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Relationship between the environmental and hydrogeological elements characterizing groundwater-dependent ecosystems in central Poland

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Abstract Results are presented for a quantitative and qualitative analysis of the relationship between hydrogeological and environmental elements characterizing the areas of groundwater-dependent ecosytems (GDEs) located in the Kampinos National Park in central Poland. Statistical analysis was used to assess the seasonal and long-term variability of groundwater conditions. A geographic information system (GIS)-based model enabled the visualization of the test results. Objectification of spatial relationships between hydrogeological and environmental elements was carried out using factor analysis. The statistical analysis of groundwater levels in the period 1999–2013 confirmed the sequence of wet and dry years. The calculation enabled the determination of the range of groundwater-level changes, but no specific trends were observed with respect to these changes. Moreover, the widespread belief that the lowering of the water table in presented GDEs is due to anthropogenic pressure and climate change was not confirmed. The factor analysis showed that GDE areas are characterized by a considerable homogeneity of abiotic elements and locally occurring heterogeneous regions, mainly related to anthropogenic pressure. Dependency between the type of plant community and depth to the water table in the typical GDEs was not defined by the delimiting factors.

Keywords Groundwater dependent ecosystem · Groundwater monitoring · Statistics · Factor analysis · Poland

Introduction

Preservation of existing ecosystems dependent on groundwater (groundwater-dependent ecosystems, GDEs) and renaturalization of selected degraded areas are important elements in most strategies related to the sustainable development and management of water resources. The hydrogeological and environmental elements affecting the condition of GDEs are mainly: regime of infiltration, land use, groundwater extraction, irrigation-discharge networks, and the types and aquatic needs of plant ecosystems. Besides effects of anthropogenic activity, those elements are defined in the literature as a continuous, structured set of relationships: the aquifer-soil-surface water-plant-atmosphere continuum (ASS-PAC; Eamus et al. 2006). The role and importance of each element vary depending on the location of protected ecosystems (Boulton 2005; Boulton and Hancock 2006; Murray et al. 2006; Whiteman et al. 2010; Klove et al. 2011; Baattrup-Pedersen et al. 2012).

This research conducted in central Poland focused on the quantitative and qualitative analysis of the relationship between hydrogeological and environmental elements characterizing the areas of GDEs (Table 1).

This analysis was primarily used to identify the relationships, and particularly to determine the spatial relationship between the type of plant community and depth to the water table in the GDE areas (Fig. 1). This was made possible through many years of research concerning spatial, seasonal and long-term variability of groundwater conditions, and gathering data about other elements such as soil types, plant communities and spatial development in GDE areas.

GDE areas are characterized by specific types of plant communities with generally high humidity requirements, which can be transposed to groundwater depth. The groundwater level occurrence needed for the existence of particular plant communities in GDE areas is presented in Table 2.

Materials and methods

Study area

Studies were conducted in part of the Vistula Valley, a large-sized river of the North European Plain (river length: 1,047 km, size of catchment: 194,424 km^2). The examined section of the Vistula Valley is located in the Kampinos Forest, part of which is a national park subjected to many forms of conservation protection. Kampinos National Park (KNP) is also an area which is part of the network NATURA 2000 and Biosphere Reservoir (UNESCO MaB). In

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Table 1 Groups and types of elements characterizing the areas of GDEs

Group of elements	Type of element
Hydrogeological	Average annual groundwater depth for the period 1999–2013
	Groundwater level in 2003
	Groundwater level in 2011
	Average annual amplitude of groundwater depth for the period 1999–2013
	Infiltration recharge
	Hydraulic conductivity of the upper part of the aquifer (depth <10 m)
	Hydraulic conductivity of the deeper part of the aquifer (depth >10 m)
Environmental	Soil types
	Plant community type
	Distance from surface watercourses
	Lithology of subsurface sediments (unsaturated zone)
	X-coordinate location (Longitude of block grid center)
	Y-coordinate location (Latitude of block grid center)

accordance with the requirements of the UNESCO programme, the reservoir has three zones: central, buffer and transit. The central zone, called the core, encompasses areas of Kampinos National Park under strict protection, with adjacent territories which are valuable in terms of nature. The most important function of the KNP is the protection of natural resources and natural processes.

Kampinos National Park, established in 1950, takes up an area of 385 km^2 that is surrounded by a protective zone established in 1977 (called a lagging) with an area of 378 km^2. The park and its lagging is bordered in the north and north-east by the Vistula River; in the east, the border runs through suburbs of Warsaw, in the south it runs through agricultural areas of the Łowicz-Błonie Plain (Błonie level); while in the west, the left shore of Bzura River constitutes the border (Fig. 1).

The hydrogeological conditions of KNP have been the subject of several research projects, including Project 2011–2014 “Model analysis of hydrogeological conditions in wetlands” (The State Committee for Scientific Research) and Project 2008–2011 “Development of the method for reconstruction of primary hydrological conditions in Kampinos National Park in order to restrain nature degradation and improve biodiversity status” (EEA Financial Mechanism and the Norwegian Financial Mechanism), and are summarized in several publications (Krogulec 2003a, b, 2004; 2013; Krogulec et al. 2009, 2011). The following criteria were used to distinguish

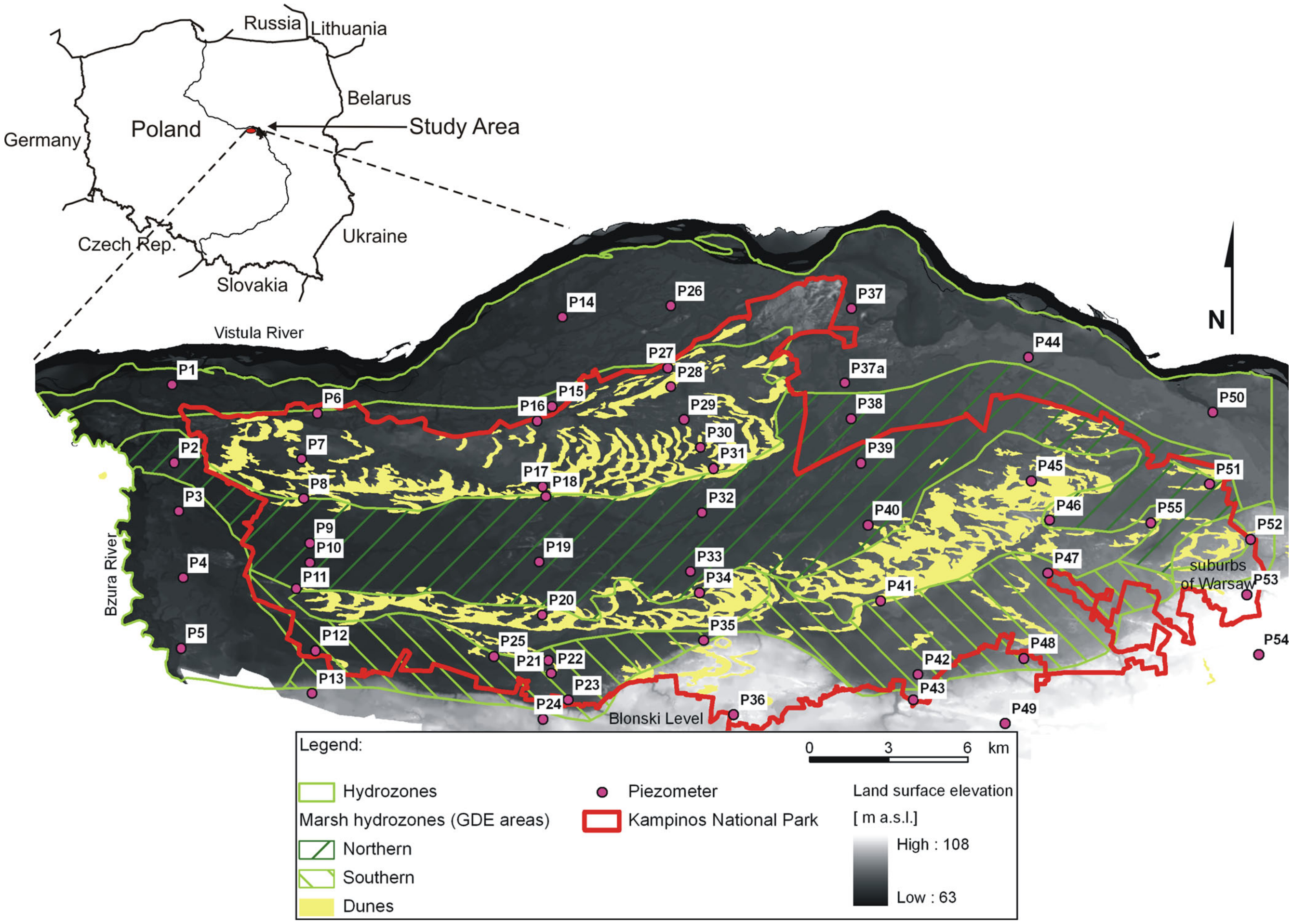

Fig. 1 Location of the GDE areas on the background of the Kampinos National Park

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Table 2 Types of plant communities occurring in GDE areas and their general humidity requirements (Kloss 2003a, b; Kucharski and Michalska-Hejduk 2003)

Plant communities	Humidity requirements of plant communities
Sparganio-Glycerietum fluitantis, *Phragmitetum communis*, *Glycerietum maximae, Phragmition*	Surface waters
Ribeso nigri-Alnetum, *Vaccinio uliginosi-pinetum, Magnocaricion*, *Scheuchzerio-Caricetea fuscae, Salicetum pentandro-cinereae*, *Cercatalia fuscae*	Water should occur above ground surface for most of the year
Fraxino-Alnetum, Molinion ceruleae, Calthion	Water should occur to 0.5 m below ground surface, with possibly short period of occurrence above ground surface
Tilio-Carpinetum, *Arrhenatherion*	Water should occur near ground surface, with possibly autumn decrease to 1 m below ground surface

zones of similar hydrodynamic and environmental conditions, known as the so-called hydrozones (Krogulec 2004): differences in geologic structure and geomorphology, lithology of subsurface sediments and related vegetation cover, depth to the water table, amplitude of water level fluctuations and human economic activities. The following hydrozones have been distinguished in the KNP area:

- The Vistula River flood plain terrace
- Two marsh zones (northern and southern)
- Two dune zones (northern and southern)
- An accumulative-erosive Warsaw-Blonie terrace called the Blonski level (with part of the upland)

Quaternary sediments occur in the entire area of the park and lagging, constituting a collector for groundwater. A clear dichotomy of this unconfined aquifer, of a total thickness up to 50 m, is connected with its lithological shape. The top part of the aquifer has a sandy and sandy-gravel character; the bottom is created by sandy-silt sediments, in places changing to sandy clay, clay and till. The surface of the aquitard created by glacial tills and more often Pliocene loams, constituting the floor of the Quaternary aquifer, occurs in the region of KNP at elevations ranging from 2 to 54 m above sea level (a.s.l.; Baraniecka and Konecka-Betley 1987; Sarnacka 1992; Krogulec et al. 2003; Fig. 2). Delimitation of the main groundwater circulation systems in the Quaternary aquifer was made by Krogulec (2004) following the methods of Tóth (1963). Although general flow direction in the aquifer is north and west to the main discharge base, i.e. the Vistula and Bzura rivers (intermediate system), groundwater circulation in GDE areas should be considered as a local system (Fig. 3). The influence of river stage on the aquifer is very limited (around 1 km), so the groundwater system in GDE areas can be viewed as independent. For the purposes of evaluation of the water balance in the Quaternary aquifer by model tests (Gruszczyński and Krogulec 2012), the groundwater system was limited from the north by the Vistula River, from the west by the Bzura River, and from the south along the edge of Blonski Level, while the eastern boundary runs along the border of the city of Warsaw. The bottom surface of the model was determined by weakly permeable deposits occurring in the base of the alluvia. More detailed characteristics of groundwater conditions are presented in the following.

Methodology

The methodology was designed to create a database describing spatial variability of all hydrogeological and environmental elements characterizing GDE areas.

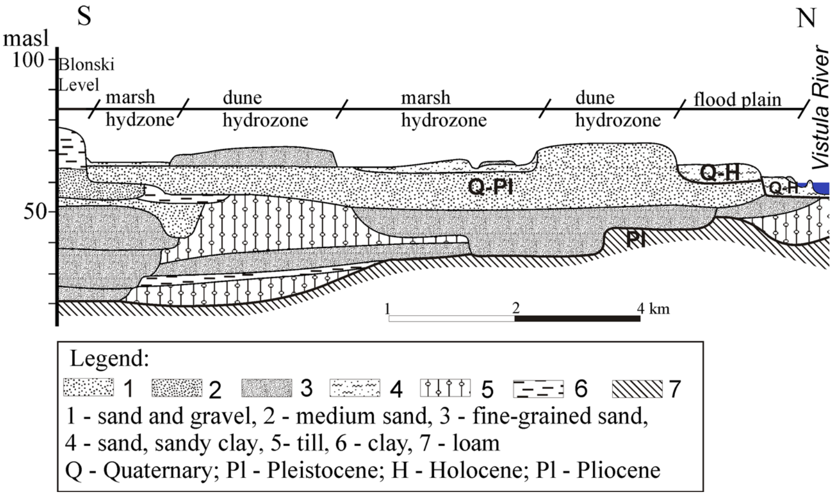

Fig. 2 Schematic cross-section of Quaternary sediment in the area of the Kampinos National Park

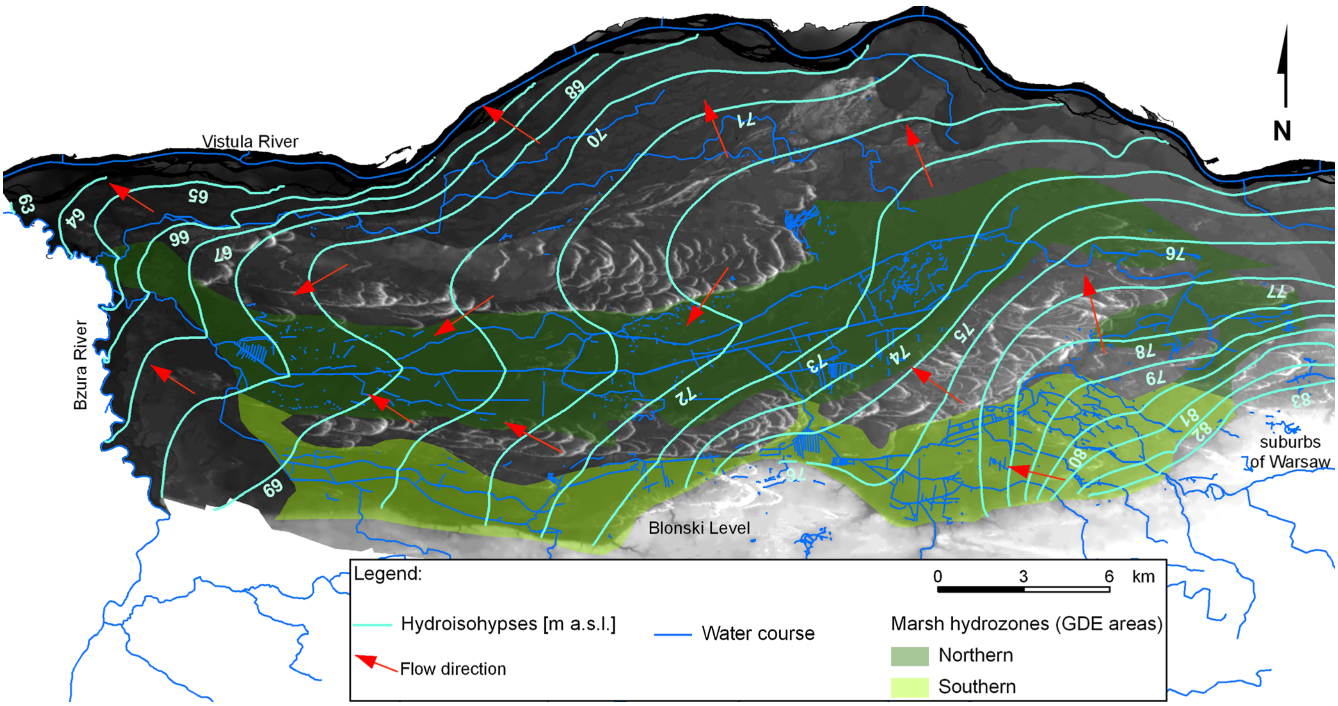

Fig. 3 Hydroisohypses of the Quaternary aquifer feeding GDE areas in KNP: results of groundwater flow model, as the average annual state during the period 1999–2013

Several steps were needed, as shown on Fig. 4, to set up the database as the input file for factor analysis.The first step was the analysis of data from the groundwater-monitoring network in KNP, which enabled the evaluation of trend changes at points and the identification of specific statistical data. The basis of the analysis was a set of data from the period 1999–2013, which provided over 7,500 observations referring to 27 observation points located in the GDEs. The statistical analysis of those monitoring observations most widely used in monitoring networks (Loaiciga et al. 1992; Moon et al. 2004; Bidwell 2005; Coppola et al. 2005; Krogulec and Zabłocki 2008; Yang et al. 2008; Baalousha 2010; Maheswaran and Khosa 2013; Shiri et al. 2013) was the basis for identifying the range of seasonal, annual and long-term groundwater level changes.

Assessment of the quantitative state of groundwater was carried out using spatial statistical analyses as well as numerical groundwater flow modeling; the GIS-based model, made by using the Visual MODFLOW software package, was employed as a tool, which is commonly used to visualize test results in hydrogeology and ecology (Olivera and Maidment 1999; Gogu et al. 2001; Store and Kangas 2001; Babiker et al. 2005; Baker et al. 2001).

The spatial interpretation of the hydrogeological data was carried out using the GIS software. The analysis was

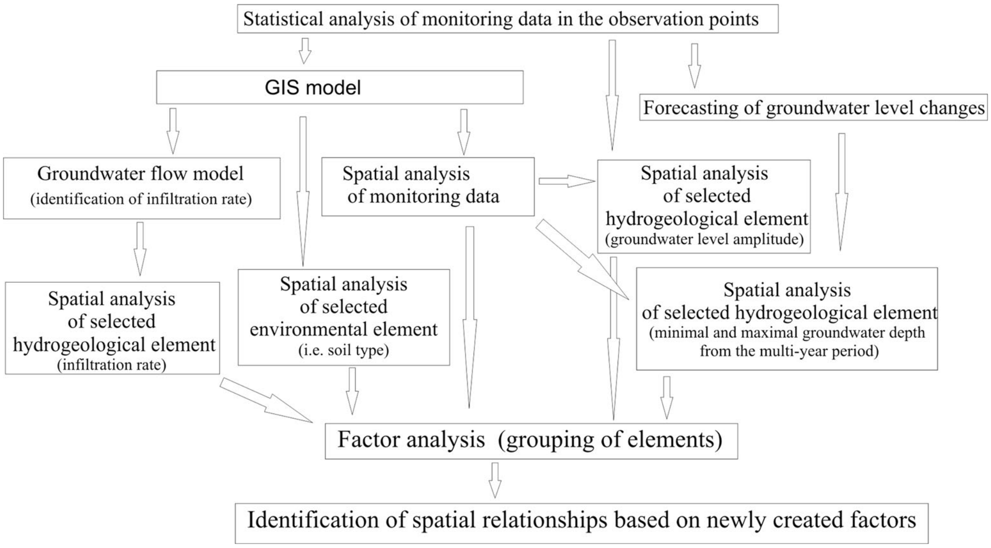

Fig. 4 Evaluation methodology of spatial relationships between hydrogeological and environmental elements in the GDE areas

conducted with the Kriging method, which involved data derived from the monitoring network (Sikorska-Maykowska et al. 1998). Uncertainty of the method results was checked by comparing groundwater-flow-model results representing steady state. In the case of particular groundwater levels (2003, 2011), computed mean square errors were lower than the mean square error of estimation in the groundwater flow model (0.167 m). The result of the spatial distribution of average annual groundwater level from period 1999–2013 was compared also to the results of the groundwater flow model. In the area of 105.67 km^2, which is 43.63 % of GDE areas, the mean square error of statistical distribution was lower than 0.167 m. The highest discrepancy was found on the southern and eastern border of GDE areas (>1 m).

The study area was digitized by adopting a discretization space step size (grid size) of 0.01 km^2 (100×100 m), and in this way the 23,814 blocks of the discretization grid were obtained. The adopted step size corresponds to the resolution of the digital elevation model and the accuracy of hydrogeological, geological and environmental reconnaissance. The continuous data (i.e., soil types, plant communities) were transformed into point observations located in the block center representing the dominant type of data occurring in the particular grid. Also discrete data were input into the factor analysis. Each discretization cell had same attributes: hydrogeological and environmental (Table 3).

The next step of research was factor analysis. The hydrogeological and environmental elements in a database enable factor analysis to be performed in order to objectify the spatial relationships between the elements that describe the hydrological system (Joreskog et al. 1976; Reyment and Joreskog 1993; Liszkowska 1995; Gangopadhyay et al. 2001; Dragon 2002; Stępień 2004). To extract the most important factors in the factor analysis and to group them into hydrogeological and environmental elements, principal component analysis (PCA) was conducted by using Statistica 10.0 software. The PCA method is most commonly used to reduce the size of a database by extracting those factors explaining the largest part to explain the smallest part of the variance in a newly established coordinate system (Bryant and Atchley 1975; Jolliffe 2002). Thus, the purpose of using this method was, first of all, to categorize hydrogeological and environmental elements in a 23,814-block grid describing the study area. The ranking is given to particular elements according to the precisely gathered information about the aquifer and the range of its variability in the presented area, making this also a subjective assessment, which is why the hydrogeologist's role in this procedure is so important. The data such as the soil type, lithology of subsurface sediments creating an unsaturated zone and plant communities, were replaced by numerical values of a ranking system in the range 1–10 using a procedure similar to the ranking procedure used in the assessment of groundwater vulnerability to pollution (Aller et al. 1987; Krogulec 2004). In the case of soil types and lithology of subsurface sediments, lower rankings generally indicate

Table 3 Class division and range of hydrogeological and environmental elements

Element number	Group of elements	Type of element	Range of variability	Class/range	Range of class values
1	Hydrogeological	Average annual groundwater depth for the period 1999–2013	<0–>5 m	Every 0.5 m	1–12
2		Groundwater level in 2003	<0–>5 m	Every 0.5 m	1–12
3		Groundwater level in 2011	<0–>5 m	Every 0.5 m	1–12
4		Average annual amplitude of groundwater depth for the period 1999–2013	0.6–1.03 m	Every 0.1 m	1–5
5		Infiltration recharge	<−60–>50 mm/year	Every 10 mm/year	1–13
6		Hydraulic conductivity of the upper part of the aquifer (depth <10 m)	2.3–12.7 m/day	Every 2 m/day	1–6
7		Hydraulic conductivity of the deeper part of the aquifer (depth >10 m)	0.44–60.0 m/day	Every 10 m/day	1–6
8	Environmental	Soil types	As in Table 8	–	5–10
9		Plant community type	As in Table 9	–	1–4
10		Distance from surface watercourses (local base of discharge)	0–1000 m	0–100 m 100–200 m 200–500 m 500–1000 m	1–4
11		Lithology of subsurface sediments (unsaturated zone)	As in Table 7	–	2–9
12		Longitude of block grid center	585,167–627,167 m	–	–
13		Latitude of block grid center	490,078–503,078 m	–	–

higher resistance to pollutant migration from the ground surface and a lower value of hydraulic conductivity; in the case of plant communities, the lowest rank informs about the relatively lower humidity requirements compared with the other groups. Based on the range of variability of particular hydrogeological elements, division into classes was also made.

All the data were standardized and transformed to the log-normal distribution in the case of skew distribution defined on the basis of the Kolmogorov-Smirnov test (Joreskog et al. 1976). The correlation matrix indicated high correlation between some elements (i.e., groundwater depth vs. infiltration recharge), so only seven major and four auxiliary elements were selected for further analysis. This step allowed for reduction of potentially created new factors from 13 elements (Table 3) to 7 before analysis was started. For element Nos. 2 and 3, groundwater levels in 2003 and 2011 (Table 3) were also excluded from analysis due to the high Pearson correlation with element No. 1. Factors with the lowest factor loadings were rejected, while for the strongest factors distinguished by the Scree test (Cattell 1966), interpretation was made on the basis of the strength of correlation between particular elements.

Characteristics of selected hydrogeological and environmental elements

There were 13 elements used that describe the GDE areas. Detailed characteristics of selected elements are presented. Selected elements were chosen with reference to (1) the gathered data from the groundwater-monitoring network and previously presented water balance from the groundwater flow model (groundwater depth; infiltration recharge) and (2) character of the data and their spatial variability (qualitative data such as soil type, plant communities and the lithology of subsurface sediments). Information about the other elements and main characteristics are presented in Table 3.

Statistical analysis of groundwater levels

Statistical analysis of groundwater levels in both marsh hydrozones included basic statistics for both the 1999–2013 period and particular years: mean, median, standard deviation, first quartile, third quartile, max, min, max amplitude, average amplitude. On the basis of these data, seasonal changes were analyzed and the scope of groundwater levels was defined. For both hydrozones a distinct characterization was established, highlighting their diversity despite their close, shared neighborhoods.

In the northern marsh hydrozone, the average annual groundwater level for the period 1999–2013 remained at the level of 0.91 m below the ground surface (Fig. 5). The average annual groundwater level in this period ranged from 0.47 m below ground surface (bgs) in 2011 to 1.14 mbgs in 2003. Groundwater levels such as 0.40 m above ground surface (2011) and 2.16 mbgs (2003), define the range of recorded measurements and, because of the long period of observation, it can be assumed that this range approximately determines the groundwater levels which can be observed in this environment.

Seasonal changes proceeded in a similar manner throughout the measurement period. The highest average groundwater level in the hydrozone occurs in the period associated with groundwater recharge linked to thawing in

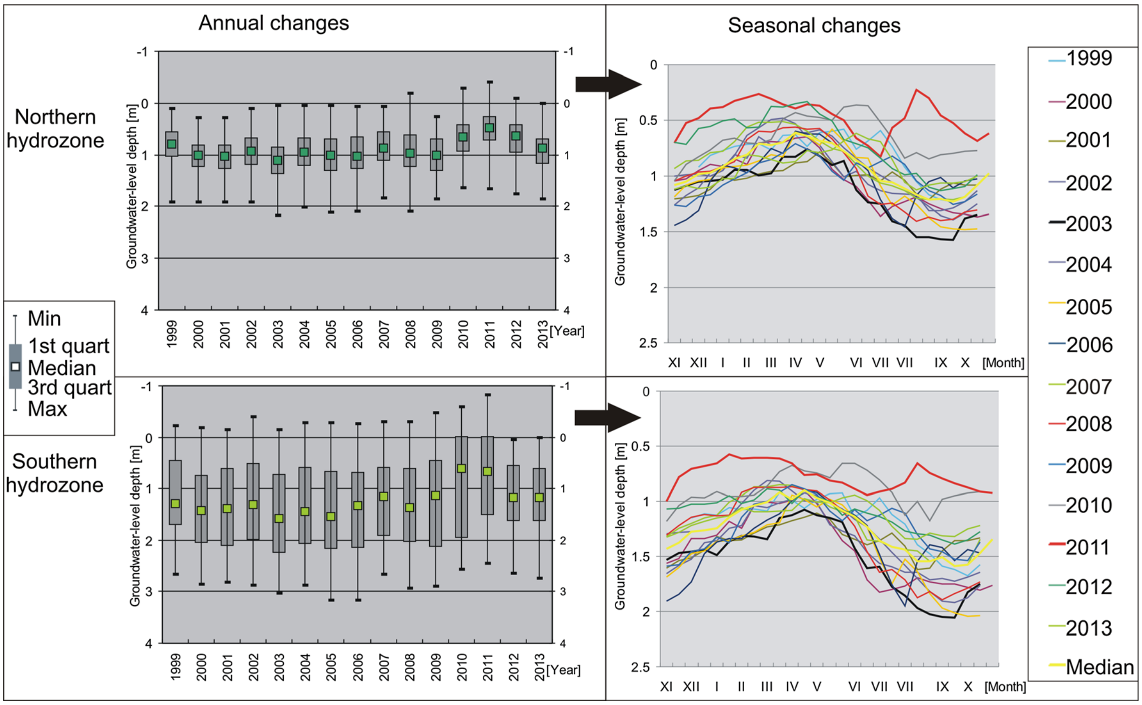

Fig. 5 Multi-year and seasonal groundwater-level changes in the GDEs areas

Table 4 Statistics related to depth to groundwater in the marsh hydrozones based of the spatial distribution: average annual groundwater level for the period 1999–2013

	Northern hydrozone	Southern hydrozone
Area [km^2]	155.68	86.62
Depth to groundwater [mbgs]		
Average	1.03	1.68
Median	0.90	1.20
Max depth	10.10	10.95
Min depth	0.60 ags	1.10 ags
First quartile	0.40	0.49
Third quartile	1.54	2.29
SD	1.01	1.97
Skewness	2.43	1.75

mbgs meters below ground surface (except where highlighted as ags); *ags* above ground surface; *SD* standard deviation

the months from February to April, when the groundwater level is at a depth of about 0.5 mbgs (Fig. 5). The lowest groundwater level occurs in late summer and autumn (from 15.09 to 15.10) and on average ranges from 1 to 1.5 mbgs in the hydrozone depending on the year. Only the year 2011 marked two periods of the highest groundwater level: February–March and August–September. Seasonal changes in the depth of groundwater in the hydrological year 2004 are the most similar to the average seasonal changes in the 1999–2013 period (median). In the southern marsh hydrozone, the average depth to groundwater for the period 1999–2013, i.e., 1.24 mbgs is slightly higher than those in the northern hydrozone. The average annual groundwater levels range from 0.77 mbgs (2011) to 1.52 mbgs (2003) (Fig. 5). The range of measurements that have been previously reported determine the groundwater levels: 0.83 m above ground surface (2011) and 3.17 mbgs (2006). Seasonal changes proceeded in a similar manner for all years of the period 1999–2013. The highest average groundwater level occurs in April when the groundwater level is at an average depth of about 0.8–1.2 mbgs (Fig. 5). The lowest groundwater

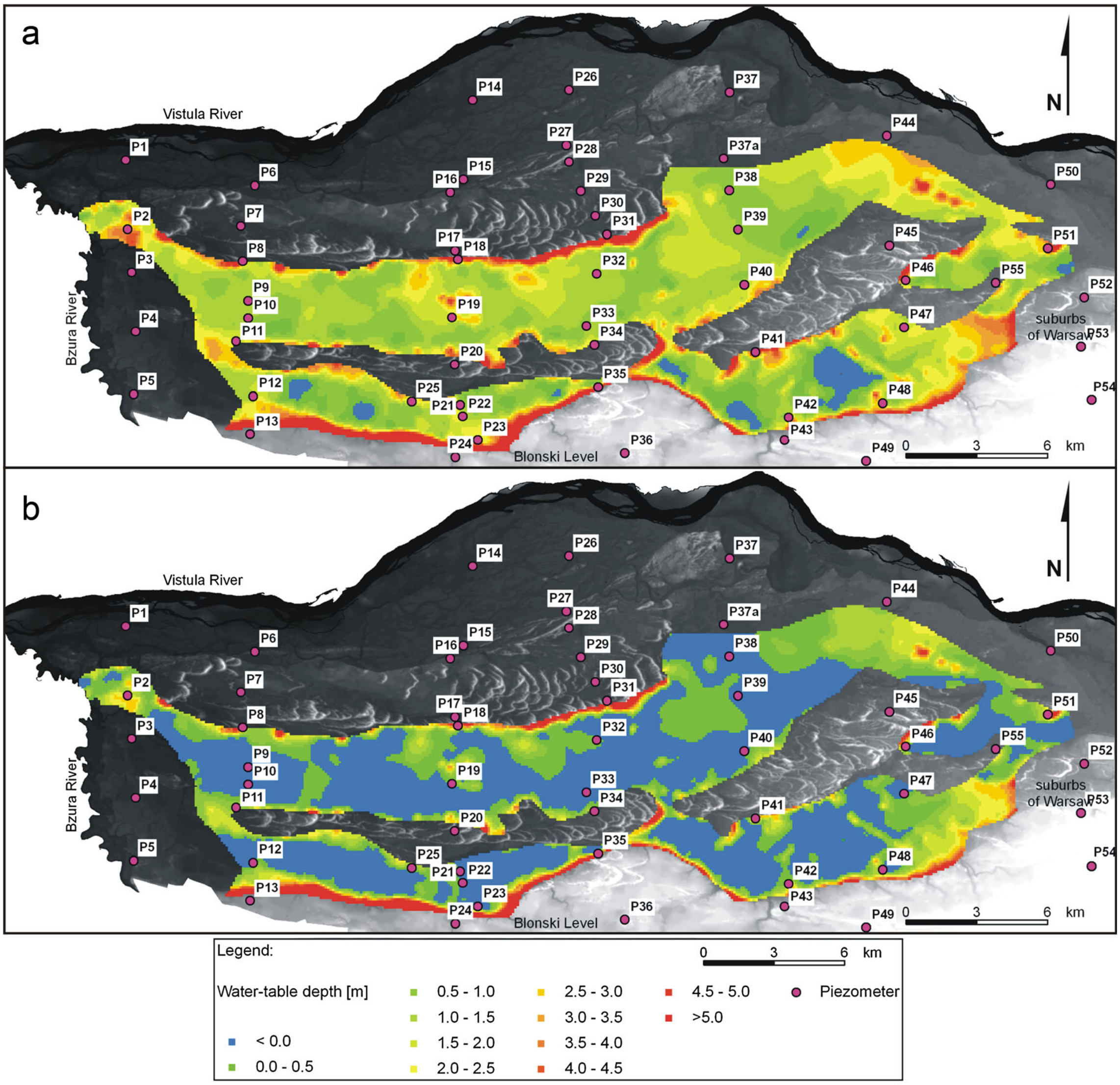

Fig. 6 Contours of water-table depth: **a** maximum depth in year 2003; **b** minimum depth in year 2011

Table 5 Water balance in the marsh hydrozones

Element of the balance	Northern marsh zone		Southern marsh zone	
	Supply [m^3/day]	Discharge [m^3/day]	Supply [m^3/day]	Discharge [m^3/day]
Exploitation	0.0	0.0	0.0	476.2
Watercourses	750.8	10029.8	2007.9	3753.5
Underground evaporation	0.0	23707.0	0.0	11651.0
Inflow through the model boundary	0.0	0.0	11312.0	0.0
Infiltration recharge	19405.0	0.0	11877.0	0.0
Supply from other hydrozones	21275.0	7996.6	1296.5	11960.4
Total	41736.0	41733.0	27841.0	27841.1

level occurs earlier than in the northern marsh hydrozone–late August and September—and the average depth to groundwater is approximately 1.5 mbgs (two periods in 2011: summer and in winter). Seasonal changes in the depth of groundwater in the hydrological year 2007 (this year is classified as wet) are the most similar to average seasonal changes in the 1999–2013 period (median). As in the northern marsh hydrozone, a range of average seasonal changes mainly determines the groundwater levels in 2003 and 2011.

Spatial analysis of groundwater levels

Based on the results of the statistical analysis of monitoring data from the period 1999–2013, the 2 years 2003 and 2011 were selected. These years illustrate the lowest and highest values of groundwater levels in the period. On the basis of measurements from these years, maps of the contours of the maximum (2003) and minimum (2011) depth to groundwater level were drawn (Table 4; Fig. 6).

In 2003, in the northern marsh hydrozone, average annual groundwater depth was 0.31 m lower than the average from the period 1999–2013, and in the southern hydrozone it was 0.56 m lower. In 2011, in both hydrozones it reached 0.80 m higher than the long-term average.

During the lowest state (2003) groundwater above ground surface occurred over an area of 0.39 km^2, mainly in natural denivelations along the Łasica channel (northern hydrozone), and over an area of 6.58 km^2 in the southern hydrozone. The highest state (2011) is characterized by groundwater occurrence above ground surface over an area of 81.43 km^2 (northern hydrozone), and 40.1 km^2 in the southern hydrozone.

Infiltration recharge

The groundwater flow model enabled the calculation of the groundwater balance of the analyzed hydrogeological system. The balance was made in steady-state conditions defined as average annual state, consisting of the total inflow and outflow throughout the study area, which involves the park and delimited hydrozone area (Gruszczyński and Krogulec 2012). The water-bearing system has been represented by means of an orthogonal discretization grid with a step of $\Delta x = \Delta y = 100$ m. A detailed description of this model-based research has been presented in several publications (Krogulec 1997; Gruszczyński and Krogulec 2012). The result of the model calculations was the water balance for marsh hydrozones (Table 5) and an infiltration grid, which, in a discrete way, represents the spatial distribution of infiltration recharge of the aquifer system as average annual recharge. The analysis of the discrete data enabled the development of an isoline image and data statistics.

The marsh hydrozones are characterized by the occurrence of a typical relationship in which evaporation from a shallow aquifer exceeds the annual effective infiltration in the annual balance (Soczyńska et al. 2003). Average infiltration for the area of the northern marsh hydrozone is approximately −12 mm/year (negative value indicates evaporation), while in the southern hydrozone it is about 2 mm/year (data from the groundwater flow model). The lowest values for infiltration occur along the axis of both marsh hydrozones and reach a minimum below −60 mm/year (Table 6), while the highest values are found along the borders of both hydrozones, in the vicinity of dune areas or the Blonski Level (>60 mm/year; Fig. 7). The areas where the infiltration process ranges from −30 to −20 mm/year are the most populous in the northern hydrozone (over 10 % of the area). In the area of the southern hydrozone, the most common range of infiltration is 30–40 mm/year (about 10 % of the area).

Table 6 Infiltration recharge in the marsh hydrozones

Range of class values [mm/year]	Class No.	Northern marsh zone		Southern marsh zone	
		Area [%]	Area [km^2]	Area [%]	Area [km^2]
< −60	1	8.82	13.74	9.55	8.28
−60 to −50	2	7.82	12.17	5.84	5.06
−50 to −40	3	9.63	14.99	6.15	5.33
−40 to −30	4	9.59	14.93	6.39	5.54
−30 to −20	5	10.23	15.94	6.87	5.95
−20 to −10	6	9.78	15.23	6.64	5.75
−10 to 0	7	9.22	14.35	6.54	5.66
0–10	8	7.91	12.31	8.28	7.17
10–20	9	5.70	8.87	7.17	6.21
20–30	10	4.87	7.58	8.79	7.61
30–40	11	4.75	7.39	10.50	9.11
40–50	12	5.98	9.31	9.18	7.95
>50	13	5.69	8.86	8.08	7.00

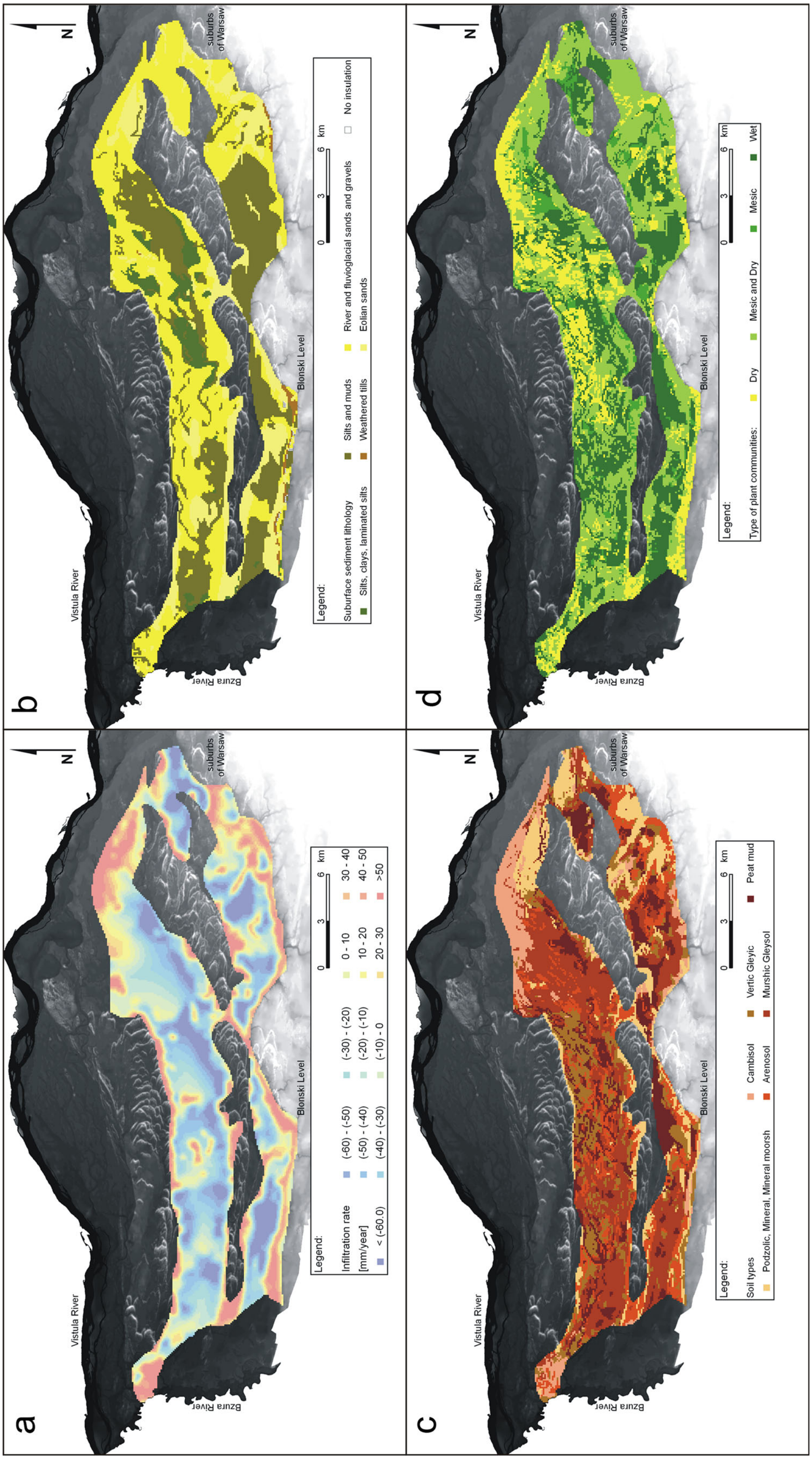

Fig. 7 Selected hydrogeological (**a–b**) and environmental elements (**c–d**): **a** infiltration rate; **b** subsurface sediment lithology; **c** soil type; **d** type of plant communities

Table 7 The lithology of subsurface sediments (unsaturated zone) in the marsh areas

Lithology of subsurface sediments	Area				Class No.
	Northern hydrozone		Southern hydrozone		
	[%]	[km^2]	[%]	[km^2]	
Silts, clays, laminated silts	8.35	13.00	0.39	13.00	2
Silts and muds	24.63	38.34	46.92	38.34	3
Weathered tills	0.02	0.03	2.14	0.03	4
River and fluvioglacial sands, gravel	51.89	80.78	21.93	80.78	8
Eolian sands	15.11	23.52	28.09	23.52	9
Areas with no insulation, surface water	0.00	0.00	0.53	0.00	9

Subsurface sediment lithology

The lithology of subsurface sediments (unsaturated zone) in the marsh areas is characterized by considerable variability. In the northern marsh hydrozone, the largest part of the area (approximately 52 %) is comprised primarily of river sediments (Baraniecka and Konecka-Betley 1987) such as sand and gravel (Table 7); however, the layer of river sediments is more differentiated, because of the occurrence of different types of organic matter in the subsurface part of the layer. The unsaturated zone (an area of approximately 38 km^2, which is 25 % of northern marsh hydrozone) consists of only silts and muds. Within the southern marsh hydrozone, these kinds of sediments occur over approximately 41 km^2 and comprise a dominant class (47 %), at the expense of river and fluvioglacial sands (22 %). There are also eolian sands within the marsh hydrozones (15–28 % of the surface), which are morphological forms locally elevated in relation to the surrounding depression with no outflow or watercourses. The sands limit the marsh hydrozones to the north and south, but also occur in the central parts, being frequently bisected by a network of channels (Fig. 7).

Soils

Two soil maps of the study area, the first one showing primary soil cover (Wicik 1995) and the second one showing the present soil cover (Piórkowski et al. 2011) were used. For the purpose of this study, a generalized map was used (Table 8; Fig. 7).The least-molded inorganic soils such as mineral moorsh, mineral, and podzolic soils, can be found in the marsh hydrozones, but only over about 10–21 % of the area (Table 8). The soils, in which during the process of creation an important role is played by the depth to groundwater, occupy the largest area. These are mainly swampy soils (peat mud) – about 15 % of the area in both hydrozones; Arenosol and Vertic Gleyic comprise approximately 12–18 %. Murshic Gleysols, which occupy the largest area (35 %) of the northern hydrozone (Fig. 7) and 26 % of the southern hydrozone area, are the result of swampy soil degradation as a result of the process of an improperly functioning melioration network.

Table 8 Soil types in the marsh hydrozones (Wicik 1995; Piórkowski et al. 2011; generalized)

Soil types	Area				Class No.
	Northern hydrozone		Southern hydrozone		
	[%]	[km^2]	[%]	[km^2]	
Mineral moorsh, mineral, podzolic soil	10.61	16.52	21.18	18.35	10
Cambisol	11.05	17.20	5.69	4.93	9
Arenosol	12.28	19.12	18.38	15.92	8
Vertic Gleyic	14.24	22.17	12.25	10.61	7
Murshic Gleysol	35.88	55.86	25.96	22.49	6
Peat mud	15.73	24.49	16.53	14.32	5

Ecosystems

On the basis of the actual vegetation map (Wicik 1995) and based on the results of the monitoring of vegetation carried out in 2007 in selected areas of the marsh hydrozones (Michalska-Hejduk et al. 2011; Kopeć et al. 2013, 2013, Krogulec 2013), the four types of plant communities were delimited according to their relative humidity (Table 9). In swampy areas, most types of plant communities refer to both soil types and relief, so that the relationship between the type of vegetation and depth to water table should also be noticeable. The largest spatial variability of plant communities can be found in the northern marsh hydrozone. In the north-eastern part of this hydrozone, there are the biggest areas where plant communities were classified as dry. The total contribution of these types of communities is approximately 20 % of the northern marsh hydrozone. Typical wet communities occur over 46.77 km^2, which represents approximately 30 % of the area.

In the southern marsh hydrozone, the plant communities form more compact spatial compositions (Fig. 7). In the eastern part, the mesic and dry communities dominated and occupy a total area of around 43 % (37.58 km^2). Communities which are typically dry, are found in the southern part of the hydrozone on the border with the

Table 9 Type of plant communities in marsh hydrozones (Wicik 1995; Michalska-Hejduk et al. 2011)

Community type	Area				Class No.
	Northern hydrozone		Southern hydrozone		
	[%]	[km^2]	[%]	[km^2]	
Dry	19.8	30.82	14.03	12.15	1
Mesic and dry	40.19	62.57	43.38	37.58	2
Mesic	9.97	15.52	7.20	6.24	3
Wet	30.04	46.77	35.39	30.65	4

Blonski Levels. Their contribution was assessed at 14 % of the hydrozone. The mesic plant communities occupy approximately 7 % of the area. Typically wet areas cover 30.65 km^2, which constitutes 35.39 % of the area.

Results and discussion

As a result of the representation of different ranges of values and measures of the particular classes and ranks, a standardization was carried out. Based on the created correlation matrix, strongly correlated elements were determined, whereby these elements were excluded from the analysis. The description of the total variance was premised on seven components—magnitude of recharge, lithology of unsaturated zone, distance from watercourses, soil types, the hydraulic conductivity of the upper part of an aquifer, average annual amplitude, and the type of plant community. The analysis of the principal components allowed, on the basis of the Scree test, for the separation of three factors, explaining 63.47 % of the total variance (Fig. 8; Table 10. The remaining four factors were characterized by an eigenvalue of less than 0.8.

An attempt at interpretation of the most influential factors in the presented population was undertaken on the basis of the factor loadings of the particular variables grouped within each factor. Loads lower than 0.2 were not taken into account. For factors highlighted in Table 11, the spatial range of impact was specified on the basis of factor values that illustrate the intensity of the impact factor. Four groups were distinguished: <−0.5, no factor impact; −0.5–0.5, mean impact; 0.5–1.0, strong impact; > 1, very strong impact.

The factor 1 accounts for 31.67 % of the population variability. On the basis of factor loadings, it should be recognized that this factor characterizes the generality of the abiotic components of wetland environments, for both hydrogeological and environmental elements. A relationship between these elements within the factor 1 situation indicates significant homogeneity of the characterized system, where regularities commonly occur in every type of environment (such as the dependence of recharge on lithology of subsurface sediments in the unsaturated zone or the depth to groundwater).

Factor scores enable the specification of those areas in marsh hydrozones where there is consistency in abiotic elements and areas where this relationship is not observed. Very strong and strong impacts of factor 1 were found on 35 % of the northern and on 32 % of the southern hydrozone, mainly in the peripheral parts (Fig. 9). Factor 1 does not affect the central part of the hydrozones where a dense discharge network exists that could transform the local discharge conditions leading primarily to long-term and irreversible changes in the structure of soils during the process of organic soil decomposition (Piórkowski et al. 2011). Areas totaling 83.31 km^2 with no factor 1 impact occur mainly along main channels— Łasica Channel in the northern hydrozone and along Zaborowski and Olszowiecki channels in the southern hydrozone. The changes in groundwater conditions in these regions are significant, taking into account that before creation of the discharge network almost 99 % of marsh hydrozone areas were occupied by areas without surface outflow (Krogulec 2004). Inconsistency in terms of abiotic elements also occurs in small depressions with no outflow, where the water table is shallow at about 0.3 m or on the surface forming a temporary overflow area. The statistical analysis of the monitoring data showed that the correlation between groundwater level and the amount of precipitation does not exist in both types of areas (Krogulec et al. 2010), so groundwater levels are affected by other factors, probably related to anthropogenic pressures (decreasing groundwater level caused by the discharge network) or animal activity (increasing groundwater level caused by beaver dams). Both

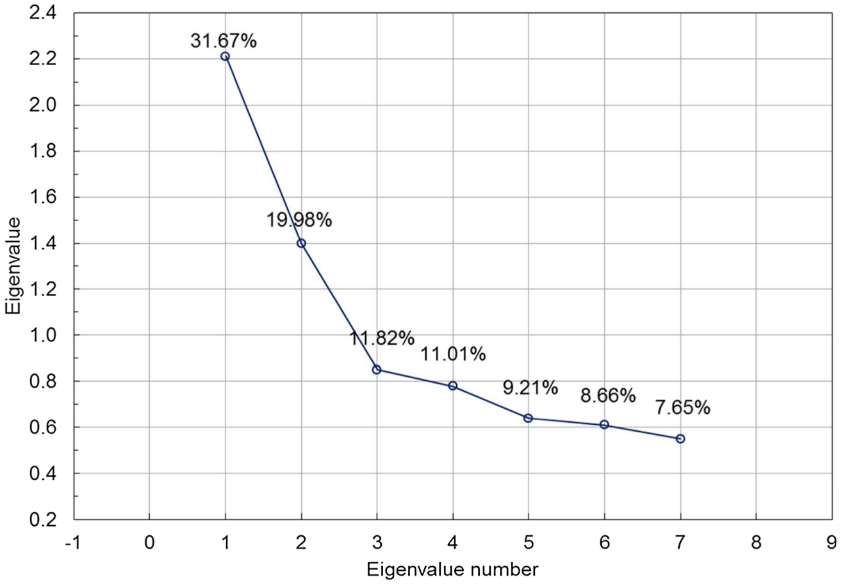

Fig. 8 Scree plot with variance of each factor

of these factors have been almost constant in the past 15 years, especially in areas of strict protection.

Factor 2 is responsible for approximately 20 % of the population variability. Within this factor, there is a correlation between both hydraulic conductivity data with the longitude of the block center. By grouping these variables in one factor, the belt arrangement characterized by parallel layouts of terrain forms, noticeable in morphology and geomorphology, was emphasized. This dependency concerns both parts of the aquifer: shallow (depth <10 m), which is obvious because it is related to geomorphology forms, but also the deep part of the aquifer, for which total thickness exceeds even 50 m. This phenomenon shows that during the formation of Vistula terraces in previous glacial and interglacial periods, the direction of erosion and accumulation processes was mainly the same—from east to west direction, especially in the area of the northern marsh hydrozone, where the highest factor values occur (approximately 53 % of the area). The areas where the factor does not have an effect account for only 12 %. In the southern marsh hydrozone, the intensity of the impact factor is lower—there is only 1.25 % of area with very strong factor impact and almost 59 % of the area has no factor impact. Regarding factor 2, dependency can be invisible in this part of the area because of the vicinity of Blonski Level, which has geological and lithological characteristics that are different compared with the KNP area.

Factor 3 is responsible for about 12 % of the population variability. There is a correlation with the type of plant community, type of soil and the lithology of subsurface sediments in the unsaturated zone. Dependency between plant community and groundwater depth was not found; however, the results point at the important role of the soil type and subsurface lithology in forming plant communities, and these elements are indirectly related with groundwater depth in presented GDE areas.

Several reasons for the lack of dependency identified by factor analysis were found. The first is connected with the changes of hydrogeological conditions due to the discharge network functioning described in the preceding. The second is connected with the high tolerance of vegetation type to the depth of the water table. The range of groundwater level changes resulting from both seasonal changes and sequences of dry and wet years (found in statistical analysis of monitoring data) is equal to the range of tolerance of plant community types (Table 12), even when considered typical for swamps: i.e., *Caricetalia fuscae* occurring in the peatlands with permanently high groundwater state (Daniels 1982), or *Calthion* (typically swamp), which is present in the range of an average depth to water table from 0.15 to 0.60 m (De Becker et al. 1999), *Molinion* (wet) from 0.1 to 1.3 m (Jansen et al. 2000), and *Arrhenatherion* (wet) from 0.4 to 1.2 m (Kryszak et al. 2008). The third is connected with the areas where no link between the type of plant community, the lithology of subsurface sediments and soil type was found (factor

Table 10 Factor loadings of elements in the separated aggregate factors 1–3. Values in *italic* are used in further interpretation

Type of element (variable)/ element number according to Table 3	Factor 1 (the abiotic components of GDE areas)	Factor 2 (correlation between hydraulic conductivity and the location of the block grid)	Factor 3 (correlation with the type of plant community, soil type and the lithology of subsurface sediments)
Infiltration recharge/5	*0.73*	−0.22	<|0.20|
Lithology of subsurface sediments (unsaturated zone)/11	*0.67*	<|0.20|	0.41
Distance from surface watercourses/10	*0.62*	<|0.20|	<|0.20|
Soil types/8	*0.50*	−0.47	0.45
Hydraulic conductivity of the upper part of the aquifer (depth <10 m)/6	0.28	0.76	<|0.20|
Average annual amplitude of groundwater depth for the period 1999–2013/4	−0.31	−0.73	−0.32
Plant community type/9	−0.64	<|0.20|	0.53
Groundwater depth (mean from multi-year 1999–2013)/1[a]	*0.70*	−0.23	<|0.20|
Hydraulic conductivity of the deeper part of the aquifer (depth >10 m)/7[a]	<|0.20|	0.44	<|0.20|
Longitude of block grid center/12[a]	<|0.20|	−0.29	<|0.20|
Latitude of block grid center/13[a]	0.25	0.55	<|0.20|
% of the variance[b]	31.67	19.98	11.82

[a] Auxiliary variables (not taken into account when determining the total variance)

[b] $\sum$% of the variance = 63.47

Table 11 Participation of spatial occurrence of the factors *1–3* in GDE areas

Factor score	Intensity of the impact factor	Factor 1		Factor 2		Factor 3	
		Northern hydrozone	Southern hydrozone	Northern hydrozone	Southern hydrozone	Northern hydrozone	Southern hydrozone
Participation of the factor [%]							
>1.0	Very strong impact	21.01	18.48	26.31	1.25	17.79	14.48
0.5–1.0	Strong impact	14.47	14.62	26.81	6.32	16.37	17.99
−0.5–0.5	Average impact	34.12	25.36	34.79	33.46	32.31	37.60
<−0.5	No factor impact	30.40	41.54	12.09	58.97	33.52	29.93
Participation of the factor [km^2]							
>1.0	Very strong impact	32.71	16.01	40.96	1.08	27.70	12.54
0.5–1.0	Strong impact	22.53	12.66	41.74	5.47	25.48	15.58
−0.5–0.5	Average impact	53.12	21.97	54.16	28.98	50.30	32.57
<−0.5	No factor impact	47.33	35.98	18.82	51.08	52.18	25.93
Area [km^2]	155.68	86.62	155.68	86.62	155.68	86.62	

3 score lower than −0.5). These areas represent about 30 % of both hydrozones, and are associated mainly with plant communities introduced by humans such as agricultural lands, orchards and the vegetation accompanying detached houses, where this kind of dependency cannot be found.

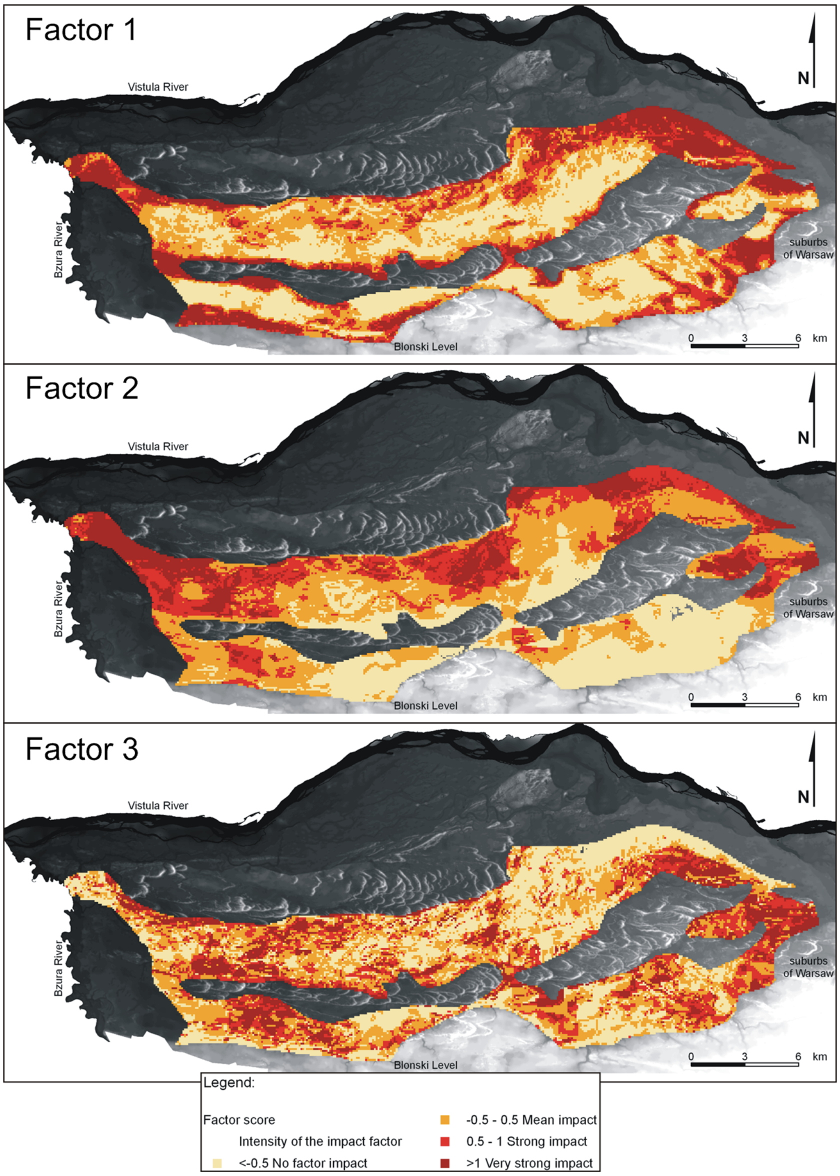

Fig. 9 Spatial development of intensity of the impact factors in the GDE areas

Table 12 Selected plant communities vs humidity requirements and groundwater (*gw*) conditions

Plant community	Groundwater depth according to the humidity requirements [m]	Average annual gw depth in 1999–2013 [m]	Average annual gw level amplitude [m]	Average factor 3 score	Area [km^2]
Caricetalia fuscae (typically swamp)	Permanently near ground surface	0.33	0.80	−0.06	0.46
Calthion (typically swamp)	0.15–0.60	0.48	0.82	0.33	27.09
Arrhenatherion (typically wet)	0.40–1.20	0.62	0.83	−0.66	1.06
Molinion (typically wet)	0.10–1.30	1.04	0.85	0.08	0.23

Strong and very strong impacts of factor 3 were found in the western part of the southern hydrozone (33 % of the area, Fig. 9) and in the western and eastern parts of the northern hydrozone (34 %), usually in the peripheral parts of the area (poorly developed soils, typical dune areas) and outside regions, where an extensive discharge network had been created (peat and marsh soils dominate).

Conclusions

Statistical analysis of the point monitoring data enabled a determination of the scope of the groundwater level changes in the period 1999–2013, and in the annual and seasonal periods. It was found that in 2003 and 2011 there were, respectively, the lowest and highest levels of groundwater. The range of changes was from 0.40 m above ground surface (2011) to 2.16 mbgs (2003) in the northern hydrozone, and from 0.83 m above ground surface (2011) to 3.17 mbgs (2006) in the southern hydrozone. Seasonal changes proceed in a similar manner in the whole period from 1999 to 2013. There were no specific trends in the depth to water table, which resulted in the occurrence of a sequence of dry and wet years in this period. This statistical analysis, which was possible to conduct on the basis of available monitoring data concerning groundwater levels, does not confirm the common belief of a lowering water table in presented GDEs due to anthropogenic pressure and climate change. There were no long-term changes in groundwater levels over this time period.

The spatial distribution of groundwater depth enabled the visualization of the characteristic maximum and minimum depth to groundwater within the marsh hydrozones. During the lowest groundwater levels occurring in 2003 in the northern marsh hydrozone, water was present beneath the surface only across 0.39 km^2, but in the period of the highest groundwater levels (2011) approximately 81 km^2 of the area was flooded. In the same year, in the southern marsh hydrozone approximately 40.1 km^2 was flooded (water table above the surface).

The factor analysis of PCA enables, after the wide recognition of the generality of hydrogeological and environmental elements, the grouping of the variables to the newly created factors and their merit interpretation on the basis of factor loadings. The factor analysis showed that the marsh hydrozone areas are characterized by a considerable homogeneity of abiotic elements occurring in factor 1. There are heterogeneous regions within the hydrozones, which are associated with the presence of a dense discharge network or the occurrence of numerous depressions with no outflow, where hydrogeological and environmental conditions are highly variable in relation to the total area. The PCA method indicated that the spatial distribution of hydraulic conductivity is related to characteristic geomorphological forms occurring on the surface. This dependency concerns both parts of the aquifer: shallow (depth <10 m) and deep (from 10 to 50 m). Dependency between the type of plant community and depth to the water table in the typical GDEs was not defined by the delimiting factors. The type of plant community vs depth to water-table relation considered as typical for GDEs, was not defined by the delimitated factors (1–3). The reasons that this dependence may not be visible are: discharge-network functioning, smaller groundwater-level changes than is tolerated by the particular plant communities (average annual amplitude does not exceed 1 m), or the existence of types of plant communities related to human activity (agricultural lands, orchards and the vegetation accompanying detached houses). Although dependence was not found, presented marsh hydrozones are groundwater-dependent ecosystems, which was confirmed by the occurrence of typical plant communities with high humidity requirements. These requirements were expressed by high correlation with soil type and lithology of subsurface sediments. Their formation was also related with shallow water-table occurrence.

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