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Transformation of Density Hydrographic Network in Headwaters of Piwonia River

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1. Introduction

Transformations of terrain significantly affect biodiversity, energy flow, biochemical cycles and climate both on the regional and local scale. In the context of spatial processes transforming the landscape, urbanization is classified as a process of perforation or abrasion (Fortin & Dale 2005). Hydrogenic landscapes are characterised by particular nature richness. At the same time they are of key importance for the stability of ecological relations of individual regions. Aquatic, wetland, peatbog and grassland ecosystems are dominant in hydrogenic landscapes (Choiński & Ptak 2009).

Poland is a country with the lowest European ratio of natural water resources per capita. On the other hand, it has 7081 water bodies larger than 1 ha (Choiński 2007, Choiński et al. 2011). The majority of natural lakes are found in the northern part of the country, with young, diverse post-glacial landscape. Remaining regions are characterised by the low number of standing water bodies. The unequal spatial distribution of lake areas is an important fact, as lakes are considered to be significant factor in sustainable development, biodiversity and economic growth (Walsh et al. 2003, Davies et al. 2008, Parparov & Gal 2012). Their role is understood more and more not only among scientist, but also among society (Skiwierawski 2018).

The scale of landscape and land use transformation is usually based on archive spatial materials, i.e. aerial photographs and maps serving as evidences of natural and anthropogenic changes (Suchożebrska & Chabudziński 2007, Myga-Piatek 2010, Nieścioruk 2013, Ignatius & Jones 2014). In recent years, the importance and popularity of spatiotemporal presentation of landscape changes and geographical background of historical facts increases significantly (Holdsworth 2003, Mościcka 2009, Withers 2009, Chabudziński et al. 2018). The role of Geographic Information System (GIS) tools in the process of verification of historical cartographic representations is not to be underestimated (Hawthorne 2011, Nita & Myga-Piątek 2012).

Lakes, as young elements of the landscape, are a subject to dramatic and rapid changes, which can be traced with the use of mentioned spatial materials and GIS tools. For example, the water surface area of Lake Udzierz decreased from 148.87 to 69.60 ha in the last century and that of Lake Mątasek from 29.5 to 0.64 ha. Such drastic morphometric changes in the case of mentioned lakes are, on the one hand, mainly due to poorly conducted drainage and, on the other hand, the eutrophication of water intensified by the anthropogenic impact (Fabich & Kwidzyńska 2012). The other example is the examination of the area of 25 lakes in the Mazurian and Pomeranian Lake District that decreased by 5.6%, while their volume has decreased by 9.9% in a period of over 50 years (Choiński & Ptak 2009). The processes of lake disappearance are responsible for parallel processes related to shallowing of lake bowls, and not only to shrinking of the shoreline. Reducing the volume of lake troughs adversely affects the natural resistance of lakes to degradation. The disappearance of lakes also contributes to the physiographic changes of the area (Marszalewski & Adamczyk 2004; Marszelewski 2005, Ptak 2013). Another hydrographic case is a drainage density in Tuchola Forest which has increased from 0.7 to 1.95 $km \cdot km^{-2}$, while the area of lakes share has increased from 1.81 to 1.93% only. However, the number of reservoirs has increased from 36 to 675 in a period of 110 years (Szumińska & Absalon 2012).

The study aims at analysing the changes in the arrangement and density of the hydrographic network of the headwaters of Piwonia river. The work contains a comparison of a pre-war state of hydrographic network with a current one, seriously modified during the hydrotechnical works in 1960s. The analysis of river network density was conducted using ArcGIS on the base of maps. The paper presents changes in river network density as a function of distance increasing from the central point. The study results in development of methodology of melioration activities assessment based on cartographic materials. The analyzes were carried out for the period 1938-2011 (73 years).

2. Material and methods

Hydrographic network in Poland was formed mainly as a result of the landforms development in the Tertiary and Quaternary. Its main elements are: rivers, lakes, ponds, wetlands, groundwater, springs, artificially constructed canals and reservoirs. One of the indicators characterizing the river network is its density. There are many different methods for calculating the density of river network. The study uses the Neumann method, which has the widest scope of applications among all other methods. The density according to the Neumann method is measured by the total length of rivers in kilometres per square kilometre (Gibson et al. 2004).

The analysed catchment is located approximately 30 km north-east from the city of Lublin. It is an area of the headwaters of Piwonia river catchment of 24.5 km^2, located near Uściwierskie Lakes in Western Polesie. There are five lakes within studied area: Bikcze, Nadrybie, Uściwierz, Uściwierzek, and Ciesacin with a total area of 3.83 km^2 and 11.23 km^2 of direct catchment (Czarnecka 2005, Grzywna 2013).

The surface geological layer is dominated by sandy and silty sediments of last two glacial periods when the analysed area was beyond the glaciation extent. The holocene organogenic sediments in a form of vast peatlands and by-lake plains also play an important role. The height differences are not big with a dominant role of erosional and depositional plains. Low slope values causing a slow outflow and a low permeability are reasons for shallow groundwater (Harasimiuk et al. 1998).

The analysis of river network density was conducted using ArcGIS and information gathered from cartographic materials. The study was based on topographic maps in a uniform scale of 1: 000 from 50 years in 1938 and 2011. The statistical analysis used the full study period (73 years), for short periods of little change.The past state was vectorised using the 1:50 000 topographic map of 1938 by Military Geographical Institute (WIG). The modern one was based on the visualisation of VMap L2 topographic database of 2011. Both materials were georeferenced into the WGS. The course of river lines was transferred to numerical maps and their lengths were measured and saved as attributes of objects. The next step was to create equidistant from the research area central point (φ = 51°22’04’’ N, λ = 23°04’23’’ E). The zones covered 4 kilometres in diameter with step every 250 meters and with limitation to the catchments area. Lakes areas were subtracted from the zones. Centroids representing specific properties were used for statistical calculations. The river was fragmented with the help of the centroid line. Then, in separated 250 m wide belts, the length of rivers was determined and their density was calculated.The river network was then intersected with the zones resulting in lengths values in every zone. They were used to calculate river network density and create a choropleth map showing the density in square fields of 250 m side. It can also be illustrated by means of variogram, presenting a change of network density with growing distance from the given centre point.

Three different spatial statistics were calculated next to assess changes in network of watercourses in the examined region. They were used to compare patterns in structure of river network density. For these tests, area of catchment was divided by criss-cross net on square fields of 250 m side. The results are illustrated by means of variogram.

Pearson's test (Verburg et al. 2006) was used to analyse the similarity level of watercourses distribution in years 1938 and 2011. CRH procedure was applied for testing significance correlation of spatial data (Clifford et al. 1989).

Ripley's K test (Dale 1999, Próchnicki 2011) was used for analysing concentration of watercourses in function of distance. It was compared to a hypothetical, ideally random sample with Poisson distribution. Regarding shape of catchment, confidence areas were obtained by means of 999 permutation of distribution of watercourses.

3. Results

3.1. Transformation area

The hydrographic phenomena in Poland are formed above all under the influence of climate, geological structure, topography and evaporation of surface water (Wilgat 1954).

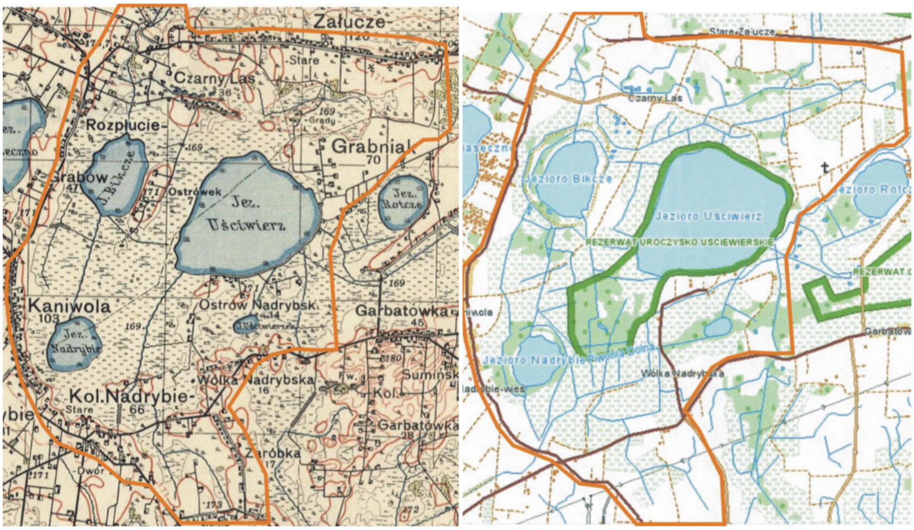

Fig. 1. The hydrographic network of the research area (1938, 2011), — basin

In 1938, Piwonia river flew across the lakes (according to WIG map). In the 1960s, the water canal being a beginning of Piwonia Dolna river was traced, passing Nadrybie to the north and Bikcze and Łukie lakes to the west. As a result of hydro-technical works, the length of the river increased by 5.3 km, from 57.4 km to 62.7 km, and the springs were moved from Nadrybie Lake to

Uściwierzek Lake (Fig. 1). Reshaping of hydrographic system and construction of Wieprz-Krzna canal in 1954-61 resulted in burying 3 km of watercourses, including 1 km of canal built in the early 20th century, which formed part of Piwonia river. In addition, Bikcze lake was surrounded with dike and all lakes were surrounded by a network of peripheral canals. In the 1950s of the twentieth century, Bikcze Lake was surrounded with dike, its water surface was elevated and the lake was converted into a retention reservoir, while the river bed was risen (Michalczyk et al. 2011).

The largest transformations of hydrographic network in Poland took place in the 60s of the 20th century and were associated with the construction of water canals, river regulations and drainage of wetland areas (Miller 2005, Solon 2009). The construction of Wieprz-Krzna drainage system contributed to the negative changes in water conditions, causing a decrease in water level in lakes and in soil, as well as increased the rate of outflow, reduction of natural retention and introduction of external, highly eutrophic waters (Janiec 1993, Chmielewski 2009). It also caused an increase in the length of watercourses and ditches almost triply in this area. The mentioned contribution is also confirmed by very large changes in the hydrographic network in the catchment area of Uściwierskie lakes. The size of water reservoirs has slightly changed (Grzywna & Nieścioruk 2016). Some of them have completely changed the shape of the shoreline. The consequence was the reduction in water surface of lakes.

The melioration works changed the course of the river completely. The water ditch being the beginning of Piwonia river was traced near Bikcze and Nadrybie lakes and further into Uściwierzek Lake. As a result of this work, the 7.3 km section of the river was created within the analyzed catchment.

In addition to Piwonia river bed regulation, 40 km of new melioration ditches were built. Moreover, construction of Bogdanka – Wola Wereszczyńska Canal (KBWW) was completed in 1973. At present, this canal is heavily vandalized and even filled with rubble in some sections. Due to the lack of a proper exploitation and maintenance of water facilities, especially within the catchment, the secondary periodic flooding of the area occurs. The canal performs an emergency function of water supply during peat bog fires.

In the early 1990s, attempts to restoration both the river bed and drainage facilities were undertaken. Changing the environmental law in the year 2000 made it impossible to continue the implementation of the harmonization of nature and economy (Chmielewski 2009). In 2007, the whole group of Uściwierskie Lakes was classified as Nature 2000.

The analysis of the use of direct catchment of Uściwierskie Lakes reveals that the largest area (40%) is covered by grasslands. The high share of the water surface of up to 34% of the total catchment area also draws some attention. However, the area of studied lakes was gradually decreased from 4.25 km^2 in 1938 to

3.68 km^2 in 2011. The biggest absolute decrease can be observed for the largest Uściwierz lake. Its area decreased by 30.1 ha during 63 years. The most significant change in the environment occurred in case of Ciesacin lake. Its areas decreased by 90%. In 2011 it was only 0.2 ha of plant-covered water. Although the analysed area is characterized by the occurrence of poorly fertile brown and black soils developed from sandy and silty forms, 15% of it are arable lands (Wilgat 1954, Harasimiuk et al. 1998, Chmielewski 2009).

Length of the hydrographic network visible on maps increased from 19.7 km in 1938 to 55.8 km in 2011 year (without 5.5 km of KBWW), being the result of the construction of a drainage ditches system in the late 60s of the 20th century. When analysing changes in the land-use structure of the catchment, it was found that the area of lakes decreased by 16.5% during 1938-2011. The open water surface of Ciesacin lake completely disappeared as a result of hydro-technical works. The history of changes in water relations in past 200 years in the analysed area (Radwan et al. 2002, Kowalewski 2012, Michalczyk et al. 2012, Grzywna 2013, Mięsiak-Wójcik et al. 2014, Grzywna & Nieścioruk 2016, Kowalewski & Żurek 2016, Michalczyk et al. 2017).

3.2. Statistical analysis

As a result of fragmentation in centroid belts, river sections were obtained for which the hydrographic network density was calculated (Fig. 2). In 1938 were identified: 11 fragments were identified with a density below 1 $km \cdot km^{-2}$, 18 with a density 1-2, 34 with a density 2-3, 42 with a density 3-5 and 5 with a density above 5 $km \cdot km^{-2}$. In 2011, 90 fragments with a density of 1-2 $km \cdot km^{-2}$, 46 with a density of 2-3, 36 with a density of 3-5 and 13 with a density of over 5 $km \cdot km^{-2}$. The density of hydrographic network increased from 0.98 $km \cdot km^{-2}$ in 1938 to 2.77 $km \cdot km^{-2}$ in 2011 year. The number of river fragments increased from 110 to 185. Obtained density of watercourses in function of distance from catchment centre shows an increase of its values in year 2011. Nowadays its values hardly ever go below 2000 meters per square kilometres, while the density for 1938 is lower than 1200 in all zones with no observation in first two zones. The general spatial character of density changes is similar, with low values in first zones preceding areas of the highest values and slow decrease of density towards edges of the research area (Fig. 3). The difference, beside values themselves, is about 2500 meters shift of both diagrams, as the 1938 peaks slightly at 1.5 km diameter zone (with 1.2 $km \cdot km^{-2}$) and the modern one at 2.75 km (with 3.7 $km \cdot km^{-2}$). In both cases, the density of the water network has similar values – density clusters in 1938 and 2011 were similarly distributed. The tendencies described are also observable at the visual assessment of source maps.

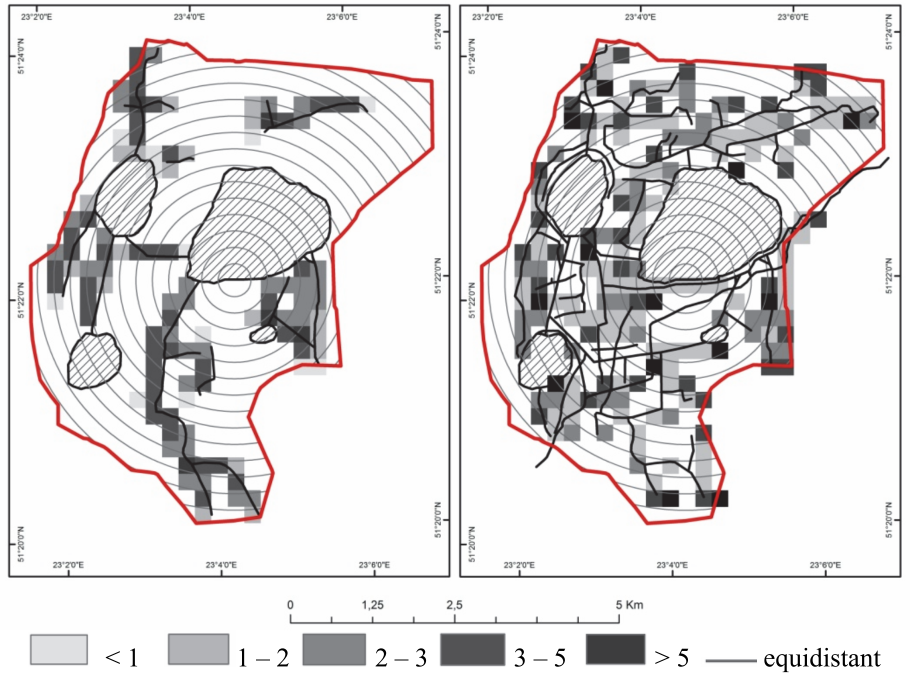

Fig. 2. River network density in 1938 and 2011 [km·km^{-2}]

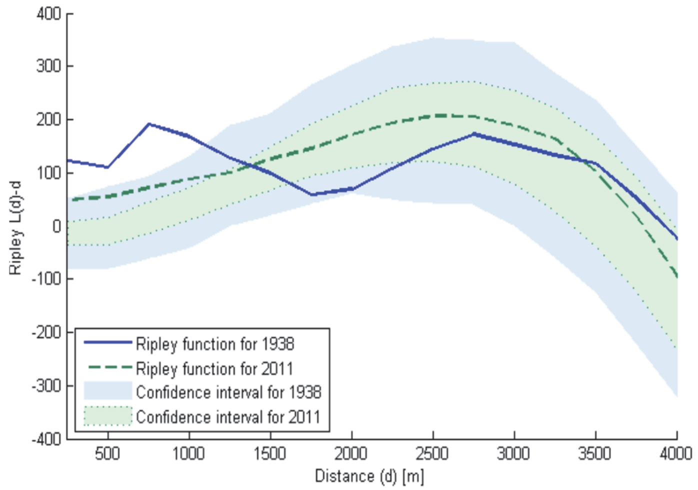

Fig. 3. Variogram as an outcome of Ripley's K test

Spatial distribution of river network in successive time pairs was analysed with the Pearson's test. Pearson's correlation coefficient r in Uściwierskie Lake for the pair 1938-2011 was significant (p-value < 0.05) amounted to 0.5. A significant correlation is a result of the development of the existing water network. Not very high value of Pearson's correlation coefficient indicates the development of existing watercourses and the emergence of new ditches.

Ripley's K test was performed on the map of watercourses intersected by criss-cross network with squares of 250 m side. In examined catchment, Ripley's K test for both years shows existence of watercourses clusters (statistically significant test values at the distance up to 1250 meters). Due to fewer number of watercourses there is a wider confidence area for test values for year 1938.

4. Conclusions

The usefulness of both maps in environmental management is unquestionable, and their complementary use guarantees comprehensive survey of issues connected with natural environment of a given area. The implications of density factor change is often a subject of research on local and regional scale, with focusing on lakes drainage, anthropogenic eutrophication, lowering the water level, land use or renaturalization of river network (Querner et al. 2004, Sidle et al. 2007, Du et al. 2011).

Length of the analysed hydrographic network increased from 19.7 km in 1938 to 55.8 km in 2011 year according to maps. The area of studied lakes was gradually decreased from 4.25 km^2 to 3.68 km^2. When analysing changes in the catchment land-use structure, it was found that the area during 1938-2011 decreased by 16.5%. It justify describing the spatial network structure in both districts as clusters of regular size and distribution. Pearson's correlation coefficient for the pair 1938-2011 was significant and amounted to 0.5 pointing emergency of additional ditches.

Generally, lakes in Poland show the tendency to decrease both in area and number. Lake basins are subject to constant evolution. Causes of changes are both natural and human activity. Among natural factors the most important role play: water level fluctuation, climate changes, depth of lake basin, hydrographic network etc. The most important anthropogenic factors are: hydrotechnical works, deforestration and agriculture.

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Abstract

The analysis of river network density was conducted using ArcGIS and information gathered from cartographic materials. The past state was vectorised using the 1:50 000 topographic map of 1938 by Military Geographical Institute. The modern one was based on the visualisation of VMap L2 topographic database of 2011. Both materials were georeferenced into the WGS. The next step was to create equidistant from the research area central point. The zones covered 4 kilometres in diameter with step every 250 meters and with limitation to the catchments area. Lakes areas were subtracted from the zones. The river network was then intersected with the zones resulting in lengths values in every zone. They were used to calculate river network density. It can be illustrated by means of variogram, presenting a change of network density with growing distance from the given centre point. The largest transformations of hydrographic network took place in the 1960s of the 20th century due to the construction of Wieprz-Krzna Canal, Piwonia regulation, and wetlands drainage. The river length increased by 5.3 km, and its headwater was transferred from Nadrybie Lake to Uściwierzek Lake. Density of hydrographic network increased from 0.98 $km \cdot km^{-2}$ in 1938 to 2.77 $km \cdot km^{-2}$ in 2011 with the decrease of area of lakes by 16.5%. On the basis of spatial statistics, the spatial network structure in examined area in both years can be described as clusters of regular size and random distribution. Pearson's correlation coefficient for the 1938 and 2011 is significant and amounts to 0.5 which is the result of new watercourses emergence. Ripley's K test shows the most significant growth of clusters at the distance of about 2.75 km from the centre of the region.

Keywords:
river network, lakes drainage, Ripley's K test, Pearson's test

Przekształcenia gęstości sieci hydrograficznej w zlewni górnej Piwonii

Streszczenie

Analizę gęstości sieci rzeki przeprowadzono przy użyciu ArcGIS i informacji zebranych z materiałów kartograficznych. Materiał historyczny został wektoryzowany za pomocą mapy topograficznej Wojskowego Instytutu Geograficznego w skali 1:50 000 z 1938 roku. Materiał współczesny opierał się na wizualizacji topograficznej bazy danych VMap L2 z 2011 roku. Oba materiały zostały przekształcone do układu WGS. Następnym krokiem było utworzenie punktu centralnego obszaru badawczego. Następnie, z ograniczeniem do obszaru zlewni, wyznaczono strefy do 4 kilometrów średnicy, z krokiem co 250 metrów. Obszary jezior zostały wycięte ze stref. Wówczas sieć hydrograficzna została przecięta strefami na oddzielne fragmenty. Wykorzystano je do obliczenia gęstości sieci rzecznej. Można to zobrazować za pomocą wariogramu, przedstawiając zmianę gęstości sieci z rosnącą odległością od wyznaczonego punktu środkowego. Największe przekształcenia sieci hydrograficznej miały miejsce w latach 60 XX wieku, ze względu na budowę Kanału Wieprz-Krzna, regulację Piwonii i odwadnianie terenów podmokłych. Długość rzeki wzrosła o 5,3 km, a jej początek został przeniesiony z jeziora Nadrybie do jeziora Uściwierzek. Gęstość sieci hydrograficznej wzrosła z 0,98 km·km^{-2} w 1938 roku do 2,77 km·km^{-2} w 2011 roku. W okresie 1938-2011 nastąpił spadek powierzchni jezior o 16,5%. Na podstawie statystyk przestrzennych strukturę sieci przestrzennej w badanym obszarze w obu okresach można określić jako klastry o regularnym rozmiarze i rozkładzie losowym. Współczynnik korelacji Pearsona dla lat 1938-2011 jest wysoki i wynosi 0,5, co jest wynikiem pojawienia się nowych cieków wodnych. Test Ripleya K pokazuje najbardziej znaczący wzrost skupisk w odległości około 2,75 km od centrum regionu.

Słowa kluczowe:
sieć rzeczna, odwodnienie jezior, test K Ripleya, test Pearsona