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THE ASSESSMENT OF THE IMPACT INDUCED BY THE INCREASE OF IMPERVIOUS AREAS ON SURFACE RUNOFF. CASE STUDY THE CITY OF CLUJ-NAPOCA, ROMANIA

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Abstract: The impervious surfaces in the city of Cluj-Napoca have experienced a continuous growth over time. These surfaces reduce the infiltration of the water into the soil, they alter the natural direction of the flow paths they lead to the increase in runoff volume and to the reduction of water quality. In the present paper we aimed to evaluate the hydrologic response to the spatial and temporal variability of impervious surfaces, for a subwatershed in the city of Cluj-Napoca. The variability of impervious surfaces was identified for the period 1986-2014 on the basis of remote sensing, and their impact on surface runoff was assessed by means of a hydrological modelling. The results have shown an increase in the peak flow along with the increase in the impervious surfaces during the period analysed. These results point out that the impervious surfaces directly influence the runoff volume, being an important variable in managing storm water.

Keywords: impervious surfaces, rainfall-runoff model, Landsat, HEC-HMS, Cluj-Napoca.

1. INTRODUCTION

The population increase in Cluj-Napoca over time has led to the expansion of urban space and also built-up areas. This expansion of built-up areas visibly influenced the use of land in the outskirts of the city, many agricultural or wooded areas being converted to residential, industrial or commercial areas.

In the present study we sought to identify impervious surfaces variability over time and the induced impact on surface runoff. Impervious surfaces lead to the decrease of water quality, the increase in the runoff volume and also the increase of the potential for urban flooding.

In order to identify the variability of impervious surfaces over time in Cluj-Napoca, we resorted to the use of remote sensing. Remote sensing allows quickly obtaining information concerning the structure and expansion of the city over time. A number of studies have demonstrated the usefulness of remote sensing data for estimating urban impervious surfaces (Deng et al., 2012; Dougherty et al., 2004; Falcone & Gomez, 2005; Hodgson et al., 2003; Liu et al., 2013; Lu & Weng, 2006; Lu et al., 2008; Lu & Weng, 2009; Lu et al., 2012; Shahtahmassebi et al., 2012; Weng, 2012; Xu, 2007; Xu, 2010; Yuan & Bauer, 2007; Yuan et al., 2008; Zhou & Wang, 2008). Among the methods widely used to extract impervious surfaces we could recall the Linear Spectral Mixture Analysis method (LSMA) (Deng et al., 2012; Lu & Weng, 2006; Lu et al., 2008; Lu & Weng, 2009; Lu et al., 2012; Yuan & Bauer, 2007), Maximum Likelihood (Hodgson et al., 2003; Parece & Campbell, 2013; Weng, 2001; Xu, 2007); MESMA-Multiple Endmember Spectral Mixture Analysis technique (Shahtahmassebi et al., 2012).

In the present study we resorted to the use of the Maximum Likelihood supervised classification method to estimate the evolution of impervious surfaces over time in Cluj-Napoca. This method is a widely used one in extracting impervious surfaces within an urban area.

In order to assess the impact induced by the increase of the impervious surfaces on runoff, we used the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model. This model allowed us to simulate the hydrologic response to the variability of the surface nature during 1986-2014.

The HEC-HMS model was used by Ahn (2007) in assessing the impact induced by the changes in land cover on the hydrological regime, by Rose (2010) to assess a series of techniques to reduce the impact of urbanization and by Emerson et al., (2003) in assessing the effect of detention basins on storm water runoff regimes.

2. DESCRIPTION OF THE STUDY AREA

In order to assess the effects the spatial and temporal variability of the impervious surfaces have on surface runoff, in this study the applications were carried out on subwatershed located in the south central of Cluj-Napoca (Fig. 1). This subwatershed analysed in the study was defined using the Hec-GeoHMS extension on the basis of Digital Elevation Model with a resolution of 5 m, obtained on the basis of 1: 5000 topographic Plans.

The analysed subwatershed has a surface of 1.54 km² and was mainly chosen due to the significant changes over time in this area in terms of land cover type.

3. METHODOLOGY

In order to estimate the hydrological response to the variability of impervious surfaces in the analysed period, it was necessary to acquire and process a complex set of data and to choose the right methods. The evaluation of the hydrological response in this study required a complex modelling between the variability of the type land cover and rainfall.

3.1 The required input data

The identification of the changes occurred over time in terms of the type of land cover in Cluj-Napoca was done based on data obtained through remote sensing. There are various sources of data available that can be obtained through remote sensing, on the basis of which impervious surfaces can be extracted, with low, medium or high resolution.

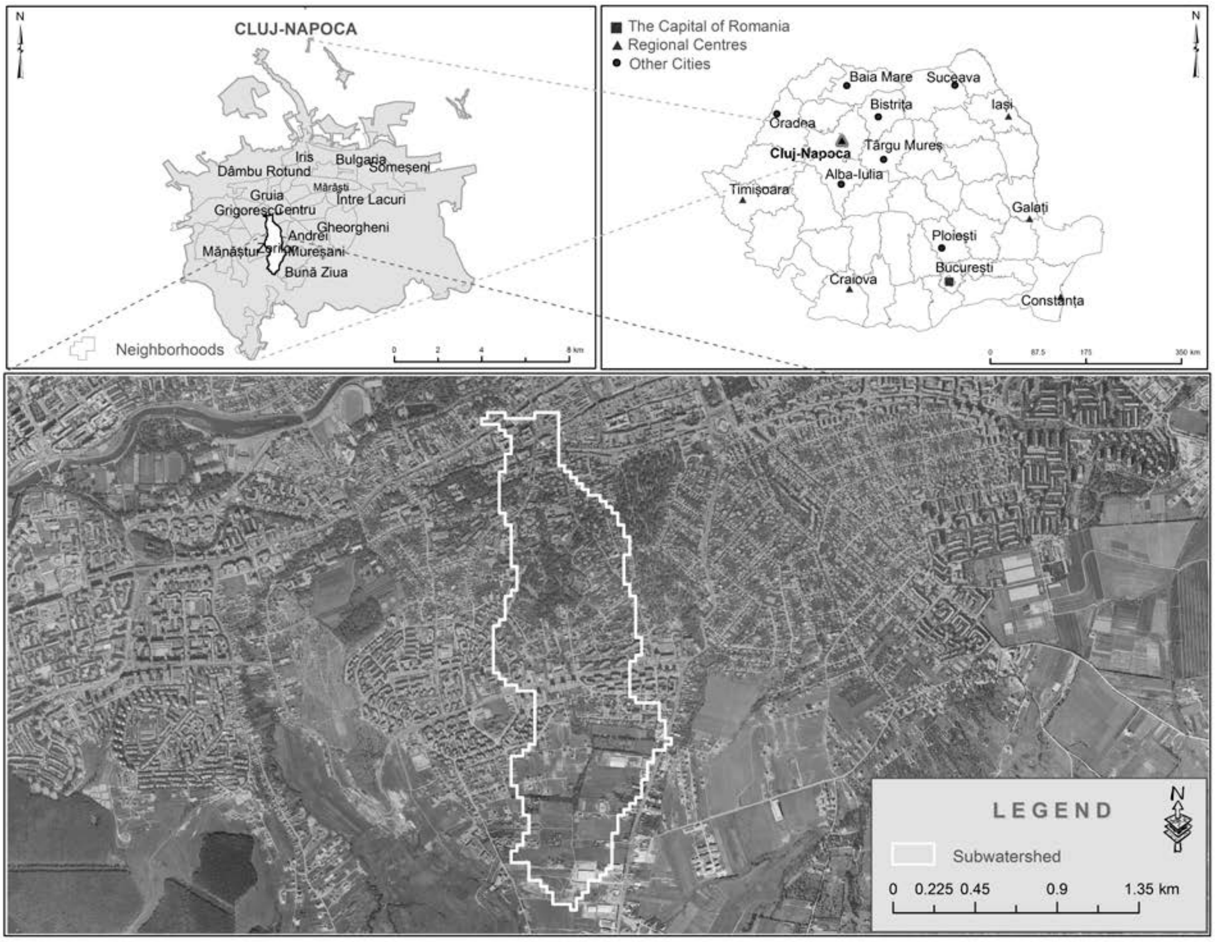

Figure 1. Location of the subwatershed in the country and in the city.

Among the high-resolution data we could remember those derived from QuickBird or IKONOS satellites, and among the category of those with medium resolution, the data derived from the Landsat and Terra ASTER satellite. High resolution satellite images can provide us high accuracy results, only that they cannot be acquired for free. Therefore, in this study, we resorted to using Landsat images, because it required no acquisition costs and because of the large existing archive of images.

In order to detect changes in the expansion of urban areas for the period 1986-2014 four Landsat scenes were selected at pre-processing Level 1, corresponding to the spring-summer season (Path 185 / Row 27). These scenes were selected from images Landsat 5 (August 8, 1986), Landsat 7 (April 21, 1993; August 28, 2002) and Landsat 8 (March 14, 2014). Thus six bands were used, respectively the bands 1-5 and 7 corresponding to the images Landsat 5 and Landsat 7, respectively bands 2-7 for Landsat 8, all with a spatial resolution of 30 m. For the validation of the results Google Earth image archive was used for the years 2002 and 2014.

The evaluation of the hydrologic response to the spatial variability of the impervious surfaces was achieved by modelling the rainfall-runoff process in the analysed subwatershed, based on a series of daily recorded rainfall values (April 11, 2014 - April 17, 2014). These daily precipitation data were obtained from NCDC (National Climatic Data Center). Due to the relatively small surface area of the study it was considered that the rainfall was uniformly distributed on the surface of the subwatershed. In addition to these data it was necessary to assign the average Curve Number for the analysed subwatershed for each reference year separately. The Curve Number was determined on the basis of the information regarding land use types (extracted on the basis of satellite images) and the type of soil for each reference year separately.

3.2. Selection of the methods

3.2.1. Estimation of impervious surfaces

Before applying a method to extract urban impervious surfaces, the acquired images type DN (Digital Numbers) required conversion to reflectance or radiance. In this study we used the calibration of the images in reflectance and it was performed using the software ENVI 5.1. Thus the images from type DN values were calibrated in TOA reflectance and, subsequently, in surface reflectance using the Dark Object Subtraction algorithm (DOS), thus eliminating the atmospheric effects.

In order to extract impervious surfaces on the basis of calibrated images we can use several methods of supervised classification, unsupervised classification or logic calculation. The purpose of using one of these methods is to achieve results close to reality, meaning an overall accuracy as high as possible. In this study, in order to extract impervious surfaces, we resorted to using a supervised classification method.

In order to find the most suitable method of supervised classification, that will allow us to obtain a high accuracy for the entire study area, first we applied four methods, widely used in extracting impervious urban surfaces namely the supervised classification Maximum-Likelihood, Mahalanobis Distance, Neural Networks and Support Vector Machine. Comparing the results obtained for the four mentioned methods showed that the best classification accuracy of the result classification is given by the method Maximum-Likelihood (96 %), which allowed us to obtain a validation in the field also high. This classification is a simple one which is based on training regions previously chosen, and in this study this enabled us to obtain results quite close to reality for all four reference years. After running the classification algorithm we obtained a thematic map corresponding to the four training regions chosen (forest, vegetation, soil and impervious surfaces) (Fig. 2). Later forest, vegetation and soil classes were grouped into pervious surfaces which enabled us to obtain a thematic map consisting of two classes: pervious and impervious. These two classes were subjected to the validation process on the basis of a number of 290 reference points, using Google Earth image archive.

The validation results have shown a good accuracy of the classification process which corresponds in a high proportion to the truth in the field, confirmed by high values of the accuracy of 90.34% for 2014, respectively 93.22% for 2002. These values indicate that the results obtained are accurate and can be used in a further study.

3.2.2. Choosing the hydrological model

The changes occurred at ground surface are reflected in the modification of water quality, in the increase of peak flow, of the runoff volume and of the watershed response (Ahn, 2007). To estimate the hydrological response to the different changes in the manner of field coverage from this period, it was necessary to choose an appropriate hydrological model. The HEC-HMS hydrological model was chosen to simulate the rainfall-runoff process based on data concerning the land cover type during 1986-2014.

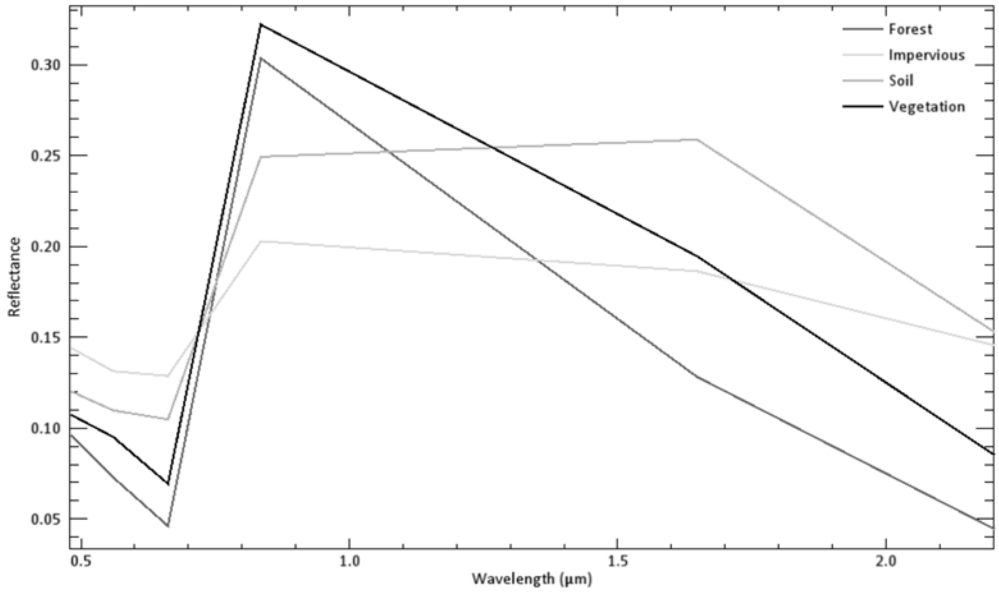

Figure 2. Spectral signatures obtained for the used training regions. Reference image 2002.

HEC-HMS was developed by the U.S. Army Corps of Engineers and is widely used in simulations of rainfall-runoff process in natural watersheds, but also in the small, urban ones. For this study, within the HEC-HMS models we have chosen the model to compute runoff volume and the model of direct runoff to assess the hydrological response to the variability of the nature of the areas for the period 1986-2014.

Within the study the simulation of the runoff volume was based on the SCS CN loss method. This model required as input parameters, in addition to the precipitation data, the average CN for subwatershed and the average percentage of impervious surfaces. The average percentage of impervious surfaces was calculated based on remote sensing data for each individual year. The SCS CN method is described as follows (USACE, 2000):

$$P_e = \frac{(P - I_a)^2}{(P - I_a) + S} \quad (1)$$

Where:

P_e - accumulated precipitation excess at time *t*

P - accumulated rainfall depth at time *t*

S - potential maximum retention

I_a - the initial abstraction

The initial abstraction (I_a) includes the water retained in surface depressions, intercepted by vegetation, infiltrated and evaporated, i.e. loss before the start of the runoff. The initial abstraction I_a is approximated by the following equation:

$$I_a = 0.2S \quad (2)$$

Parameter estimation of water retention is based on the formula:

$$S = \left(\frac{1000}{CN} - 10\right) \quad (3)$$

The Curve Number Index (CN) is assigned on the basis of tables depending on the type of soil and the land use data. This index reflects the potential of the drain water on different lands and may range from 0-100. The lowest values of the index correspond to pervious surfaces, and the highest to impervious surfaces.

The transformation of the precipitation excess into direct runoff can be achieved on the basis of an empirical model (unit hydrograph model) or a conceptual model (kinematic-wave model). In the present study we have chosen an empirical model, SCS Unit Hydrograph transform method. This model determines the water volume that drains at ground surface after the soil is saturated, that is it transforms precipitation excess into runoff. The input parameters of the model, the lag time (*t lag*) and the subwatershed area, were determined using HEC-GeoHMS.

On the basis of the lag time (*t lag*) expressed in hours, the time of concentration (*Tc*) was calculated, corresponding to the subwatershed, thus (USACE, 2000; Győri & Haidu, 2011):

$$t_{lag} = 0.6 \times T_c \quad (4)$$

The time of peak, *Tp* was calculated as:

$$T_p = \frac{\Delta t}{2} + t_{lag} \qquad (5)$$

Where:

Δt - the excess precipitation duration

t_{lag} - the basin lag

The peak of the Unit Hydrograph (*Up*) was calculated as:

$$U_p = 2.08 \frac{A}{T_p} \qquad (6)$$

Where: A – subwatershed area

Thus, on the basis of the characteristics and input parameters, we modelled the runoff volume using the SCS CN loss method and, on the basis of the SCS Unit Hydrograph method, the direct runoff.

4. HYDROLOGICAL RESPONSE TO THE SPATIAL-TEMPORAL VARIABILITY OF IMPERVIOUS SURFACES

The simulation results for each reference year separately for the analysed subwatershed showed differences in the total runoff volume, the values of the peak flow and the total loss. The results of the simulations showed a trend to increase the peak flows, while increasing the percentage occupied by impervious surfaces in the four reference years (1986-2014). These results are embodied in the form of hydrographs corresponding to each reference year separately (Fig. 3).

The impervious surfaces within the analysed subwatershed have increased from 41.7% in 1986 to 76.1% in 2014. These increases in impervious surfaces within the subwatershed were due, mainly, to the expansion of construction areas, amid increasing population density from the study area. Thus, many green areas have been replaced with built areas, leading to a decrease in pervious surfaces and an increase in impervious surfaces.

These increases in impervious surfaces led to an increase of the total runoff volume in the period 1986-2014. The statistical relationship between these two variables, total runoff and the average percentage of impervious surfaces in the subwatershed can be seen on the regression line in Figure 4. The intensity of the linear dependence between two variables was determined using Pearson's correlation coefficient, it being 0.99. The determination coefficient of 0.9969 indicates that the impervious surfaces (X) explain variable variation (Y) total runoff volume in a ratio of 99 %.

Across the pervious surfaces, some of the water from rainfall infiltrates, evaporates or accumulates on the surface of the land in the form of small depression areas. On the background of decreasing permeable surfaces from the study area, the total loss shows a downward trend along with the increase of the impervious surfaces. Research of statistical relationship between the variable impervious surfaces and the total loss has revealed a linear dependence between them.

On the correlation graph it can be seen that, with the increase of the impervious surfaces, the total loss values within the subwatershed decrease simultaneously (Fig. 5). The determination coefficient of 0.9968 indicates that the variable (X) the percentage of impervious surfaces explains the variable variation (Y) total loss in proportion of 99%.

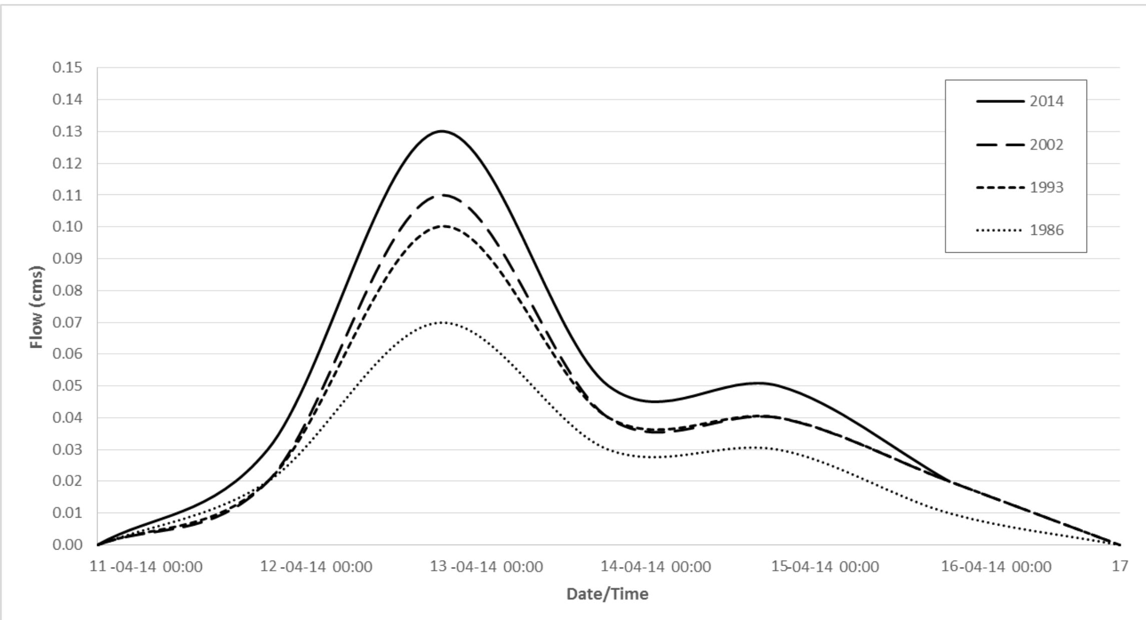

Figure 3. The series of hydrographs results for the analysed subwatershed (1986-2014).

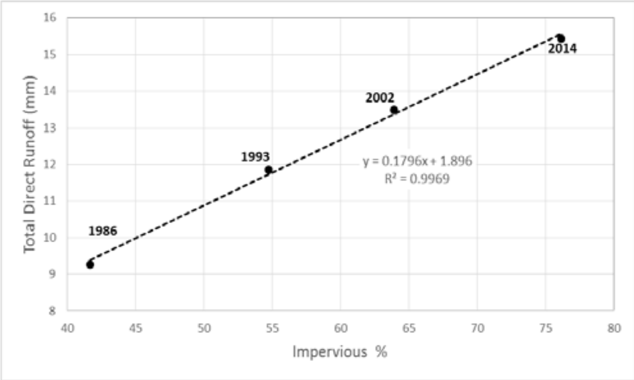

Figure 4. The relationship between impervious surfaces and the total runoff (1986-2014).

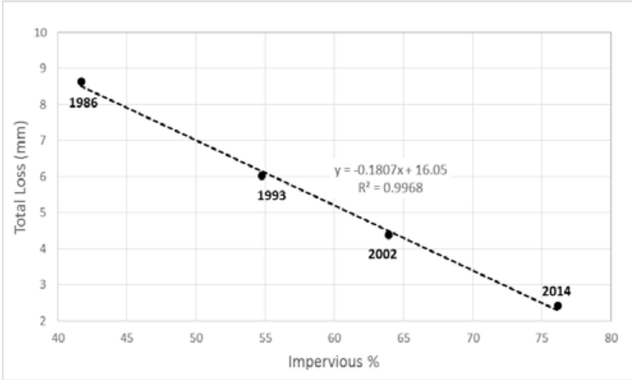

Figure 5. The relationship between impervious surfaces and the total loss (1986-2014).

5. CONCLUSIONS

The data obtained through remote sensing and the Maximum Likelihood classification method, have enabled us to obtain information on the nature of the surfaces in the area of study for the year 1986, 1993, 2002 and 2014. This information enabled us to analyse the variability of both the spatial and temporal nature of the surfaces in the analysed subwatershed. The results have shown an increase of the impervious surfaces in the analysed subwatershed from 41.7% in 1986 to 76.1% in 2014.

The increase of the impervious surfaces within the study area has directly affected the peak flow, the total runoff volume and the total loss in the period 1986-2014. The hydrographs resulting for each individual year have shown an increase in peak flows, along with the increase of the impervious surfaces. The research of the statistical relationship between the percentage of the impervious surfaces and the total runoff volume, respectively the total loss, for each reference year separately, revealed a strong link between these variables.

In order to reduce the runoff, in the future some sustainable solutions should be implemented by local authorities, such as paving sidewalks and parking facilities with pervious concrete, the implementation of water collection techniques, respectively expanding urban green spaces.

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