3D GIS analysis of PSInSAR data as a source of information in monitoring of areas endangered by terrain deformations

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Summary

Properly selected methods of dynamics and range of ground displacement monitoring can be fruitful in environmental protection. One of very important techniques is satellite radar interferometry for permanent scatterer - PSInSAR. It gives us possibility to measure small, long period ground deformations which can be caused by human activities (e.g. water pumping, coal exploitation, roads use) or naturally occurring (neotectonic movements, landslides). Long period ground deformations can be dangerous for surface and subsurface infrastructure.

In this article the GIS methods were used to analyze the PSInSAR data. This analysis includes the study of the ground displacements in space and time. In order to do this work the ortophotomap and topography map were used. A vector map, which was obtained by digitalizing the ortophotomap, was used in the analysis. The GIS analysis of PSInSAR data gives us possibilities to study stability of ground during the last several years. This analysis derives information which are very important while making decisions aimed to protect surface and subsurface infrastructure in areas threatened by terrain deformations. The results of analysis are also important for planning the land development.

Key words: interferometry, PSInSAR, GIS, ground deformation

Introduction

The ground deformations, with different rates and intensities, occur in many regions in Poland. They can have natural or anthropological character. The explanation of the origin and mechanism of these ground displacements is very important while making decisions aimed to protect surface and subsurface infrastructure. To fulfill this requirement, the permanent monitoring of unstable areas is necessary. The measurements of ground deformations can be performed using different methods. In Poland the most common method is levelling. The development of satellite radar interferometry derives techniques which provide very precise measurements of ground displacements for large areas. One of these techniques is PSInSAR (Permanent Scatterer Interferometry Synthetic Aperture Radar) method, which derives information about small, long period displacements of points which are stable radar targets [4].

In order to perform effective monitoring of unstable areas, except measurements methods selection, we have to work out the rules of analysis of data which are derived by these methods. The schemes and algorithms have to take into account the spatial character of data and their dynamics changes in time. In case of analysis of PSInSAR data the good solution is to use the GIS (Geographic Information System) tools and methods. Integration of the results of geostatistical analysis of PSInSAR data with different measurements (e.g. leveling, InSAR data) enables to monitor the unstable areas in more efficient way.

Description of PSInSAR technique

The PSInSAR method is an improvement of widely uses InSAR (Interferometry Synthetic Aperture Radar) technique [7, 8]. PSInSAR technique exploits dozens of satellite radar images in order to identify the stable radar targets so called PS (Permanent Scatterer) points. These points have stable phases and amplitudes of backscattered radar signal in each exploited radar image and they correspond very well with ground development (e.g. buildings, bridge, viaduct, outcrops and lanterns). For each PS point the value of average annual motion rate and coherence coefficient of radar signal are determined. In PSInSAR technique we use the archival radar images and we can measure the values of previous ground deformations. It is very important that this technique enables monitoring of large areas and derives dense, irregular grid of PS points (for urban areas the density of PS points can be higher then 100 PS/km^2). PSInSAR method can be also used to study the stability of individual buildings. The accuracy of this technique is very good. When we use more than thirty radar images we can detect ground deformations up to 0.1 mm/yr. The main limitations of the method are values of ground displacements which can be measured. PSInSAR technique can only detect small ground deformations, not larger than several centimeters per year. This limitation is connected with lengths of radar wanes used by SAR system. PSInSAR also does not give good results in monitoring rural areas, because there are no stable radar targets. There are a lot of published results which showed that PSInSAR technique is very useful in studying the ground deformations caused by e.g. water pumping [2] or volcano activity [3]. This method finds also applicability in monitoring ground movements for mining and postmining areas [5, 6].

Due to mentioned constraints of PSInSAR technique it can not be independent tool for monitoring ground displacements in unstable areas. It is necessary to complements PSInSAR data by other measurements performed using e.g. levelling or InSAR method. We can perform this task using GIS software. Such a solution gives us possibilities to perform efficient analyze for all ground deformations what is necessary to recognition hazards which are caused by these ground movements. Using GIS we can also perform risk analysis connected with ground deformations.

GIS analysis

The development of computer science and systems for database management caused the huge progress of Geographic Information Systems. Nowadays GIS is an irreplaceable tool to work with geographically referenced data [10]. The main aims of GIS are: processing, analysis and visualization of data which come from different sources and have different scales. Using GIS we can modify and present objects that fulfill defined requirements in a very fast way. Geographic information systems are used also in statistical data analysis. Without any doubts we can say that GIS is a system aimed to support decision-making process based on analysis of geographically referenced data.

Nowadays various of commercial and free GIS software tools are available to process raster and vector data. GIS GRASS and SAGA-GIS are very important open source, free software. In this work the analysis of PSInSAR data was performed using commercial ArcGIS software produced by ESRI which is the word leader in GIS. ArcGIS is a complete tool to work with data which are spatial referenced.

Available PSInSAR data

In this work the analysis of PSInSAR data was performed for area which covers approximately 27km^2. It corresponds to part of the Sosnowiec town, which is located in the Dabrowskie Coal Basin. It is industrial region where the coal exploitation was carried on for about two hundred years. This region is particularly threatened by ground deformations. It needs to be stressed that Sosnowiec has the highest values of population density in area of Dabrowskie Coal Basin. Therefore the ground deformation in this region has to be monitoring permanently and very accurately.

The PSInSAR data, which were used in this work, were obtained as a result of radar images processing performed by ERS-1, ERS-2 and ENVISAT satellites which belong to ESA (European Space Agency). In area of study 1701 PS points were identified. For each of them the value of average annual motion rate (between years 1992-2003) and the coherence coefficient were determined. For each PS point the relative ground deformations, which occurred between times when the two SAR images were performed (about 35 days), were also measured. In the figure 1 we can observe that the location of PS points, in the studying area, is very irregular. In the areas without building development the number of PS points is lower then in the built-up areas, where PS points coincide very well with roofs of buildings. We can also select regions without PS points. These regions overlap with e.g. forests, meadow (without stable radar targets) and areas where values of ground deformations are to high to be detected by PSInSAR technique. Average annual motion rate for all PS points in the area of study is equal to -2.19 mm/yr and the maximum rate of subsidence is 11.6 mm/yr. In the area of study there are no PS points for which measured values of displacements can indicate the ground lifting.

The GIS analysis of PSInSAR data, described in this work, includes three stages. In the first one the unreliable PS points were removed from dataset. In the next part of work the values of ground displacements were interpolated to evaluate the subsidence values at points for which the ground movements ware not measured by PSInSAR technique. This interpolation was performed not only for space but also for time (for each moment between years 1992-2003). Third part of analysis includes selections of buildings which are located in the area with highest values of subsidence. In presented work, the values of ground displacements along main roads were also studied. In order to perform this analysis the PSInSAR data, ortophotomap, topography map and vector maps (which represent buildings and main roads) were integrated in GIS environment.

The elimination of unreliable PS points

In his work the PSInSAR technique were used to select areas with the highest values of ground displacements. The accuracy of the results depends on the reliability of data which were used. Therefore in the first step of analysis the PS points with the highest values of displacements were examined very carefully in order to remove these PS points for which the measured displacements are unreliable (due to time decorrelation of radar signal caused by temporal changes of observed surface). This task is very important because these unreliable measurements can have great impact on the accuracy of results of analysis.

The GIS software gives us possibility to select on the map features which fulfill defined requirements. In this part of work the PS points with average annual subsidence rate higher then 3 mm/yr were selected (selection by attribute). From selected subset, PS points which correspond with buildings were removed (selection by localization). From 1701 PS points only 4 of them satisfy defined criteria of selection. Based on analysis of ortophotomap it was found that two of selected PS points correspond with transition poles, one with glasshouse and one PS point is located in area without stable radar targets, near some bushes (Fig. 2c). For last mentioned PS point buffer of distance equal 10 km was created and for PS points which were located in this buffer the average annual motion rates were checked. It was found that their values are considerably lower than values of ground deformations measured in point for which buffer was created therefore this point was removed from PSInSAR dataset and it was not used in the analysis. In figure 2a and 2b the typical PS points were showed, they correspond with the roofs of buildings.

The geostatistical analysis of PSInSAR data

The next stage of the performed analysis includes the interpolation of values of ground deformations at points in space and in moment of time for which the ground movements were not measured by PSInSAR technique. In order to do that the geostatistical methods were used. They were developed for analysis and interpretations of geographically referenced data. The main tool in geostatistics is a semivariogram which is defined as a semivariance evaluated as a function of distance (Eq.1) [9].

$$\gamma(h) = \frac{1}{2N_h}\sum_{i=1}^{N_h}(z(s_i) - z(s_i + h))^2 \qquad (1)$$

where:

$z(s_i), z(s_i + h)$ - values of parameter at points within the distance equal to vector *h*;

N_h - number of pairs of points within the distance equal to vector *h*;

The geostatistical method of interpolation of a particular parameter is called kriging. A standard and widely uses version of kriging is an ordinary kriging. The estimator has form of weighted average (Eq. 2).

$$\hat{z}_{OK} = \sum_{i=1}^{n} w_i(s_0) z(s_i) \qquad (2)$$

where:

$w_i(s_0)$ - are weighted coefficients

The values of weighting coefficients for kriging interpolation are based on spatial autocorrelation of analyzed parameter, described by function of semivariogram.

In our work the interpolation of ground deformations was performed using ArcGIS packages for geostatistical analysis. The interpolation was performed using ordinary kriging method. In the figure 3 the ortophotomap of Sosnowiec town was used as a background of presented results of kriging. The black, dotted lines enclose the areas with the highest values of subsidence and the black lines enclose the stable areas. For area of study the subsidence can be easily noticed. We can distinguish four regions with average annual motion rate higher then -3 mm/yr and two stable regions located in the east and south-west part of area of study.
It is very important that PSInSAR technique derives information not only about values of ground deformations in space but also it supplies information about ground displacements which occurred between moments in time when the two SAR images were performed. Using geostatistical methods we can interpolate values of ground displacements for any period of time between years 1992-2003. In this work maps of   ground displacements were prepared for each month within the period 1992-2003. These maps enable us to study the correlation between values of ground deformations and factors which can influence on these ground movements (e.g. coal exploitation, water pumping). In the figure 4 the maps of relative ground deformations are presented. Figure 4a presents the map of interpolated values of displacements which occurs between 05.1992-05.1995 and figure 4b presents interpolated values of displacements which occurred between 08.1999-08.2003. It can be observed that for second analyzed period of time the range of highest values of subsidence is smaller than for first period of time. These changes can be correlated with termination of the coal exploitation in two mines “Sosnowiec” (1997 – end of coal exploitation) and “Niwka-Modrzejow” (1999 – end of coal exploitation). Using PSInSAR technique we can also estimate the values of ground displacements which can occur in the future. It is very important information for planning the land development. In the figure 5 the diagram of ground displacements of PS point, which correspond with building located at Stroma street in Sosnowiec, is presented.

Buildings stability and ground deformations along main roads

The next stage, of the presented work, was to select buildings which are located in the areas with the largest values of subsidence revealed by PSInSAR technique. In order to perform this task the maps of previously performed kriging results were used. In this analysis the vector map represents buildings in area of study was also used (6a). This vector map which was prepared by digitalizing the topography map of the Sosnowiec town. Using methods of selection by attributes and space location the buildings located in the areas with average annual subsidence rate higher then 3 mm/yr were localized. In the figure 6a these buildings are marked as black and in the figure 6b they are put on ortophotomap of Sosnowiec. It needs to be stressed that selected buildings located in central part of studying area are in neighborhoods of “Sosnowiec” coal mine whereas selected buildings in south part of region are in neighborhood of “Niwka-Modrzejow” coal mine. The information about the stability of individual buildings can help us to identify the potential hazards and allows better protection of these objects.

In this work the analysis of values of ground deformations along main roads was also performed. Based on the topography map the vector map of main roads was prepared (Fig. 7). Around the main roads the distance buffers were created. PS points which are located within the distance of 30m from these roads were used in this analysis. Figure 7 presents the ortophotomap with vector map of main roads and 218 PS points used in analysis. The average value of annual motion rate for all selected PS points is equal -2.33 mm/yr and it is not significantly different from average for all 1701 PS points. However in the figure 7 we can observe that the average values of subsidence are different for particular parts of roads. The largest values of subsidence can be observed for roads which are located in the central part of area of study. These results indicate the non-uniform subsidence of road, what can be the reason for their deformations and pavement damages.

Conclusions

The performed analysis of PSInSAR data, using GIS tools and methods, gave us possibility of elimination the unreliable PS points, which do not correspond with stable radar targets. This task was very important in order to increase the reliability of analysis results. The geostatistical analysis, which included the interpolation of ground deformations at points for which the ground movements were not measured by PSInSAR technique, revealed four regions with the values of subsidence higher then 3 mm/yr. In this work the map of terrain deformations for each month in period 1992-2003 were performed. Integration of PSInSAR data, results of their geostatistical analysis (map of kriging) and vector maps (which represent buildings and roads) enabled us to select buildings and fragments of roads threatened by terrain deformations.

Application of GIS methods to PSInSAR data enables us to perform their precise and fast analysis. Using GIS method we can monitor ground deformations not only in space but also in time to select areas which are the most threatened by terrain deformations. All results obtained in performed analysis develop the database about ground deformations in Sosnowiec. Their integration with different data, can support decision-making in which the problem of ground displacements has to be taken into account. It has to be said that about the usability of the maps decide not only their accuracy but also their accessibility. The SVG (Scalable Vector Graphics) language allows presentation fully scalable vector maps in the Internet [1]. Using SVG formats firms and institutions can use these maps in easy way. All maps performed in this work can be export to SVG files using ArcGIS. The exchange and reentrancy of data are crucial in ground deformations monitoring.

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Figures:

Fig.1. Topography map of area of study (a) with location of PS points (b)

Fig.2. Localization of PS points with high values of subsidence

Fig.3. Kriging results superimposed on ortophotomap of Sosnowiec

Fig.4. Maps of displacements which occurs between 05.1992-05.1995 (a) and between 08.1999-08.2003 (b)

Fig.5. Values of ground deformations for selected point between years 1992-2003 (reference scene: 1997.08.13)

Fig.6. Vector map of building (a) superimposed on ortophotomap of Sosnowiec (b)

Fig.7. Ortophotomap of Sosnowiec with main roads and PS points which are located within the distance of 30m from these roads

Figure 1

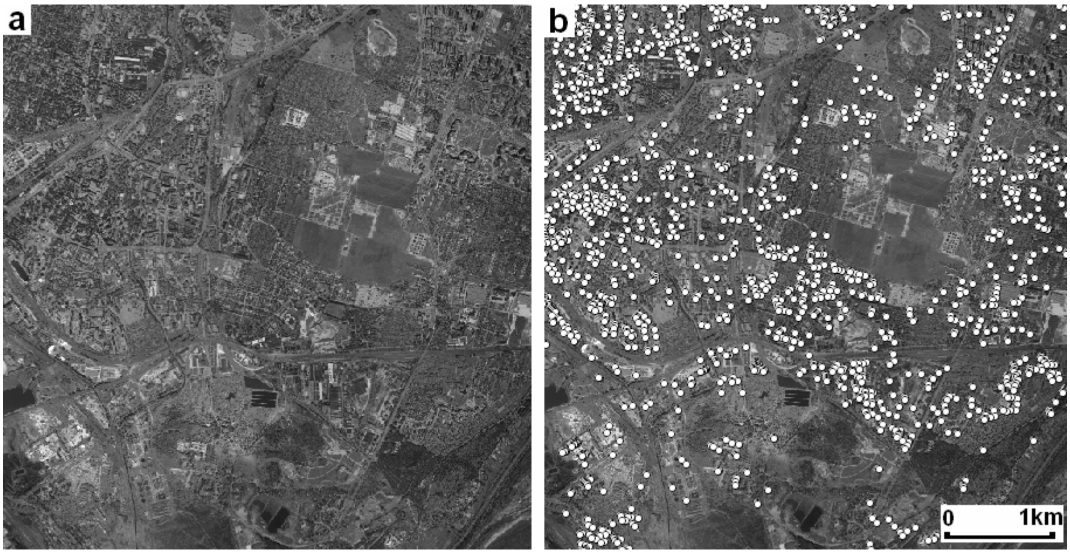


Figure 2

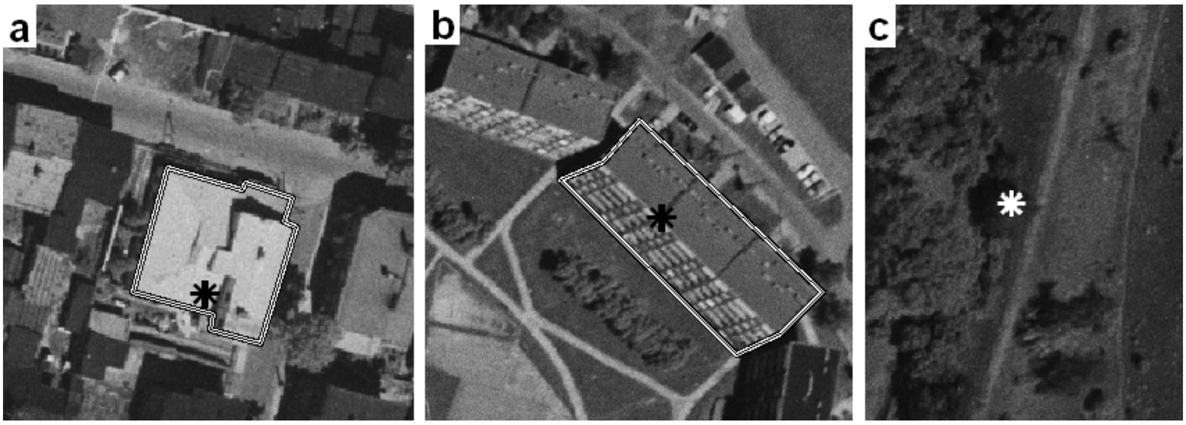


Figure 3

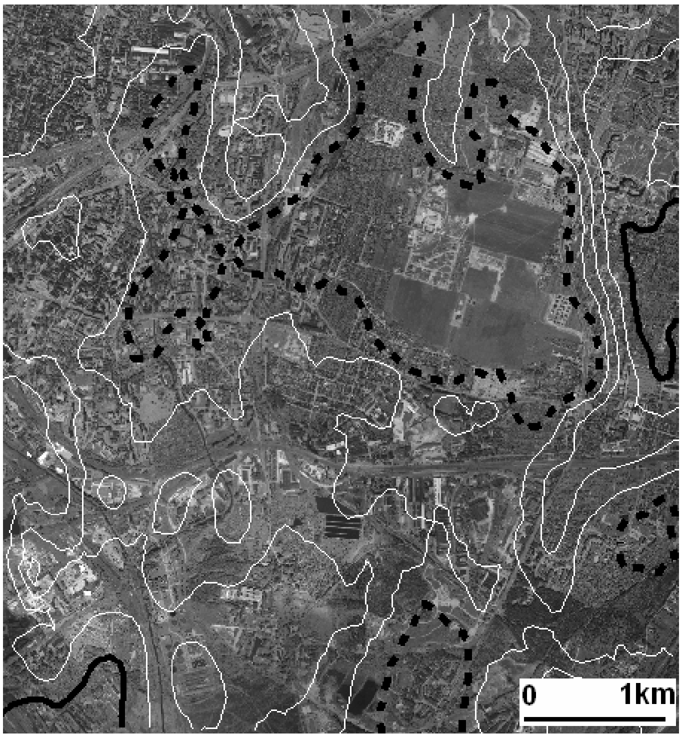


Figure 4

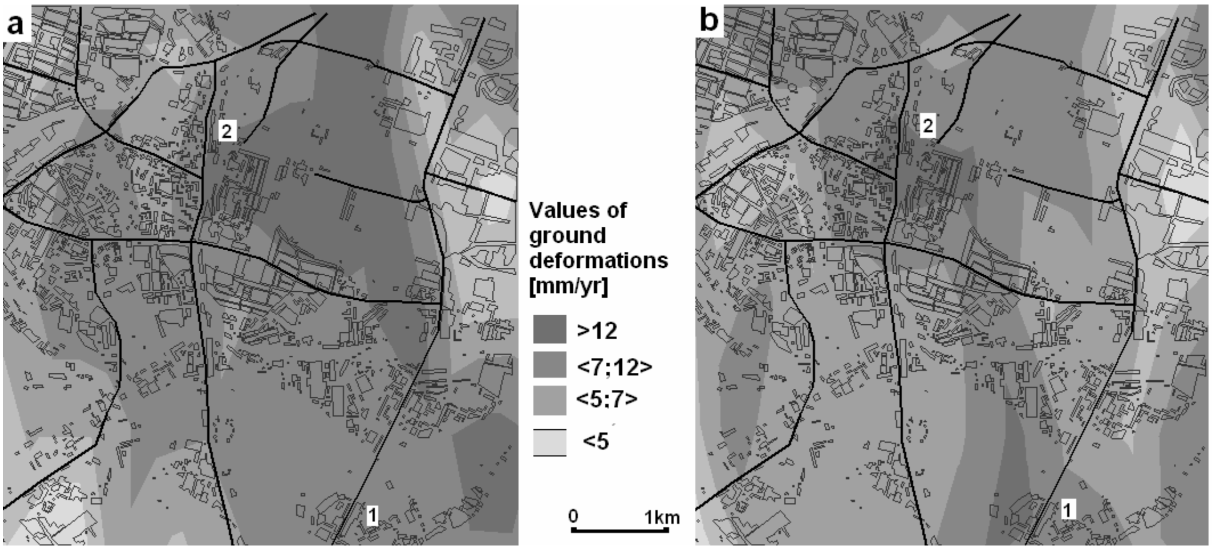
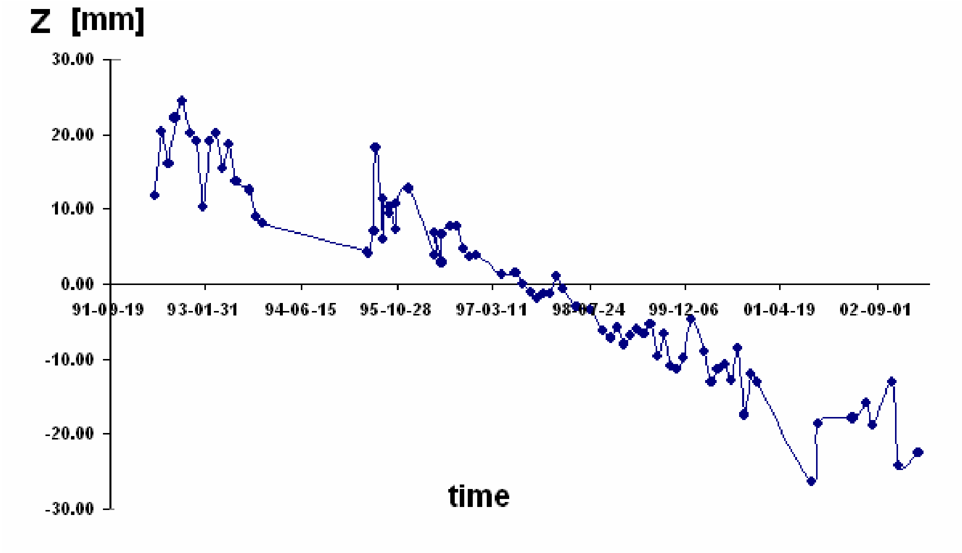


Figure 5



Z [mm]
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
91-09-19
93-01-31
94-06-15
95-10-28
97-03-11
98-07-24
99-12-06
01-04-19
02-09-01
time

Figure 6

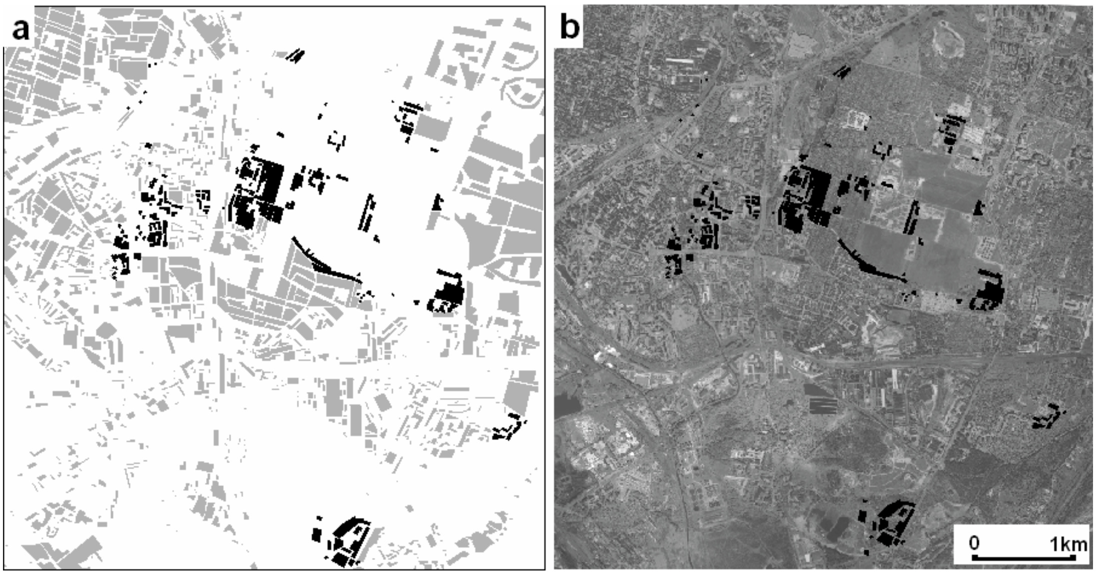


Figure 7