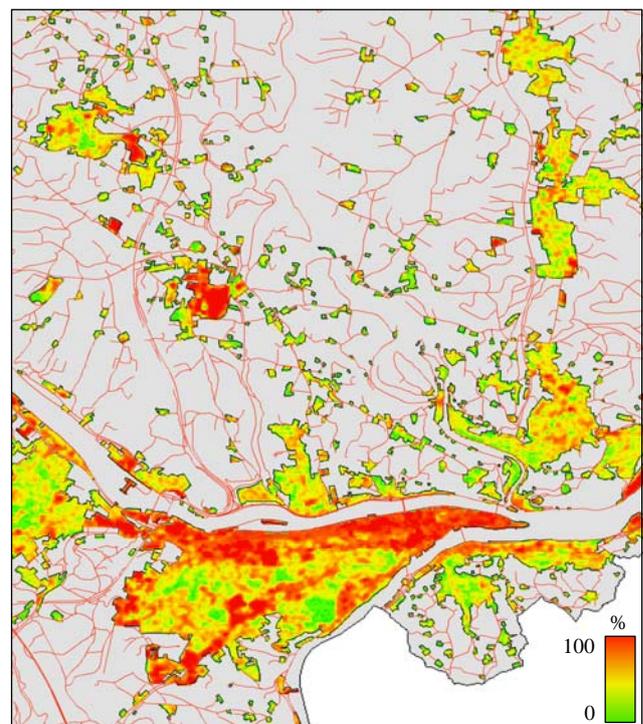


Figure 1. Combined product of impervious surface raster derived from Landsat imagery and information on linear infrastructure provided by ATKIS vector data.

By combining the impervious surface raster derived from the Landsat data with the vector information on linear infrastructure, the impervious surface for entire Bavaria can be calculated. This information is finally aggregated to various administrative and landscape-related units of Bavaria (see Figure. 2).

4. RESULTS

The validation of the impervious surface raster generated on the basis of the Landsat data via 17.800 reference points derived from the reference map of the municipality of Passau shows a mean absolute error of 14 percent and – due to a Gaussian distribution of the error around the zero value – a mean error of 0.9 percent. Moreover the plausibility is verified by means of data on the degree of impervious surface provided on a block by block basis for the city of Munich. Here, the reference data features a mean degree of imperviousness of 54 percent whereas the modeled degree of impervious surface comes up to 50 percent. The final product – representing the combination of the impervious surface raster and the linear infrastructure such as roads and railways provided by the ATKIS data – is also validated on the basis of the Passau reference map. For that purpose the proportion of impervious surface given by the reference data set is compared to the proportion estimated on the basis of the modeling. According to the reference information 15 percent of the municipality is covered by impervious surface, whereas the model-based estimation

features a value of 16 percent. Additionally, the plausibility was checked by comparing the modeled degree of impervious surface for the total of residential, industrial and transport areas in Bavaria with an according value that was estimated by means of a novel approach based on the analysis of official statistics (Frie and Hensel, 2007). While the statistical approach indicates that 46.3 percent of the residential, industrial and transport areas in Bavaria fall upon impervious surface the proposed approach based on remote sensing imagery and ATKIS data provides a value of 47.2 percent.

Discrepancies between the estimated impervious surface and the true situation still emerge in the context of confusions with certain bare soils whose spectral signature barely differs from these of impervious materials such as concrete, bricks or stones. Further errors originate from shadowing effects or dense tree coverage hiding impervious surfaces located underneath.

5. CONCLUSIONS

The result of this study documents that the proposed approach is qualified for an area-wide mapping of the degree of impervious surface. The advantage of the presented technique lies in the ability of a fast, area-wide and at the same time spatially detailed and accurate mapping of impervious surfaces – requirements that can not be met with existing reporting based on official statistics or survey. The proposed method allows describing the structure and distribution of sealed surfaces even

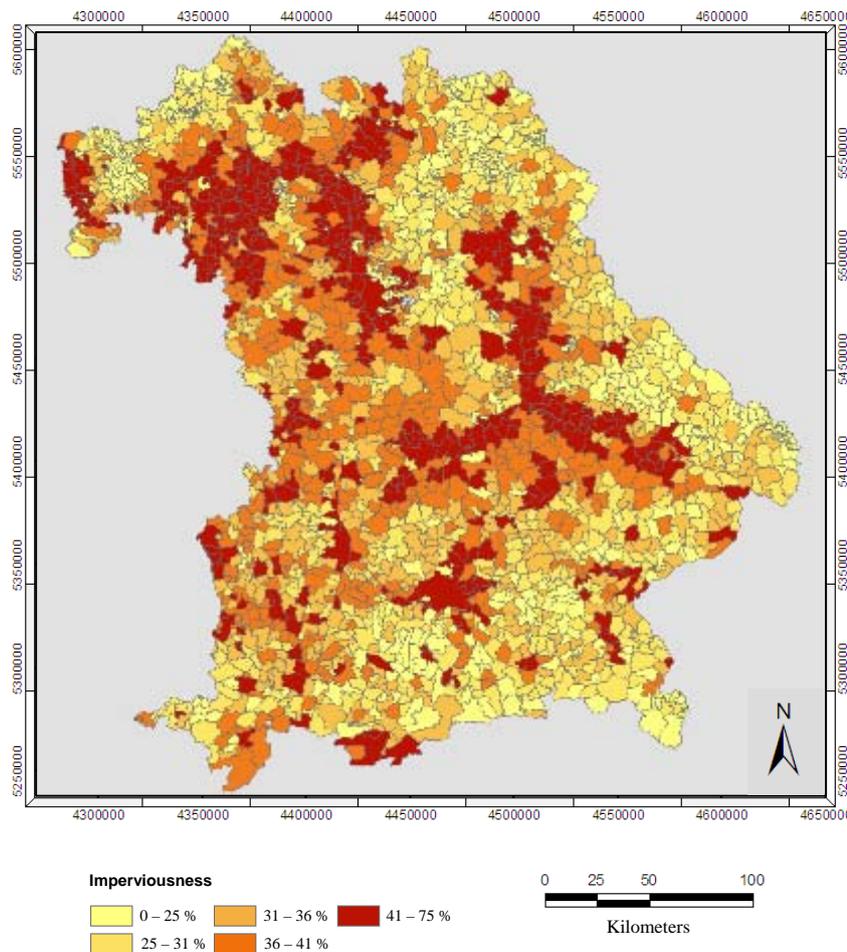


Figure 2. Degree of impervious surface for total of residential, industrial and transport areas calculated on the basis of the administrative units of the Bavarian municipalities.

within the perimeter of villages or towns. Moreover, the information on impervious surface can be addressed to arbitrary spatial or administrative units. The approach also guarantees the mapping and assessment of impervious surfaces by constant and objective rules - a key issue in view of regional or national surveys. Finally, the design of the developed approach facilitates the use of very high resolution data such as Ikonos and QuickBird imagery or aerial photographs instead of Landsat data. Thus, the level of detail can be further increased in order to meet the high demands of municipalities with respect to the spatial resolution of according analyses.

Nevertheless, the application of existing models to identical imagery of another region or with another acquisition date requires a strict radiometric standardization of the satellite data - e.g., by means of atmospheric correction and histogram matching. This procedure still requires a significant amount of user interaction. The transferability of a generated model to a completely different cultural or natural area might be limited because the spectral characteristics of the land cover might differ too drastically from the characteristics of the land cover types used for the generation of the original model. In this case new training data featuring the respective region must be considered in order to generate a locally appropriate model. Nevertheless, this study could provide spatially detailed and precise data on the characteristics and distribution of impervious surfaces for an entire German federal state and its administrative and landscape-related subdivisions. Thus, this approach might serve as a helpful instrument in the context of future discussions on the assessment of sustainable urban development.

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