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Special Issue

Transformation of a Water Network in a Moraine Upland-Outwash Plain-Valley Landscape

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Abstract

The area under study in this paper was subject to landscape transformations, including changes in hydrographical networks. These changes were especially intense in the second half of the 19th century during the Prussian partition, when extensive hydrotechnical works were conducted. Based on a comparison of cartographic materials at a scale of 1:25,000, Prussian topographic maps from 1874, and Polish maps from the second half of the 20th century, it was found that the hydrographic network has changed significantly. A characteristic anthropogenic pattern of water structures was observed that correlates with certain individual morphological units. In the bottoms of the valleys and hollows there is a dense irrigation network, and in the moraine areas, numerous reservoirs of anthropogenic origin were found that are characterized by a rather small size and circular shape. The drainage density in the area under study has increased from 0.7 to 1.95 $km \cdot km^{-2}$, but the lake percentage has only increased from 1.81 to 1.93%. However, the number of reservoirs has increased from 36 to 675. The anthropogenic water reservoirs were found first and foremost in the area of the uplands, where the reservoir frequency has increased from 0.3 $km \cdot km^{-2}$ to 7.7 $km \cdot km^{-2}$.

The results of the conducted research can be used to perform an automatic analysis of the transformations of the water network in Tuchola Forest and other areas of the last glacial extent. The results of the study presented in this paper should also be used when taking any decisions and actions that may lead to changes in water network and water management. The discussed "anthropogenic lakeland" located in the area of poor industrial and urban development, the Tuchola Forest, may also be the premise for verifying views on a large number of lakes situated in kettle holes within the Polish Lowland (Niż Polski).

Keywords: water network changes, irrigation, water reservoirs, archival maps, anthropogenic lakelands, Tuchola Forest

Introduction

The hydrographic network of the last glacial extent shows a diversified degree of organization and various stages of development, which mainly depend on natural conditions such as geological structure, aquifer arrangement, land relief, and climate. An additional factor that diversifies and affects the shape and functioning of the water network is multidirectional human activity. This activity is manifested everywhere, including forested areas, and in various ways, such as changes in land use and numerous other ways that directly affect outflow conditions. These activities include river regulation, water lifting of rivers and lakes, melioration of wetlands, water drawing, and diversion of water.

An analysis of the transformations of the water network was conducted in an area in the central part of the Tuchola Forest region, which is the largest compact complex of pine

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forests in Poland, covering a vast area of outwash plains diversified in some places by a number of moraine islands[1]. Compared with other regions of Poland, the area is not well-populated (30-50 people per km^2 in 2009, [1]), and it has relatively poor industrial and urban development (Fig. 1).

The area of Tuchola chosen for our study is located between the watersheds of the basins of the Niechwaszcz River, and it covers an area of 209.7 km^2. This area involves a complex of morphological structures that are typical of the last glacial area, including moraine uplands, outwash plains, valley bottoms, and hollows of various origins (mostly kettle holes) (Fig. 1). Thus, the results can be related to a broader area, and it is possible to specify the anthropogenic patterns of water networks typical of Tuchola. The area under study has always been separated from any major settlements and urban centers developed at the Baltic Sea, in the Vistula valley, and the lower Brda valley. The area appears to form a border zone between the historical districts of Pomorze, Kujawy, and Wielkoposka. In the years 1772-1913 the area remained within the territory of the Prussian partition and was the main source of wood for many investments conducted by the Prussian government.

Methods

As the basis for an analysis of the water network, maps at a scale of 1:25,000 were used. The maps belong to two periods: the second half of the 19th century (Prussian topographic maps [2], so-called *Messtischblatt* from 1874) and the second half of the 20th century (Polish topographic maps from 1977-1985 [3]). All the maps have been rectified to the PUWG1992 coordinate system, and the following elements were digitized: water networks, hydrotechnical infrastructure elements, and locations of peat excavation. The obtained results were also compared with data from the Digital Hydrographic Map of Poland [4].

The geological and morphological structure was analyzed with the use of a geological map of Poland at a scale of 1:200,000 (base maps at a scale of 1:50,000 [5]), which were then rectified and digitized. The changes in the water network were analyzed in reference to the main types of morphological units.

All the analyses were conducted with the use of ArcGIS 9.0 software.

Results

The Niechwaszcz River is a right-bank tributary of the Wda River. The Niechwaszcz is 40.16 km long, and the drainage basin covers 209.7 km^2. The source area is located to the north of Brusy town, where the Niechwaszcz begins as a ditch that drains the glacial channel (Fig. 1A). In the northern part of the glacial channel, still within the drainage basin of the Brda River, there are two lakes connected with a ditch: Leśno Górne and Leśno Dolne. The ditch crosses the watershed of the Niechwaszcz drainage basin. Here, a gate in the watershed can be found. In the Niechwaszcz basin, the glacial channel turns into a hollow that exhibits less distinctive edges. The channel then changes its direction, running parallel to the latitude, and eventually turns into a wide valley in the middle of the Niechwaszcz. The water network in the basin is asymmetrical. Its longest left-bank tributary, the Parzenica River, flows from Skąpe Lake and drains the glacial channel. The longitudinally running glacial channels serve as the drainage area of the underground water and most likely constitute one of the main areas that feed the Niechwaszcz River.

At the surface of the area under study, three main types of morphological units can be identified: an outwash plain that covers 48% of the area, moraine uplands covering 32% of the area, and the bottoms of valleys and hollows of various origin that constitute 20% of the area (Fig. 1A). The outwash plain is made of sand and gravel, and it exemplifies

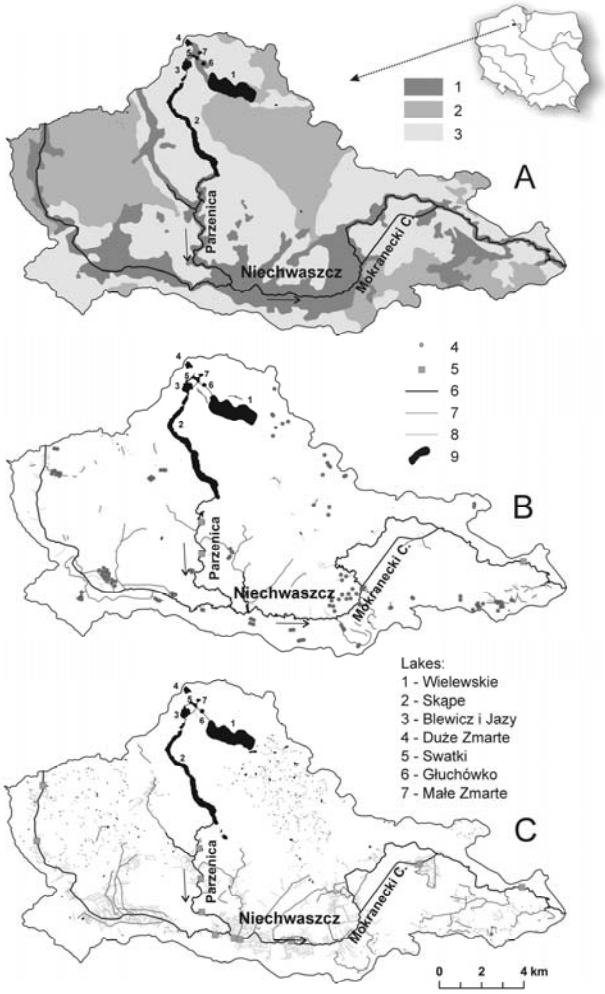

Fig. 1. The Niechwaszcz catchment: A – main morphological units, B – water network in 1874, C – water network in 1977-85 (made on the basis of Prussian and Polish topographic maps [2, 3]): 1 – valley and hollow bottoms, 2 – moraine islands, 3 – outwash plain, 4 – hollows after peat excavation, 5 – weirs, 6 – main rivers and the Mokranecki Canal, 7 – 1st-order ditches, 8 – 2nd-order ditches, 9 – lakes and water reservoirs

[1]Small patches of moraine surrounded by outwash plain sediments

good infiltration conditions. The uplands, by contrast, are poor to very poor, and the bottoms of the valleys and hollows are filled with organic aggregate mud and peat, and are poor or varying. The patterns of the morphological units and geological structure are reflected in the land usage. Within the area of the outwash plains, 75% is covered with forests and only 23% constitute cultivated areas, meadows, and pastures [6]. In the moraine uplands, 85% of the area is cultivated, and forest covers only 10% of the terrain. Of the bottoms of the valleys and hollows, 72% is taken up by meadows and pastures. Forests constitute 18% of the terrain, and the cultivated areas cover 9% of the area. Within the entire area under study, the urban terrains occupy merely 1.3%.

Water Network before Strong Anthropogenic Changes – by the End of the 19^{th} Century

From the analysis of Schrötter's map from the end of the 18^{th} century [7] one can conclude that the natural elements of water network are the Niechwaszcz River with its left-bank tributary, the Parzenica River, and a group of lakes formed in the glacial channels and kettle holes located in the northeastern part of the area under study (Fig. 1B). The Niechwaszcz River was composed of numerous bends and pseudo-meanders, and its course was typical of valleys with bottoms covered with wetlands and filled with peat (Fig. 2).

As can be observed in Schrötter's map, the moraine upland areas were deforested at the beginning of the Prussian reign. Compared with the current borderline between the forested and deforested terrains, there appeared to be a much greater fragmentation of forest areas in the 18^{th} century, especially within the vicinities of large lakes.

A comparison between the water network on Schrötter's map and on maps from 1874 (Fig. 1B) shows minor changes, mainly in the Niechwaszcz River course. The straightforward upstream course, significantly less winding than the channel in the midsection depicted on Schrötter's map, as well as the presence of ditches and numerous hollows formed due to peat excavation (Fig. 1B), indicate the first attempts to regulate hydrographic conditions to develop the valley economically[2]. Due to increased moisture content in the valley, the water gathered in the hollows formed after the excavation of peat and thus functioned as reservoirs. Despite certain symptoms of human activity, the Niechwaszcz Valley was still covered with wetlands and bogs at the end of the 19^{th} century [2].

Changes of Water Network between the Ends of the 19^{th} and 20^{th} Centuries

From analysis of cartographic materials depicting the hydrographic network in 1874 and between 1977 and 1985, one can conclude that the current structure of the water network markedly diverges from its original condition (Fig. 1B and 1C). Two main types of transformations can be observed: the increase of length of the river network, (especially the 2^{nd}-order ditches) and the appearance of a number of water reservoirs (Table 1).

The combined length of streams increased from 146.30 km to 409.23 km, which caused an increase in drainage density from 0.7 $km \cdot km^{-2}$ to 1.95 $km \cdot km^{-2}$. The artificial elements of river network covered approximately 16% of the drainage basin's surface. The total number of water reservoirs increased from 35 to 675. Based on a comparison of cartographic data, it was concluded that 653 new reservoirs were formed and the 13 that still existed in 1874 have disappeared.

The changes show spatial regularities and strong dependence from the main types of morphological units (Fig. 1C and Table 2).

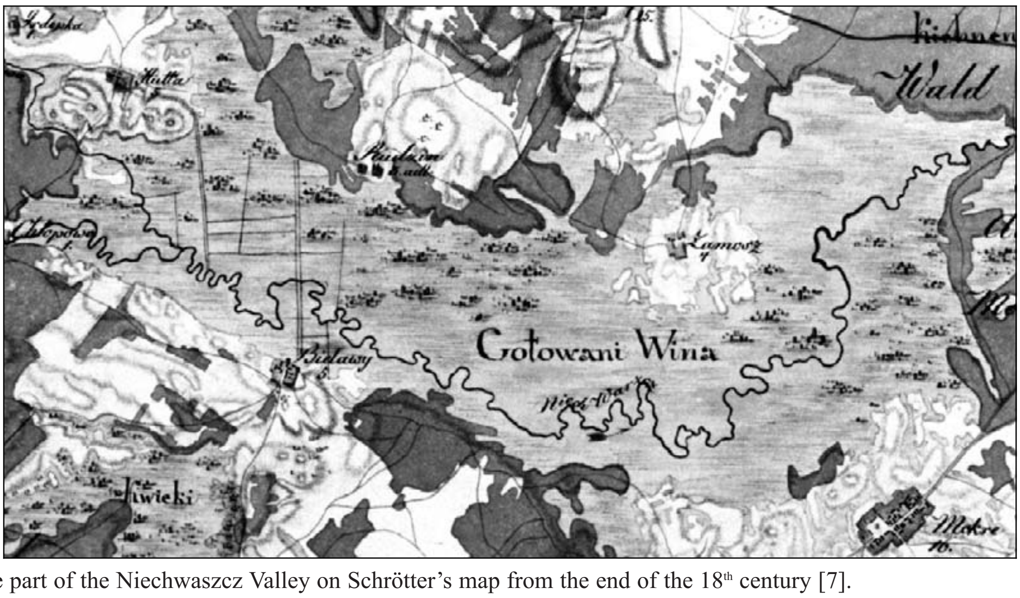

Fig. 2. Middle part of the Niechwaszcz Valley on Schrötter's map from the end of the 18^{th} century [7].

[2]In the 19^{th} century Wdydze Lake, located to the northeastern, and its surrounding areas appeared to be intensively used. Fishery, as well as horse- and sheep-breeding, was well developed; thus, the Niechwaszcz valley was potentially a very attractive pasture area.

Table 1. Changes in the hydrographic network of the Niechwaszcz basin, 1874-1985.

Elements of hydrographic network	1874	1977-1985
River network [km]	146.30	409.23
Main streams [km]	54.65	53.89
1st-order ditches [km]	63.61	77.73
2nd-order ditches [km]	28.04	277.61
Drainage density [km·km^{-2}]	0.70	1.95
Number of water reservoirs	36	675
Lake area [ha]	383.38	405.76
Lake percentage [%]	1.81	1.93

Estimated with the use of Prussian and Polish topographic maps at a scale of 1:25,000 [2, 3].

Water Network Changes in the Valley and Hollow Bottoms

Artificial channels and ditches were built in the valley and hollow bottoms and length of river network increased from 110.01 km to 329.57 km (Table 2). In consequence, new anthropogenic structures appeared in the water network of the Niechwaszcz river and its tributary valleys (Fig. 1C). Among the artificial elements of the outflow network one can identify regulated streams, major channels, and ditches of the 1st-order and melioration ditches of the 2nd-order. The first two appeared by the end of the 19th century, and the third after 1874. Until 1874 the natural course was maintained only within selected reaches of the rivers, for example in the middle of the Niechwaszcz River or lower part of the Parzenica River. Until the 1980s, the length of the melioration ditches of the 1st-order increased by 11.42 km, and the main rivers (Niechwaszcz and Parzenica) shortened slightly (Table 2). Between the end of the 19th and 20th centuries, a large-scale melioration system was constructed (mainly ditches of the 2nd-order), which entirely changed the character of the bottom of the Niechwaszcz River Valley. The combined length of the 2nd-order ditches increased from 11.92 km to 221.15 km, which caused an increase in the drainage density from 2.62 km·km^{-2} to 7.85 km·km^{-2} (Table 2).

The later issue of Prussian maps[3] shows that the majority of the melioration elements were created by the end of the 19th century or in the first part of the 20th century due to the hydrotechnical works conducted during the Prussian partition.

The melioration system developed in the basin of the Niechwaszcz River was not just meant to drain the terrain, as was the situation in the other areas. The highly developed system of weirs maintained the retention of water and thus increased the production rate of meadows in the growing period. Such intensive management was employed by the Prussian government in other meadow complexes in Tuchola Forest. All of the irrigated terrains constituted so-called Łąki Królewskie (Ger. Königswiese). Many of the structures exist even now, and their thoughtfully planned system enabled the controlled flooding of the Niechwaszcz Valley in 1981, when high precipitation (in this and the previous year annual rainfall reached 1000 mm) caused floods in the Wda River and its tributaries. The cessation of outflow from the Niechwaszcz drainage basin allowed reduction of the flood wave on the Wda.

The condition of the weirs and meadows was inspected during field research. It was found that a large number of meadows are not mowed regularly, the ditches have became overgrown and the barrages are left open all the

Table 2. Changes in the hydrographic network of the main morphological units in the Niechwaszcz basin in 1874-1985.

Elements of the hydrographic network	Morphological unit					
	Valley and hollow bottoms		Moraine areas		Outwash plains	
	Period					
	1874	1977-1985	1874	1977-1985	1874	1977-1985
River network [km]	110.01	329.57	17.98	31.31	18.31	48.35
Main streams [km]	53.98	52.89	-	-	0.67	1.0
1st-order ditches [km]	44.11	55.53	5.5	7.0	14.0	15.2
2nd-order ditches [km]	11.92	221.15	12.48	24.31	3.64	32.15
Drainage density [km·km^{-2}]	2.62	7.85	0.26	0.46	0.18	0.48
Number of water reservoirs	11	65	18	518	7	92
Number of water reservoirs per km^2	0.3	1.5	0.3	7.7	0.1	1.0
Lake area [ha]	29.98	24.34	106.82	145.11	246.58	234.76
Lake percentage [%]	0.71	0.58	1.58	2.15	2.47	2.35

Estimated with the use of Prussian and Polish topographic maps at a scale of 1:25,000 [2, 3].

[3]The maps from the years 1905-10 present a hydrographic network similar to the one depicted on maps from the 1980s.

time. The condition of the structures indicates that they are no longer used. In most of the permits under the water management act issued for the use of barrages of the hydrotechnical system of the Niechwaszcz River, the expiration date was set to the year 2000. Records included in the water logbooks (Regional Water Management Board in Gdańsk) suggest that the permits have not been renewed since 2005. The only renovated dam, now used as a small hydropower plant, is located in the lower section of the Niechwaszcz River in Zawada village (Fig. 1C).

Another type of change was the appearance of artificial reservoirs. The number of reservoirs in the valley and hollow bottoms increased from 11 to 65 between the end of the 19^{th} century and the end of the 20^{th} century (Table 2). The reservoirs that appear within the bottoms of the valleys and hollows are typical of post-excavation sites (peat excavation) and are characterized by a rectangular shape. The reservoirs that were formed due to damming are of marginal importance. There are three such reservoirs marked on the maps from the end of the 19^{th} century (two on the Parzenica River and one on Niechwaszcz).

Water Network Changes in the Moraine Uplands

Another crucial change in the water network involves the moraine areas found within the area under study and identified as bottom moraine islands and terminal moraine hills.

In the years 1874-1985, the number of water reservoirs in this area increased markedly from 0.3 to 7.7 reservoirs per 1 km^2 (Table 2). Within the remaining groups of morphological units, the number of lakes also increased, albeit less significantly. For the entire area under study the number of water reservoirs increased from 36 to 675 and within the moraine areas from 18 to 518. The largest of the newly formed reservoirs covers 4.2 ha, and the smallest covers 0.1 ha. In the 19^{th} century, the places where the new water reservoirs appeared constituted minor hollows in the deforested areas of the uplands. The appearance of water in the hollows was most probably caused by the deepening of their bottoms due to resource excavation (clay, peat). The small size of the anthropogenic water reservoirs caused only a minor increase in the lake percentage from 1.58% to 2.15% (Table 2).

Less important changes were observed in the case of the drainage network. Drainage density increased slightly, from 0.18 $km \cdot km^{-2}$ to 0.48 $km \cdot km^{-2}$ (Table 2), mainly due to the construction of small ditches to force the water outflow in the time of snowmelt (winter, spring) or high precipitation.

Water Network Changes in the Outwash Plain

In the outwash plain area the changes of water network are relatively insignificant (Fig. 1). The drainage density increased only slightly, from 0.18 $km \cdot km^{-2}$ to 0.48 $km \cdot km^{-2}$ (Table 2). The most important change involved the construction of the 4.95-km-long Mokranecki Canal (Kanał Mokranecki) in the 1840s. This canal is the shortest of three irrigation channels built in this period in Tuchola Forest[4]. The purpose of the canal was to provide water to the meadows, covering 1200 ha, located in the outwash plain in the eastern part of Niechwaszcz basin.

Table 3. Changes in the surface area of selected lakes in the Niechwaszcz basin in 1874-1985.

Number on Fig. 1B and 1C	Lake	1874 [ha]	1977-1985 [ha]	Change [%]
1	Wielewskie	166.0	157.1	-5.4
2	Skąpe	146.0	125.9	-13.8
3	Blewicz and Jazy	27.8	22.3	-19.8
4	Duże Zmarte	8.1	7.6	-6.2
5	Swatki	6.7	4.7	-29.9
6	Głuchówko	3.0	3.3	+10.0
7	Małe Zmarte	2.4	2.5	+4.2

Estimated with the use of Prussian and Polish topographic maps at a scale of 1:25,000 [2, 3].

In some parts of the outwash plain areas one can observe an appearance of artificial water reservoirs similar to those in the moraine uplands. The total number of reservoirs changed from 7 at the end of the 19^{th} century to 92 in the end of the 20^{th} century (Table 2). Such reservoirs are most common near the borderline with the uplands (Fig. 1), where the clay is shallowly placed below the gravel and sands deposits and thus facilitates the collection of water in the hollows.

In this part of the investigated catchment there is a number of natural lakes located in the glacial channels. Borderlines of the lakes depicted on cartographic materials shows decreasing surface area a few to a dozen or so per cent in the case of six from seven analyzed lakes (Table 3). As an effect, lake percentage in the outwash plain decreased from 2.47% to 2.35%, despite the appearance of some artificial reservoirs.

Discussion of Results

Due to the low urbanization and high forestation rate of this particular region of Tuchola, it is regarded as an area that is relatively sparsely transformed. Previous research has shown, however, that despite the predominance of forests within the spatial structure of terrain management, the hydrographic network has changed markedly in a number of places, and such transformations have influenced the conditions of river outflow [8-11]. It should be noted that many changes were introduced a relatively long time ago. These changes allowed the environment to adapt to the new

[4]Apart from the Mokranecki Canal, two other irrigation channels were built: Great Brda Canal (Wielki Kanał Brdy) (22 km) and Wda Canal (Kanał Wdy) (23 km).

conditions and to partially mask the traces that would prove the anthropogenic transformations of the water network.

With the available cartographic materials, it is easy to interpret the changes of the bottoms of the valleys and hollows in the Niechwaszcz basin. However, it appears to be more difficult to identify the anthropogenic character of the water reservoirs within the moraine islands, as the small reservoirs constitute a typical element of the last glacial landscape of both outwash plains and moraine uplands. The anthropogenic origins of these reservoirs can be identified on the premise of their frequent occurrence and regular spatial pattern. In the moraine uplands, the natural hollows occur most commonly in sequences that coincide with the range of the ice sheet. In the outwash plain, however, they occur in the line of the glacial channel. In the second case, often only the deepest parts of the channel are preserved, and thus the landscape involves a stretch of lakes on the surface of the outwash plain. The anthropogenic origins are also indicated by their frequent occurrence, which greatly exceeds the occurrence of such lakes in natural conditions. If the analysis was to be limited only to the lake percentage, the transformations for the entire area under study constitute a mere 0.1% and appear to be caused mainly by the changes in the surface area size of the large lakes.

It should be emphasized that it tends to be far more common to describe the analysis of the process of lake disappearance, its magnitude and its causes. A similar analysis of changes in the surface area of reservoirs was conducted for the nearby Pojezierze Raduńskie using the same set of maps as employed in the present study [12]. Within the group of 49 analyzed reservoirs, the lake disappearance rate in most cases oscillated from a few to approximately 12% of the water surface. However, only three of the 49 analyzed reservoirs showed a loss of surface area exceeding 20%. Another seven reduced their surface area by less than 10%. The greatest number of lakes that indicated a significant loss of surface area coincided with glacial channels, and the least noticeable changes involved the lakes located within the watershed areas. Compared with the results obtained for Pojezierze Raduńskie, it can be stated that the loss of the surface area of the large lakes within the Niechwaszcz basin is considerable and that the increase of the surface area is true only for the relatively small lakes.

As mentioned above, it is much less common to examine the changes in the number and surface area of small reservoirs. The reservoirs with a surface area below 1 ha are often not accounted for in the research of changes of both surface area and the number of lakes [13-15]. Some studies, however, have already touched upon the subject of so-called *anthropogenic lakelands* in Poland [16]. Nevertheless, such studies are usually conducted for the most urbanized areas [17-19]. R. Graf [19] described the post-excavation reservoirs in reference to the brick-making industry found in the suburbs of Poznań. Perhaps the formation of some of the hollows that were found in the moraine area of the Niechwaszcz basin may also be connected to the excavation of clay needed in brick-making. Determining the purpose of the hollows require further research. It can be speculated that the scarcely occurring moraine islands in this area might also have been excavated for the use of the neighboring towns located within the outwash plain areas.

It should be emphasized that in the area of scarcely occurring natural lakes, the appearance of a large number of small water reservoirs may greatly affect both the hydrographical network and the structure of the landscape. The large number of such reservoirs radically decreases the distance from water, which improves life conditions for amphibians, birds, and many other organisms.

A typical indicator of anthropogenic transformation within the bottoms of valleys and hollows filled with peat is an increased density of river networks and their geometrical arrangement. In natural conditions, the drainage density varies from 1 to 2 $km \cdot km^{-2}$. Similar indicators were obtained for other river valleys of the Wda basin with the use of the data collected in the Digital Hydrographic Map of Poland [4, 9]. Only sporadically was the density of the river network within the valley bottoms estimated to be less than 1 $km \cdot km^{-2}$. It should be noted, however, that the map is slightly less precise (scale of 1:50,000). For example, the drainage density for the entire Niechwaszcz basin was estimated to be 1.75 $km \cdot km^{-2}$, which is smaller by 0.2 $km \cdot km^{-2}$ compared with the results obtained with the 1:25,000 maps. In the case of the other morphological units analyzed in the Niechwaszcz basin, the drainage density from the end of the 19^{th} century did not exceed 0.3 $km \cdot km^{-2}$, being only slightly higher a hundred years later (0.5 $km \cdot km^{-2}$). Within the outwash plain area, the reason for this situation appears to be the lack of a need to regulate the water conditions, while in the uplands, drain tiles were built instead of open ditches.

Conclusions

The water network of the area under study shows a great degree of transformation. The dominating directions of change are closely related to the main morphological units, which, on the one hand, determined the course of the water network development from before the intensive anthropogenic transformations and, on the other hand, influenced the nature of human activities. The anthropogenic elements of the water network were dominated by linear formations (channels and ditches) within the areas of valleys, hollows and outwash plain outflow routes and the overland formations in the moraine uplands (reservoirs). The primary function of the first type of object was drainage and periodical irrigation, and the second type retained water (often as a secondary effect of excavation activities).

On a broader spectrum, the results of the conducted analysis can be used to perform an automatic analysis of the transformations of the water network in Tuchola Forest, which allows the time-consuming procedure of the digitization of water networks from archival maps to be shortened. The drainage density indicators in reference to the bottoms of the valleys and hollows (as well as the frequency of water reservoir occurrence in the moraine uplands and outwash plain areas) may serve as elements that allow determination of the areas with transformed water networks.

In the case of outwash plains, the irregularity in water reservoir occurrence, the presence of residential developments and shallowly located sediments that obstruct water infiltration may additionally indicate its anthropogenic character. The studies presented in this paper also indicate that while it is advisable to analyze the surface area of reservoirs to examine the changes in water resources and lake disappearance, the indicator of reservoir occurrence frequency is more useful in the case of landscape and ecological research. Determining the origins of small water reservoirs within the Niechwaszcz basin may also be the premise to verify views on a large number of lakes in kettle holes within the Polish Lowland.

The results of the research presented in this paper should also be taken into account when taking any decisions and actions that may lead to changes in water network and water management. Certain examples of areas with water conditions heavily transformed during the Prussian partition were presented in previous papers [9, 10]. The results show that contemporary hydrological conditions in Tuchola are frequently classified as natural or quasi-natural. In consequence, some hydrotechnical works or water management may lead to unexpected processes.

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