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Application of Landsat Imagery Based Vegetation Indices to Imperviousness Index Mapping**

1. Introduction

The imperviousness index for a given area can be defined as a ratio of the impervious surfaces area to the total considered area. Impervious surfaces are defined as any surface that rainfall cannot infiltrate, like rooftops, streets, drives, car parks etc. Rising percent of such surfaces indicates increase in the amount of built--up areas within the region under consideration. Obviously, it influences many of the functions of environment. Ground water recharge or rainfall-runoff transformation can be mentioned here as examples. Higher percentage of impervious surfaces leads to a lower level of ground water recharge, larger surface runoff and higher frequency of floods [6]. It has also been noticed that the rate of imperviousness within a catchment has influence on the quality of water in the river [1]. As a result, the imperviousness index is considered one of the main indicators of environmental quality [1].

There are many methods applied to obtain maps of impervious surfaces. The most accurate but also labour-intensive and costly are the ones based on ground surveying (e.g. tachymetry or GPS). Another group comprises of methods where the imperviousness index is assessed with the use of easier accessible data. A standard example is the method where given classes of land use are applied mean imperviousness index. Other methods are based on the correlation between the area of impervious surfaces and other indices like the density of population, number of households, rate of employment or distance from the city centre [4].

Between these two main groups of methods there exist others which apply remote sensing data like aerial or satellite images. Still, there is possible a further

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** The investigation has been made within the scope of research project AGH 10.10.150.897

division within this group. One can distinguish techniques based on photo interpretation and digital processing of remote sensed data. Two examples of photo interpretation technique are vectorisation and sampling. In the latter one, a sample grid is overlaid on an image. Each point is analysed and categorised as placed on an impervious or permeable surface. Aerial images and high-resolution satellite images are usually used in both cases.

Impervious surface mapping can be also based on digital image processing of both middle- and high-resolution data. The first attempts to make use of the middle-resolution images took place in the 1970s. At the beginning the aim was to categorise different forms of land use such as streets, car parks or buildings. In the recent years we have observed fast developments in this field. New techniques emerged which allow assessing the percentage of the impervious surfaces within one pixel, e.g. spectral mixture analysis [12, 14, 15] and regression trees [16, 17]. In the present study sub-pixel assessment of imperviousness based on vegetation indices has been applied.

The survey was undertaken to assess the applicability of Landsat TM based vegetation indices for impervious surface mapping in Poland. Landsat TM 30-metre resolution multispectral images have been obtained since the 1980s. It is possible to use the images to create maps of imperviousness covering the whole area of Poland for any year of the last two decades. As acquisition of similar images is planned to be continued in the future, they provide an important source of data for land use and land cover monitoring.

2. Applications of Vegetation Indices for Imperviousness Mapping

Vegetation indices are defined as dimensionless, radiometric measures of relative abundance and activity of green vegetation [8]. They can be obtained as images through transforming original spectral bands. Over twenty such transformations have been defined [8]. Their use in imperviousness mapping is based on the assumption that the amounts of green vegetation and the impervious surfaces within the satellite image pixel are related each other. As a result, we have to assume that there exist only two types of land cover – plants and impervious surfaces. Such simplification limits the applicability of this method to urban areas only.

Applicability of vegetation indices to imperviousness mapping has been shown in many studies. For example, Bauer et al. [2] used the Greenness component of Tasselled Cap transformation in their studies of Twin Cities area (Minnesota, USA). The relationship between Landsat Greenness and percent impervious surface area was described by quadratic equation with standard error of 8.1%.

Similar approach was chosen by Bauer *et al.* [3] to map imperviousness for the entire State of Minnesota in 1990 and 2000. Fourteen images were used for each year and standard errors were ranging from 7.7 to 15.9, depending on image. Overall agreement was quite high with standard errors of 11.8 (for year 1990) and 11.7 (for year 2000). Tasselled Cap transformation was also used by Yang and Liu [18] in their studies for Pensacola city (Florida, USA). In this case multiply linear regression model between Brightness and Greenness components and percent impervious surface area was used. The standard error was assessed as 8.4%.

Imperviousness maps based on NDVI index have also been prepared in Germany with the use of ASTER images of 15-metre resolution [5, 11]. Simple linear model of regression was applied. Unfortunately, the authors do not provide information about the possible accuracy of the index. As far as we know, this method of imperviousness mapping has not been tested in Poland yet.

3. Imperviousness Index Estimation

3.1. Data

The City of Cracow (Poland) was chosen as a study area. Landsat TM satellite image taken on 24th August 1996 (Path/Row: 188/25) has been used in the research. The image was orthorectified using the nearest neighbour resampling method.

Obtaining calibration data is the first stage to prepare imperviousness maps in a continuous classification process. These calibration sites have the form of single pixels of middle-resolution satellite image. The percentage of impervious surfaces area is assessed within each pixel, usually through photo interpretation of aerial images or high-resolution satellite images. In the present research there has been used colour orthophotomaps of scale 1:10 000 (pixel size – 0.75 m). The aerial photos were taken in 1997.

3.2. Referential Map of Imperviousness Index

Thirty-four sites (10×10 satellite image pixels each) were chosen to obtain the necessary data for calibration and verification. These fields were located in places of various land use and land cover like urban centre, continuous built-up areas, discontinuous built-up areas, block estates, cemeteries, commercial, industrial and railway areas. For each square a map presenting two kinds of areas – impervious and permeable – was created through photo interpretation.

Imperviousness maps obtained in this way were converted into a raster form. In order to maintain proper accuracy of the results a pixel size of 0.3 m was used.

As the result, each Landsat TM pixel was covered with 10,000 pixels on the impervious surfaces maps.

Processed in such way data provided the basis to prepare the referential map of imperviousness index for each of the thirty-four calibration areas. These maps show the percentage of impervious surfaces area calculated for each pixel of the satellite image.

3.3. Maps of Vegetation Indices

For vegetation index mapping two standard methods have been applied in the present research – NDVI (Normalised Differential Vegetation Index) [13] and Tasselled Cap transformation [9].

NDVI is the most frequently used vegetation index. Its value is assessed on the basis of pixel values in red and near infra-red bands:

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED}) \quad (1)$$

where:

RED – pixel value in red band,
NIR – pixel value in near infra-red band.

Kauth and Thomas [9] proposed Tasselled Cap transformation for Landsat MSS where four new images are obtained from the original spectral bands. One of them can be interpreted as the vegetation index. The equations of Tasselled Cap transformation, suggested by Mather [10] for Landsat TM images, have been used in the present research. The vegetation index model in this case is defined as

$$\begin{aligned} \text{GVI} = &-0.2848(\text{TM1}) - 0.2435(\text{TM2}) - 0.5436(\text{TM3}) + \\ &+ 0.7243(\text{TM4}) + 0.0840(\text{TM5}) - 0.1800(\text{TM7}) \end{aligned} \quad (2)$$

where TM1–TM7 – pixel value for given Landsat TM spectral band.

3.4. Imperviousness Model

Simple regression model was used in the research to define the relation between the value of vegetation index and the imperviousness index:

$$y = \mathrm{a}x + b \quad (3)$$

where:

x – pixel value on the vegetation index image (NDVI, GVI),
y – imperviousness index value,
a, b – coefficients.

The regression was assessed on the basis of 1020 pixels – within each of the 34 calibration areas 30 pixels were randomly selected. Figures 1 and 2 present the regression modelling results.

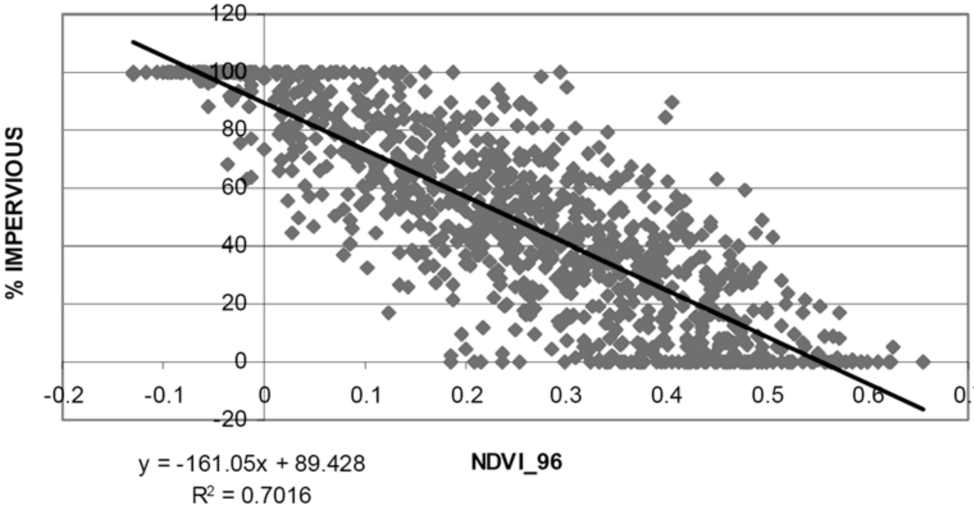

Fig. 1. Linear regression model based on NDVI values

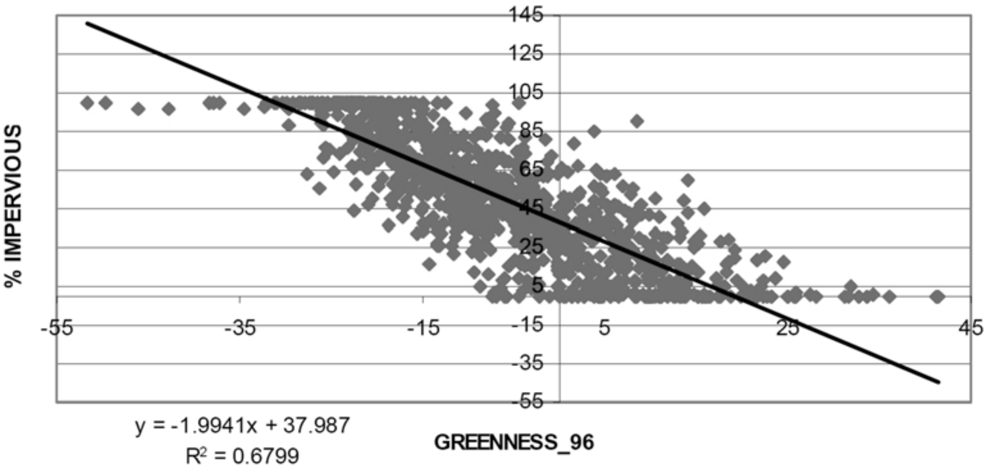

Fig. 2. Linear regression model based on GVI values

Coefficient of determination (R^2) of 0.70 and standard error of 17.8 were calculated for NDVI-based model. For GVI-based regression model the values were 0.68 and 18.4, respectively.

Obtained regression models were used to prepare imperviousness maps. As the application of vegetation index method is limited to urban areas only, the values of imperviousness index were calculated for the developed areas of Cracow derived from KAWK (Computer Atlas of Cracow Province) database. Pixels with regression modelled estimate of imperviousness greater than 100% were reclassified to 100% and those with values less then 0% + to 0%. Figure 3 presents the final map based on NDVI index.

Fig. 3. Imperviousness index map of Cracow based on NDVI index calculated for Landsat TM image taken on 24th August 1996

3.5. Accuracy Assessment

To assess the accuracy of imperviousness index estimation obtained with the use of regression model, its values were compared to the values of the imperviousness index obtained through photo interpretation for 320 pixels which were not used in the process of calibration (40 pixels were randomly selected for each of 8 various types of land cover). Mean error and standard error values have been assessed for all 320 pixels used for the verification and additionally for each land cover type. Table 1 presents the results.

Mean error can be interpreted as a bias (system error) and standard error provides a measure of estimate uncertainty. Both methods gave similar final results. Mean error and standard error values for NDVI-based estimate were assessed as 1.97 and 19.54, respectively. In case of GVI-based models these values were just slightly higher – 2.13 and 20.05. In both cases the value of imperviousness index is somewhat underestimated. The methods resulted in quite large uncertainty of the assessment.

Table 1. Results of the accuracy assessment

Land cover type	NDVI-based imperviousness index [%]				GVI-based imperviousness index [%]			
	Mean value (predicted)	Mean value (measured)	Mean error	Standard error	Mean value (predicted)	Mean value (measured)	Mean error	Standard error
Block estates	43.59	48.87	5.28	18.21	47.80	48.87	1.08	18.28
Cemeteries	34.11	25.92	–8.19	22.48	32.96	25.92	–7.05	22.76
Commercial areas	77.06	86.29	9.23	15.29	78.94	86.29	7.35	16.77
Urban centre	56.13	56.52	0.39	24.57	59.11	56.52	–2.59	23.40
Industrial areas	88.56	90.43	1.87	10.34	77.86	90.43	12.56	10.89
Railway areas	64.28	70.81	6.53	18.17	65.54	70.81	5.27	19.68
Discontinuous built-up	26.29	28.89	2.60	20.80	26.07	28.89	2.82	20.51
Continuous built-up	65.98	64.01	–1.98	17.41	66.40	64.01	–2.39	18.31
All pixels	57.00	58.97	1.97	19.54	56.84	58.97	2.13	20.05

More detailed analysis of the results suggest that there exists a tendency to underestimate the imperviousness index in case of areas where its value is high. The biggest in-plus differences between the mean values of imperviousness index were observed for commercial and industrial areas, where the percentage of impervious areas is the highest. At the same time, these areas have the lowest standard errors.

Six out of 34 areas used as testing sites in presented study were also the testing areas in the experimental research held by Hejmanowska *et al.* [7]. Its aim was to assess the accuracy of photo interpretation of the impervious surfaces on high-resolution satellite images. There was also assessed the accuracy of the imperviousness index derived from Ikonos images (1m resolution) for simulated areas on

Landsat TM pixels (30 m × 30 m). System and standard errors were respectively 10 and 18% for panchromatic images and 4 and 12% for colour (pan-sharpened) images. The method of imperviousness index estimation based on Landsat TM images gave the comparable standard error to photo interpretation of high-resolution panchromatic satellite image, but with much lower mean (system) error.

The accuracy of imperviousness index obtained in our study differs from the ones presented in quoted papers [2, 3, 18]. One of possible reasons may be seen in fact that in Poland we more often deal with bare soil within urban areas. This is especially true in case of discontinuous built-up areas and cemeteries, both having low accuracy of predicted imperviousness index. Other potential causes of the differences will be considered in further research.

4. Conclusions

The method of imperviousness index mapping based on vegetation indices calculated from middle-resolution satellite image was tested in presented study. The method is simple, fast and relatively cheap for large areas and has comparatively similar accuracy as in case of photo interpretation of high-resolution panchromatic satellite images. With the use of Landsat TM images it is possible to provide imperviousness index maps for any area of Poland for any time moment during the last twenty years, providing the calibration data are available. Fortunately, at least two sets of data can be used for the majority of Poland – PHARE aerial images from the 1990s and recent LPIS orthophotomaps. As processes of urbanisation (and especially the urban sprawl phenomena) have accelerated in recent years, imperviousness index maps obtained with remote sensing methods can be seen as important tool to monitor changes of land cover in the urban areas. The approach is worth our interest and further research.

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