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**CHANGES OF THE URBAN POPULATION  
DENSITY IN CENTRAL POLAND.  
Population Density Distribution Estimation Using  
Nonparametric Kernel Functions**

**Introduction**

Throughout the 20th century the population density in most of the cities increased accompanied by the growth of urbanisation rate understood as the percentage of urban population. It was not a continuous process. The Second World War interrupted it and after then many cities never regained its former population – even until now in some cases, e.g. Brzeziny. In communist Poland stress on intense industrialization of the country caused growing migration to cities and increase of urban population. Then, at the turn of the 20th and the 21st centuries the migration direction changed, birth rate decreased and in many cities population started to decrease. Demographic processes and urbanization had influence on the density of urban population which was not evenly distributed throughout Poland and which is presented on the maps of cities and population density in the successive decades of the 20th century (Jażdżewska 2009).

Population density maps are made in a variety of ways and their basic goal is to present this phenomenon in space as reliably as possible.

Usually, they were construed by way of a cartogram which presented the quotient of the population by the area of the spatial unit in individual administrative units (such as communes, powiats, voivodeships, etc.) (Ratajski 1989).

Another way to present population density is the estimation method which is based on a set of points and their ordinates in space (e.g. settlement units) with assigned population numbers. Its application eliminates problems connected with comparing the results of cross-sectional studies from different periods in which changes of the administrative division occurred (Longley P.A. and others 2008, Silverman 1981).

Using GIS tools for presenting population density in the first of the above-mentioned methods needs a layer with administrative unit areas (polygon type) bound with a table of attributes in which the necessary information concerning population numbers and unit areas (optionally, as the area may be counted using an appropriate GIS function) is recorded. If the presentation and analysis is concerned with one study year the cartogram author needs to decide which cartogram construction method to apply (Kraak, Ormeling 1998, Paślawski 2003). If the analysis entails several census periods, the results may be presented in the administrative division that is valid for the census year, but comparison with the next census year requires additional work – recalculation (estimation) of the population numbers into new administrative units. Poland has experienced frequent changes of the administrative borders both on the international level like in the years 1918 – 1945 and on the national level: numerous changes of the number and territory of the voivodeships after 1945, liquidation and recreation of powiats, separation of new communes, incorporation of settlement units to cities or, to the opposite, separation of settlements from cities like in the Silesia region. Having all the above factors in mind, the subject method does not always precisely present the phenomenon.

In the other case – using the nonparametric kernel functions – the presentation and analysis of population density is based on a settlement unit layer presented in points. These points are associated with unambiguous information concerning population in the census year. Then, one of the estimation methods such as *kernel function* may be applied. The results presented on the map are not dependant on the administrative borders but only on the number of points and the weights allocated thereto and the assumed parameter values.

The article presents the results of the analysis of urban population density changes in the 20th century using the estimation method and its short characteristics. The author thinks the method is worth spreading for analyzing phenomena that have a discrete (point) character.

## **Study Area and Source Data**

The study was carried out in the area of Poland entailing 60 thousand km<sup>2</sup> which had 164 cities and total population of ca. 6 million in 2002. These are the agglomerations of Łódź and of Warsaw (Fig. 1). After 1918 the area belonged to the Polish state and was the scene of numerous changes of administrative borders on the national level. This makes cartogram

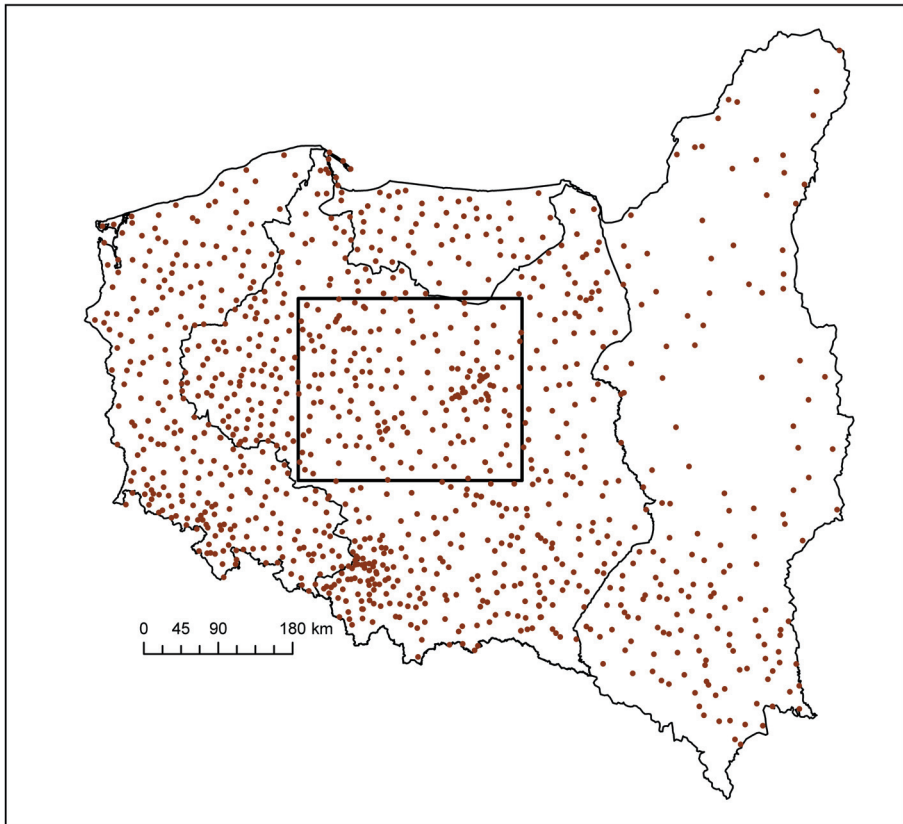


Fig. 1. Study area presented on the borders of Poland from 1931 and contemporary borders.

*Source:* own work

presentation of population density in the administrative units in the successive census years incomparable.

The studies are based on the data of censuses conducted in Poland in the years 1931, 1950, 1960, 1970, 1988, 2002, and the data of the Central Statistical Office of 1978 and 2010. Numerical layers were used with the network of cities presented as points to which the number of inhabitants in the census year was allocated. Throughout the 20th century not only the population of Poland changed but also the number of cities. New cities were created, some cities were incorporated in other ones and some were deprived of their municipal rights (Jażdżewska 2009), and this fact was taken into account in each census and the set of cities contained their true number.

## Kernel Function Estimation Method

The kernel function estimation method uses a set of points distributed in space. In this study cities were represented by points in which population was one of the attributes. This means that the data were represented by discrete objects and as such fulfilled the requirements of the method. To gain this kind of data estimation of density distribution is used rather than interpolation. This is a nonparametric method connected with the so-called kernel functions. The function has the following form:

$$f_h(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right)$$

In this formula  $n$  is the sample size,  $h$  is the smoothing coefficient (bandwidth),  $x_1, x_2, \dots, x_n$  are the points of the  $n$ -element random sample (Peters 2011),  $K$  is the kernel function with some characteristics such as symmetry to zero or integration to the value of one. It usually has a Gauss function form:

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right)$$

The probability density function mostly depends on the  $h$  parameter value, the so-called smoothing coefficient – the higher the  $h$  value, the bigger the flattening (Longley P.A. and others 2008, p. 344).

In the beginning of this method application a mesh of squares of assigned area is created. The length of the square side is chosen subjectively and it depends on the map scale and result accuracy rate<sup>1</sup>. Then, around each of the square a circle of assigned radius is drawn and within each of these circles the number of settlement points is counted. The key task is to choose the correct radius length. If it is too long, the results become exceedingly smoothed (generalized) and if it is too short the results become too detailed. In this study of urban population density  $r = 25$  km whereas the square side length is 0.5 km.

Calculation of density is carried out in the following way: the quotient value (number of cities divided by the area of the circle) becomes allocated to each of the squares with the objects (points) located near the centre of the square are of more significance than those located further aside. The values allocated to the cells are first weighed and then the weighs are summed up, after which the result is divided by the circle area. This way a density map of points (e.g. settlement units) is created. If the points are given another type of weight (e.g. population) the resulting map is the map of population density.

## **Study Results**

The analysis entailed a series of urban population density maps in the census years. The maps were created using the density function estimation method. Each of the maps presents the current number of cities in the given census year and the estimated density. The method was chosen purposefully as it does not give regard to administrative divisions which took place in the studied period in Poland. The maps have the same scale and the legend is uniform to make the maps comparable.

Note that in the 20th century the number of cities in the studied area grew from 136 in 1931 to 164 in 2002. These were mainly small towns with population reaching 2 to 20 thousand. The growth of urban population in the analysed area of Poland was significant: the population was double – in 1931 it was above 3 million and in 2010 – 6 million. In the 20th century both spatial distribution of cities and urban population density changed (Fig. 2-8).

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<sup>1</sup> ArcMap 9.2 application *Spatial Analysis* module by ESRI was used.

In 1931, 13 years after regaining independence, the distribution of cities in the central Poland was quite even. The Łódź agglomeration was different because there were 10 cities within the area of 25 km from Łódź. At the same time there was only half this number of cities around Warsaw. Although it is true that the cities were distributed evenly, the distribution of urban population was significantly concentrated (fig. 2). The agglomerations of Warsaw and Łódź had a great significance in this respect. In the first one there was the dominating role of Warsaw, and the urban population spread to the south-west along the railway leading to Pruszków, Grodzisk Mazowiecki, Żyrardów, Skierniewice, Łowicz. In the Łódź agglomeration the urban population spread in three directions: to the west (Zduńska Wola, Sieradz), to the south (Piotrków Trybunalski, Tomaszów Mazowiecki) and to the north (Zgierz, Ozorków, Łęczyca – in the direction of Płock). Note that there is no high density of urban population between the Warsaw and the Łódź agglomerations. In 1931 on the map of urban population density there was a strong position of Bydgoszcz with over a hundred thousand people creating a set of cities with Toruń and Inowrocław as well as medium-sized cities such as Włocławek, Kalisz, Radom and Piotrków Trybunalski.

After the Second World War two cities were incorporated into the neighbouring bigger cities. Podgórz became part of Toruń and Ruda Pabianicka – of Łódź. The number of cities became lower but the population still had the urban population status. Chorzele lost its municipal rights. Urban population density in the Warsaw and the Łódź agglomerations and their spatial layout did not change but new cities were created in the area: Brwinów and Milanówek next to Warsaw and Koluszki in the distance of ca. 25 km to the south-east of Łódź. The biggest changes occurred outside these agglomerations. To the north-west the urban population density grew in Bydgoszcz and Toruń, and in the opposite direction Radom gained significance. Then, to the north-east such cities as Mława, Pułusk, Ostrów Mazowiecka and others had lost a large percentage of population during the Second World War and even in 1950 still had lower population than in the pre-war period. As a result, in 1950 this area had the lowest density of urban population in the whole analysed area.

After 10 years changes of urban population density was noticeable in the studied area. The Warsaw agglomeration had more cities. Municipal rights were given to Karczew, Legionowo, Piastów and Zielonka. The area of the agglomeration grew in all directions and so did the urban population density. On the east it reached Mińsk Mazowiecki, on the south – Góra Kalwaria, on the north – Serock and on the west – Sochaczew and – a sig-

nificant moment – became connected with the Łódź agglomeration that did not change its shape significantly in the years 1950-1960 but reached the city of Płock. Outside the Łódź agglomeration municipal rights were given to Żelów. The remaining cities became more significant by increasing their population and its density. In the north Mława rebuilt its wartime losses. Ciechanów and Konin increased their population density for the first time (fig. 3).

In the years 1960-1970 more villages got municipal rights: Janikowo, Sompolno, Izbica Kujawska, Nowe Skalmierzyce, Łochów, Łaskarzew. New cities were created in the Warsaw agglomeration: Podkowa Leśna, Ożarów Mazowiecki, Marki, Ząbki, Kobyłka, Sulejówek, Konstancin Jeziorna, Tłuszcz, Tarczyn, which made its territory grow evenly to the north, east and south. The western part of the agglomeration had higher population density and adhered to the Łódź agglomeration more strongly, and through it, surprisingly, to the area of Płock. In 1970 the Bydgoszcz-Toruń-Inowrocław city set connects with Włocławek. Population density was increased in the Konin Basin (Konin and Turek), which resulted from new industrial investments in the area. In the north-east Ostrołęka increased its population and changes the urban population density distribution of this area.

In the years 1970-1978 urbanisation in Poland continued, which is well visible on the maps of urban population density (fig. 4). In 1975 an administration reform was carried out increasing the number of voivodeships to 49 and cancelled the division to powiats. Several medium-sized cities localized in the analysed area gained the rank of voivodeship capital. These included Ciechanów, Kalisz, Konin, Sieradz, Ostrołęka, Piotrków Trybunalski, Płock, Radom. After three years no results of the reform were visible in terms of increasing urban population density. Note that the density increased in Ciechanów, Konin, Ostrołęka, Toruń. Some cities which had not been important before started gaining significance. These were Mława Ostrów Mazowiecka, Pułtusk. After 1970 the sanction connected with registering residence were abolished and as a result a lot of immigrants registered their residence in Łódź and Warsaw thus increasing population density in these cities. This did not stop the growth of population density around these cities. The Warsaw agglomeration was still growing towards Łódź but also reached Wyszaków. A new city of Józefów was created near Warsaw too. The Łódź agglomeration was spreading in the area of the basin of Bełchatów. The population density in many medium-sized cities increased: Płock, Radom, Konin and Kalisz. Bydgoszcz, Włocławek,

Toruń and Inowrocław joined together forming one area with high urban population density.

In the years 1978-1988 further serious changes of urban population density were occurring. The reach of the urban areas grew significantly in comparison with 1978 not only in the western direction as to-date, but also to the north-east in the direction of Wyszaków and Pułtusk. Some satellite cities appeared near the agglomeration: Płońsk, Garwolin, Ostrów Mazowiecka. It is worth noticing that the Warsaw agglomeration went north from its Łódź 'extension' and neared Płock. Also the Łódź agglomeration increased its population density not only around Łódź but also in the area of Piotrków Trybunalski, Tomaszów Mazowiecki, Sieradz, Zduńska Wola and Kutno. Ciechanów and Mława form a heightened population density area which may connect with the Warsaw agglomeration in the future. In the south of the Łódź agglomeration Bełchatów spread its heightened population density area, which resulted from development connected with lignite mining and the construction of the power plant. In the south-east Radom widened its zone and connected with the Łódź agglomeration via the area of Opoczno. It also spreads towards Kozienice and connects with the areas located eastwards. Till 2002 more cities were created: Halinów, Łomianki, Piotrków Kujawski, Skępe, Biezuń, Pilawa, Drzewica, Glinojec. The development of the Warsaw agglomeration to the west lowered its intensity or even regressed as a result of diminishing population of such cities as Żychlin, Brzeziny, Łowicz. In the other directions the development became significantly faster especially northwards. The agglomeration of Łódź did not increase its area significantly. Only in the south Bełchatów connected with Piotrków Trybunalski and Tomaszów Mazowiecki with which it formed an area with heightened urban population density. Płock did not connect with Włocławek or with Warsaw but with Łódź which is situated twice as far. The two cities got connected with a heightened urban population density corridor. In the north a heightened density area was forming nearing the cities of Bydgoszcz, Toruń, Włocławek and Inowrocław.

The last time interval to be analysed is the years 2002-2010 during which no violent changes in the urban population density occurred. The situation in this part of Poland became stabilized. New changes, contrary to the ones described above in this study, have started. The diminishing population of such towns as Brzeziny, Głowno, Łowicz and Żychlin may result in their separation from each other. A small decrease of the population in Golub-Dobrzyń caused that the connection of the Pomerania towns with Toruń and Bydgoszcz broke. The applied method does not yet present the



results of decreasing population in the cities having more than one hundred thousand people. This may result from the selection of intervals having the highest density in the cartogram.

## **Summary**

Throughout 70 years of the 20th century serious changes of urban population density in central Poland occurred. The growth of urban population from 3 to 6 million changed its spatial distribution significantly. In 1931 the Warsaw and the Łódź agglomerations as well as several smaller cities (Bydgoszcz, Toruń, Włocławek, Płock and Radom) concentrated urban population. Most of the analysed area population density did not exceed 25 people per kilometre squared. In the successive decades after the Second World War urban population did not only concentrate in these cities but was scattered throughout the whole central Poland. The analysis of a map series shows the influence of economic factors (discovery and extraction of lignite) on the increase of urban population near Konin and Bełchatów, of administrative factors (formation of 49 voivodeships) and increased significance of new municipalities (Ciechanów, Kalisz, Sieradz, Piotrków Trybunalski, Radom and other). It is interesting to follow the changes around the Warsaw agglomeration and the Łódź agglomeration as well as the group of Bydgoszcz, Toruń, Inowrocław and Włocławek). The Warsaw zone of influence used to spread westwards in the direction of Łódź for many years, however in the nineteen eighties started its expansion in all the other directions. In the analysed period 16 new cities were created in the distance of 25 km of Warsaw by gaining municipal rights. The capital city and its agglomeration have the population of 2.5 million. The agglomeration of Łódź experienced the biggest changes before 1988 and then it visibly regressed (except from Bełchatów). In the beginning of the 20th century Łódź and the neighbouring towns had the population of ca. 1.5 million.

In the west of the łódzkie voivodeship the population fell in such towns as Głowno, Brzeziny, Łowicz, Rawa Mazowiecka, Biała Rawska, which resulted there could not be urban population density increase between Łódź and Warsaw.

Bydgoszcz and Toruń formed a group joined soon by Inowrocław and Włocławek, which could soon be populated by a million people. In the remaining area there are cities which had the population of over a

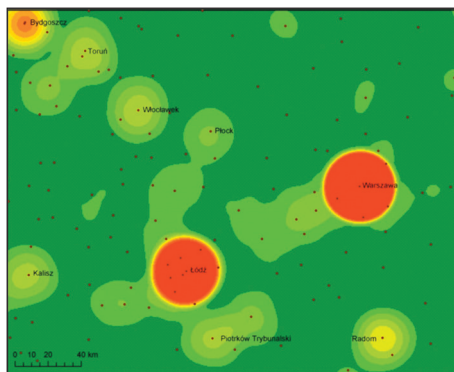


Fig. 2 Urban population density in 1931.

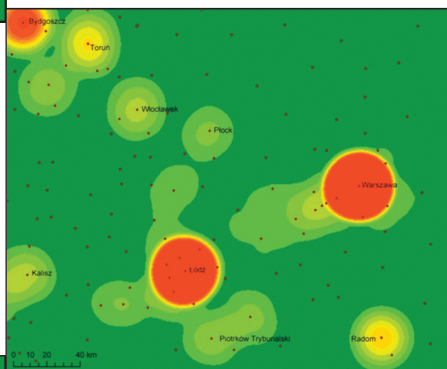


Fig. 3 Urban population density in 1950

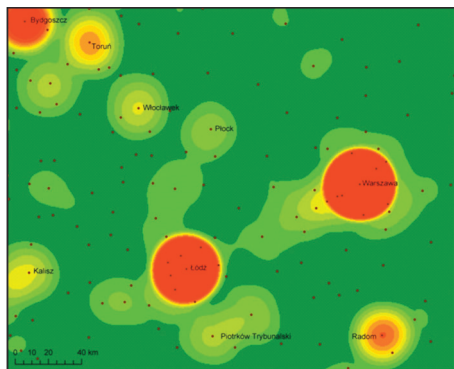


Fig. 4 Urban population density in 1950.

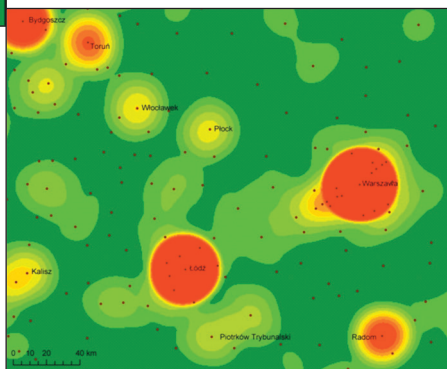


Fig. 5 Urban population density in 1970

Source: own work

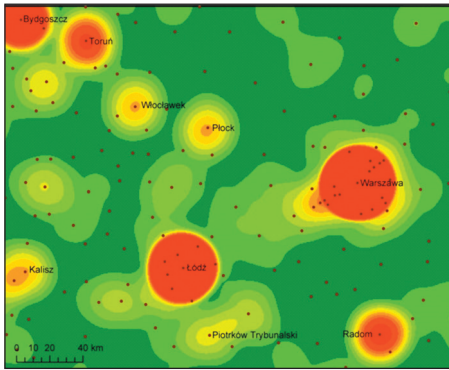


Fig. 6 Urban population density in 1978

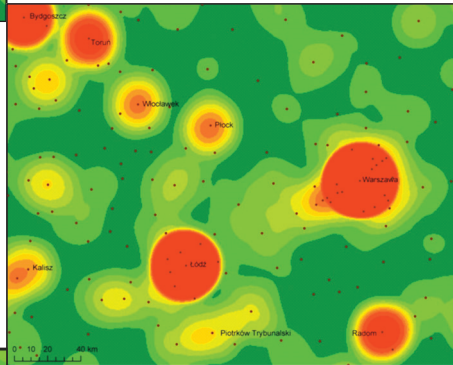


Fig. 7 Urban population density in 1988

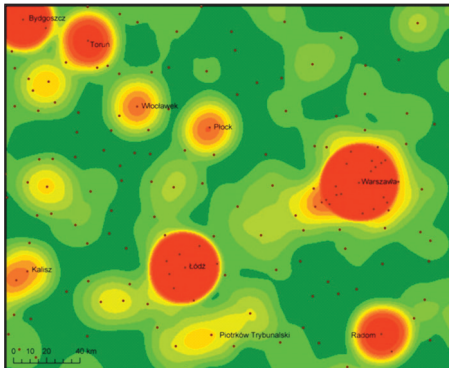


Fig. 8 Urban population density in 2002

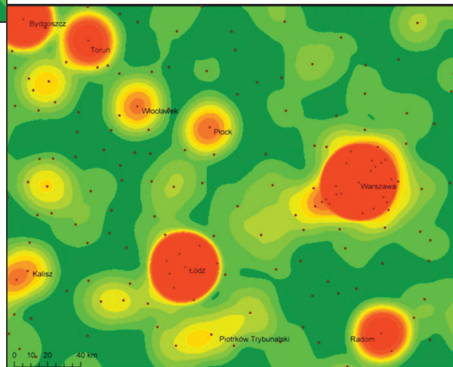
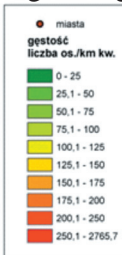


Fig. 9 Urban population density in 2010

Figures legend



Source: own work

million in the beginning of the 20 century. These were evenly distributed in this part of Poland. Many of them were small and medium-sized municipalities.

The applied estimation method dynamically presents the changes occurring in the Polish geographical space from the point of view of urban population density and its most significant directions. The method not only shows urbanization progress that has occurred in this area but also its regression in the post-war years and in the beginning of the 21st century. Using this method showed it is sensitive to all kinds of weight changes (of urban population), which results in the appropriate changes on the map that are not always possible to seize by a traditional cartogram. It is recommended for application in similar studies.

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**ABSTRACT**

The article presents the results of the analysis of changes of the urban population density in Central Poland in the 20th century using one of the statistical methods meant for the estimation of discrete distributions, the so-called kernel function, and its brief characteristics.

The studies cover the period, for which comparable data has been gathered (from 1931 to 2010). The results of the studies have been presented in a textual form and on 9 drawings, showcasing the changes of the population density in Central Poland in the analyzed period.

