Acta Geologica Polonica, Vol. 66 (2016), No. 3, pp. 525–540
DOI: 10.1515/agp-2016-0024

DE G DE GRUYTER OPEN

Changes in groundwater regime during vegetation period in Groundwater Dependent Ecosystems

EWA KROGULEC*, SEBASTIAN ZABŁOCKI and KATARZYNA SAWICKA

Faculty of Geology, University of Warsaw, Żwirki i Wigury 93, PL-02-089 Warszawa, Poland.
* *Email: Ewa.Krogulec@uw.edu.pl*

ABSTRACT:

Krogulec, E., Zabłocki, S. and Sawicka, K. 2016. Changes in groundwater regime during vegetation period in Groundwater Dependent Ecosystems. *Acta Geologica Polonica*, **66** (3), 525–540. Warszawa.

An analysis of the dynamics of groundwater levels in the Groundwater Dependent Ecosystems (GDEs), which cover a vast part of the middle Vistula River valley in central Poland was carried out. The study area, typical of large river valleys, was investigated by detailed monitoring of groundwater levels. Based on statistical analysis and the geostatistical modeling of monitoring data for 1999–2013, the range and dynamics of groundwater level fluctuations were determined for the entire interval and for the vegetation periods. The values of retention and infiltration recharge in various periods were compared with average values, indicating intervals of potential groundwater deficiency in GDEs. The amplitude of groundwater fluctuations, retention and infiltration were determined for vegetation periods characterized by the highest water intake by plants and the highest evapotranspiration. Particular attention has been drawn to the analysis of low groundwater levels in the vegetation periods, with water deficiencies potentially threatening the correct functioning of plant communities in GDEs. Moreover, the study has allowed us to indicate areas with insufficient groundwater levels during vegetation periods that may be hazardous to plant communities. The results may be a basis for the elaboration of correct management plans, protection measures and projects, or GDE renaturalization.

Key words: Groundwater-dependent ecosystems; Groundwater monitoring; Vegetation period; Recharge; Poland.

INTRODUCTION

Groundwater Dependent Ecosystems (GDEs) were first recognised and classified in Australia by Hatton and Evans (1998). GDEs comprise the groups of ecosystems with a huge variety of groundwater conditions and biodiversity, which is the main cause of difficulties in their proper classification (Hatton and Evans 1998; Evans and Clifton 2001; Eamus *et al*. 2006; Foster *et al*. 2006). Within this variety of attributes it is possible to classify GDEs by their groundwater flow mechanism and the geomorphological setting associated with it.

Wetlands belong to particularly threatened GDEs in the world (Amezaga *et al*. 2002; Bronmark and Hansson 2002; Bobbink *et al*. 2006; Kelly *et al.* 2011; Rashford *et al*. 2011; Wang *et al*. 2011; Laurance *et al*. 2012). Groundwater hazards in GDEs include changes of the hydrogeological regime mainly with regard to water table decrease (Mahoney and Rood 1991; Ridolfi *et al*. 2006; Booth and Loheide 2012; Kopeć *et al.* 2013), and to projects related to the renaturalization or increase of groundwater levels (Boulton 2005; Le Maitre *et al*. 1999; Steube *et al*. 2009). Plans and attempts to reintroduce natural conditions in GDE areas that have already been subject to "synanthropization" with regard to water conditions are common, therefore their renaturalization may cause potential hazards.

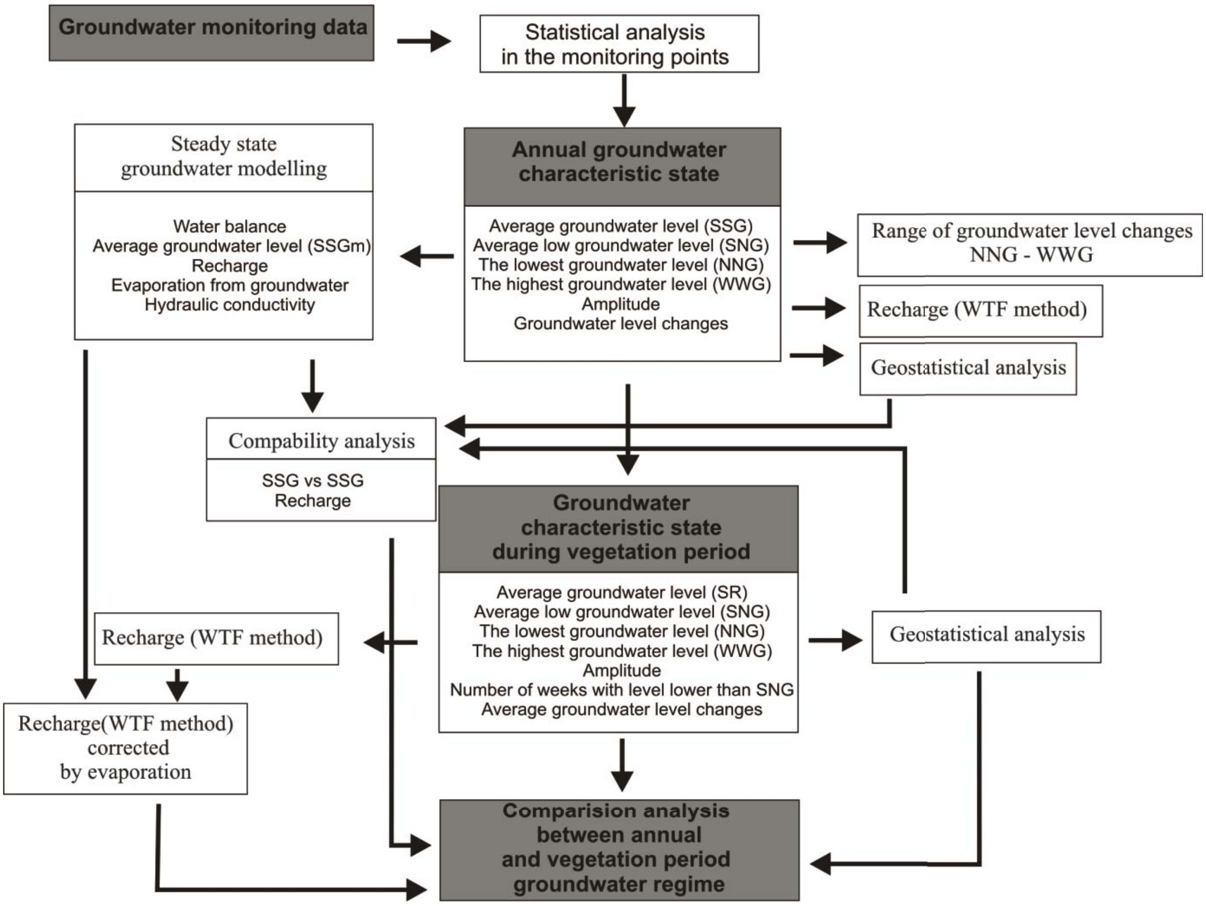
Generally, environmental and hydrogeological factors influencing GDEs include: regime of infiltration recharge, spatial management, groundwater intake, drainage through melioration network, and occurrence of plant ecosystems. The role and significance of particular factors depends on the location of particular GDEs (Boulton 2005; Boulton and Hancock 2006; Murray *et al.* 2006; Muneepeerakul *et al*. 2008; Orellana *et al*. 2012; Grant *et al*. 2012; Münch and Conrad 2007; Grimaldi *et al*. 2015), but their influence is, among others, recorded in the fluctuations of groundwater levels. In the case of the investigated GDEs, the main factor influencing groundwater level fluctuations is the relationship: rainfall – infiltration recharge – ecosystem type – drainage through streams. Anthropogenic factors, such as groundwater intake through captures and drainage through the melioration network, are of marginal significance.

Analysis of monitoring data allows for assessing the dynamics of groundwater level fluctuations, magnitude of recharge, identification of intervals of potential groundwater retention, and seasonal deficiencies resulting from mutually interacting phenomena such as water intake by plants and underground evaporation (Text-fig. 1). Application of statistical methods and geostatistical modelling has allowed the identification of groundwater levels in multiannual and annual intervals, and for vegetation periods, in which the water table may on the one hand influence correct functioning of plant ecosystems, and on the other hand – decrease due to water intake from the root zone and decrease of effective recharge caused by evaporation from plants.

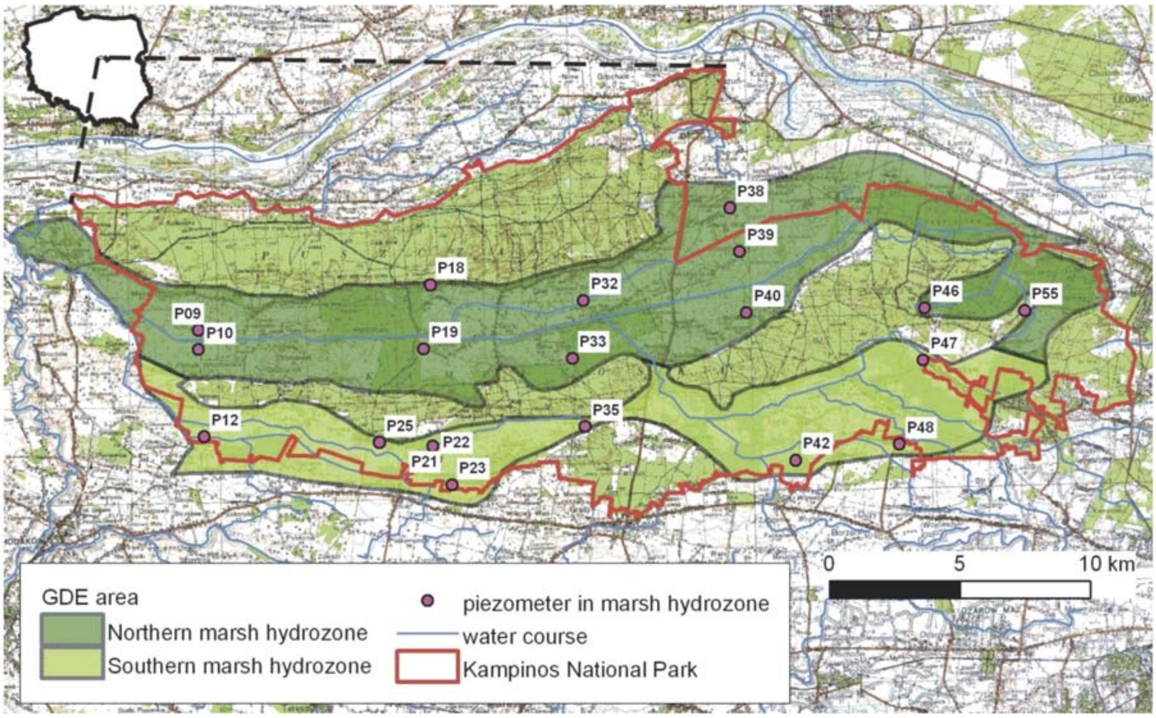
STUDY AREA

The marsh areas presented in the paper, situated in the Vistula valley, a large river of the North European Plain, are the most common type in Europe, classified as a groundwater-related ecosystem associated with groundwater flow regime (Foster *et al*. 2006).

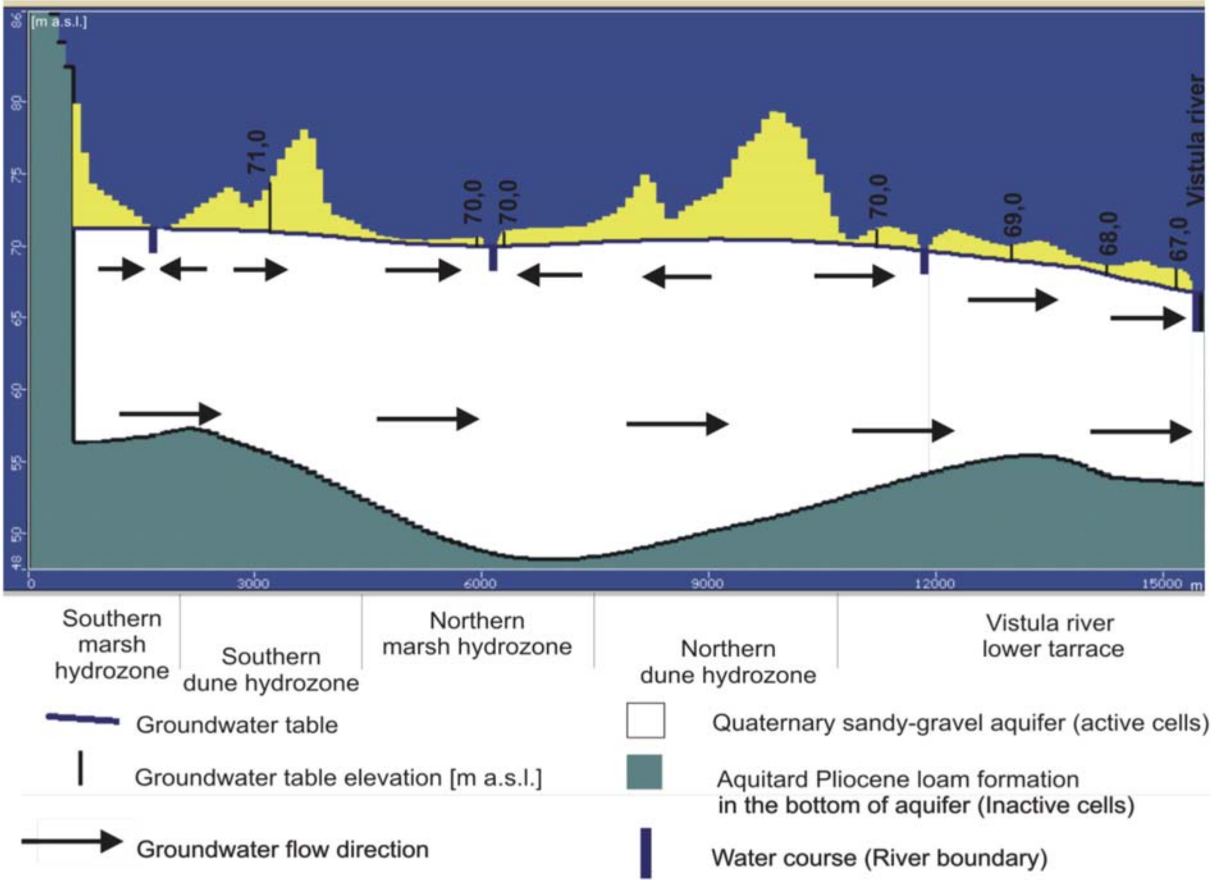
The investigated GDE area (wetlands) in the Vistula valley cover 242.3 km^2 (Text-fig. 2) and it is located in the Kampinos National Park (KNP). The GDE area is created by two marsh hydrozones: northern (155.6 km^2) and southern (86.6 km^2), separated by dune hydrozones.



Text-fig. 1. Possibilities of using groundwater monitoring data for statistical and geostatistical analyses to define groundwater regime changes



Text-fig. 2. Location of the GDE areas on the background of the Kampinos National Park



Text-fig. 3. Hydrogeological cross section in the central part of Kampinos National Park (groundwater flow modelling result, Gruszczyński and Krogulec 2011, changed)

The term hydrozone refers to the area characterized by similar hydrodynamic and environmental conditions (Krogulec 2004).

The hydrogeological conditions of KNP are summarized in several publications (e.g., Krogulec 2003, 2004; Krogulec and Zabłocki 2015). Quaternary sediments occur over the entire area of the park and lagging, constituting a collector of groundwater, with a shallow unconfined groundwater table. The total thickness of the aquifer is up to 50 m with a dichotomy connected with its lithological shape. The top part of the aquifer has a sandy and sandy-gravel character, the bottom is occupied by sandy-silt sediments. The surface of the aquitard created by glacial tills and more often Pliocene loams, constituting the floor of the Quaternary aquifer (Baraniecka and Konecka-Betley 1987; Sarnacka 1992; Krogulec 2004). The unsaturated zone is built of medium and fine-grained sands with the local occurrence of organic sediments such as muds and peats. The general flow direction in the aquifer is north and west to the main discharge base, which is the Vistula and Bzura rivers, but the groundwater circulation in the GDE areas can be considered as a local system (Text-fig. 3).

WATER REQUIREMENTS OF PLANT ECOSYSTEMS

The functioning of plant ecosystems in GDEs is shaped by the mutual relationships between the depth of the root system of various types of plants, the depth of the water table, humidity and soil type. Water demands of plants depend on their species and their growth phase. They increase during the vegetation periods with increase of plant biomass and transpiration.

The area of the Kampinos National Park is characterized by the presence of a very diverse plant system occurring as a mosaic of communities and plant environments covering dune hydrozones and marsh hydrozones. The plant community is dominated by forests (about 73% of the park area), which are coniferous within the dune hydrozones, and deciduous and mixed within the marsh hydrozones. The remaining plant communities cover small, patchily dispersed areas. In the studied area of the GDEs, a total of 118 plant communities were observed, including: bulrushes, sedge bogs, fens, transitional fens, bogs, humid and fresh meadows, pastures, heaths, sand grass pitches and xerthermic grasslands, and a large group of weeds (Kucharski 2011). The complex, patchy distribution of particular plant communities results in the occurrence of non-uniform and complex ecosystems. Assessment of the water demands of plants in GDEs requires generalization of the occurrence of plant communities.

Table 1 presents characteristic statistical values for the depth of the root system of various plant groups based on botanical reports (Foxx *et al.* 1984; Schenk and Jackson 2002) and relates them to the water table conditions in the KNP area, based on a generalized phytoindicative assessment of the water regime for actual vegetation (Solon 1994) that assumes indispensable generalization and simplification resulting from the variability of plant communities. The shallowest depth, at which the root system occurs, was observed for annual grasses – averagely 0.52 m, with minimal depths at only 0.05 m.

Plants	Root zone depth [m]								Groundwater table depth [m]	
	Average		Max.		Min.	Geometric average	Median	Std. deviation	Max. in year	Min. in year
	1)	2)	1)	2)	1)	2)	2)	1)	3)	3)
Trees	3.34	5.78	60.9	58	0.1	3.27	3	6.11	>3.0	>3.0
Conifers	3.36	b.d.	60.9	b.d.	0.1	b.d.	b.d.	9.54	>3.0	>3.0
Deciduous trees	3.32	b.d.	30	b.d.	0.73	b.d.	b.d.	4.51	>3.0	>3.0
Shrubs	3.5	2.92	17.3	20	0.15	2.14	2.15	3.5	>1.5	>1.5
Sub-shrubs	1.4	1.67	6.4	20	0.51	1.27	1.3	1	>1.2	>1.2
Perennial plants	1.7	1.46	39.3	6.5	0.02	1.05	1.22	2.5	0.9-1.5(2.0)	0.5-1.2
Perennial grasses	1.4	1.27	8.2	6	0.05	1.04	1.07	0.9	>1.0	(0.5)0.7-1.0
Herbaceous annuals	0.8	0.62	3	3	0.04	0.38	0.37	0.3	0.5-0.9	0.15-0.3
Annual grasses	0.52	b.d.	1.1	b.d.	0.05	b.d.	b.d.	0.41	0.15-0.3(1.0)	0.0

1) (Foxx *et al*. 1984); 2) (Schenk and Jackson 2002) ; 3) (Solon 1994)

Table 1. Variety of root zone depth and humidity requirements for main plant groups of KNP

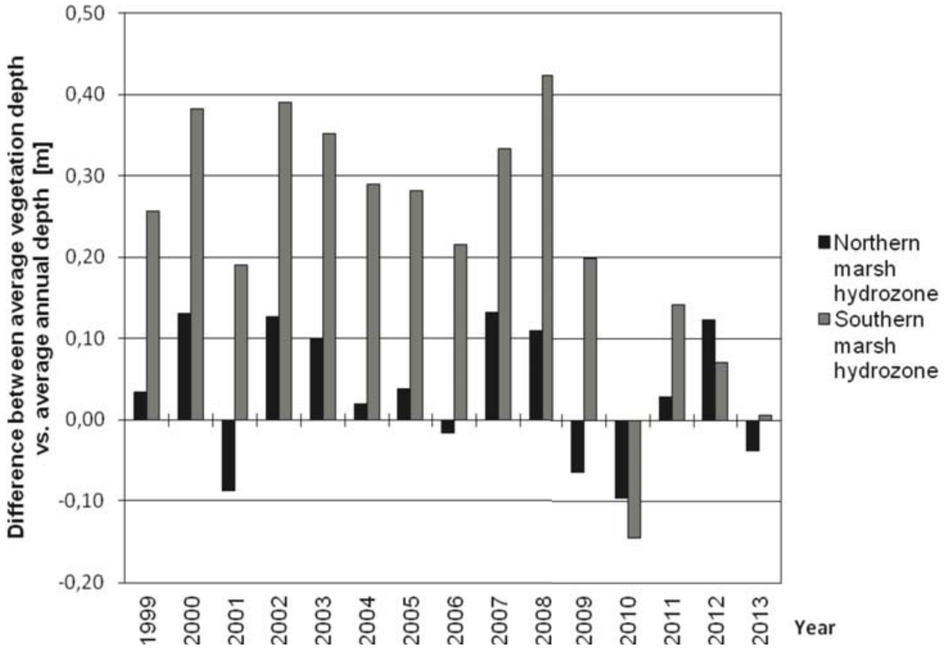
DYNAMICS OF GROUNDWATER LEVEL FLUCTUATIONS IN GDEs

Analysis of groundwater levels was conducted based on measurements of the depth of the water table conducted for 1999–2013, carried out regularly in the northern and southern marsh hydrozones (Text-fig. 2). Analysis of groundwater levels was made for the entire interval of 1999–2013 (Krogulec and Zabłocki 2015) and for the vegetation periods, for which the definition of low levels and their duration was the most significant, because water deficiencies threatening the correct functioning of plant communities characteristic of GDE areas may occur within them. The database includes 7,800 observations for 1999-2013 and 3,980 observations for the vegetation periods.

The vegetation period is defined as a part of the year, in which the average 24h air temperature exceeds +5°C (Szajda 1997); according to other reports, the boundary temperature of the vegetation period is assumed as +10°C (Puchalski and Prusinkiewicz 1990; Andrzejewska 2007). In the KNP, the vegetation period with average 24h temperatures exceeding +5°C has an average duration of 185 days. The longest vegetation period was in 2000 and lasted for 214 days, whereas the shortest – in 1996 and lasted for 164 days. For 1999–2013, the vegetation period lasted averagely for 185 days, that is from 16th April till 16th October. In the vegetation period, the average annual depth of the water table for 1999–2013 exceeds the annual average depth by 0.07 m in the northern marsh hydrozone and by 0.09 m in the southern marsh hydrozone (Table 2). In particular years, these differences reached maximally 0.13 m and 0.42 m, respectively. In order to indicate periods of low water levels, two levels characteristic for 1999–2013 were determined: a low average level in the interval (SNG) and the lowest level in the interval (NNG). Levels below SNG did not occur in the vegetation period only in: 1999, 2007, 2010–2012, whereas very low levels, close to NNG, occurred in: 2003, 2005 and 2008, with the longest in 2003 lasting from 11 to 13 weeks, and up to 7–9 weeks in 2005.

In the northern marsh hydrozone, a sporadic occurrence of intervals with average vegetation groundwater level (SR) of the vegetation period exceeding that for the entire year was noted (in 2001, 2006, 2009–2010, 2013), with a maximum in both marsh hydrozones in 2010 (Text-fig. 4). The minimal groundwater level was noted on 29.09.2003. This was a date with the absolute minimum level for the vegetation period in 19 out of 20 piezometers representing the GDE (largest depth to the water table).

Geostatistical modeling using site monitoring data with the application of simple Kriging in ArcGIS 10.1 with a discretization step of 100 m × 100 m (Text-fig. 5) was applied to determine the spatial variability of groundwater depth for average annual levels (SSG) and characteristic SNG and NNG levels for 1999-2013. Parameters of the prepared geostatistical distributions were characterized by an average error at 0.006–0.01 m and average square error at 0.90–0.94 m. The reliability of the conducted geostatistical model was verified by



Text-fig. 4. Difference between average vegetation groundwater level (SR) and average annual groundwater level (SSG) in the marsh hydrozone

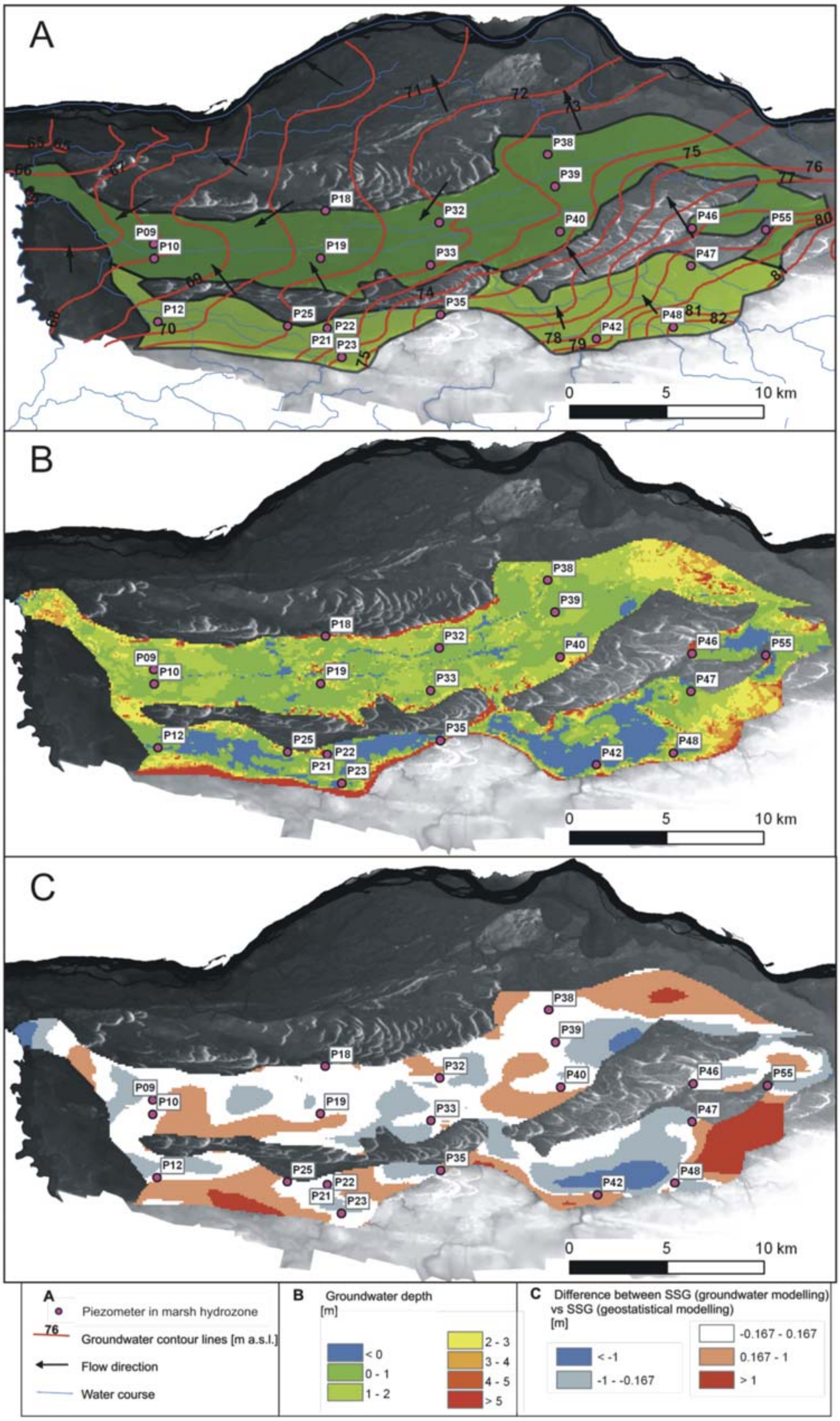
Groundwater depth [m]	Northern marsh hydrozone			
	Hydrological year (1999-2013)	Vegetation period (1999-2013)	SNG (1999-2013)	NNG (1999-2013)
Average	0.91	0.98	1.34	1.62
Median	0.91	1.05	1.18	1.52
Min	0.23	0.23	0.91	1.11
Max	1.57	1.57	1.84	2.16
Average annual amplitude	0.72	0.67	-	-
Maximal amplitude	1.35	1.35	-	-
First quartile	0.69	0.82	1.10	1.40
Third quartile	1.11	1.16	1.63	1.90
Standard deviation	0.29	0.22	0.34	0.36
Groundwater depth [m]	Southern marsh hydrozone			
	Hydrological year (1999-2013)	Vegetation period (1999-2013)	SNG (1999-2013)	NNG (1999-2013)
Average	1.24	1.33	1.72	2.13
Median	1.20	1.41	1.61	2.25
Min	0.58	0.66	0.55	0.98
Max	2.05	2.05	2.75	3.17
Average annual amplitude	0.77	0.73	-	-
Maximal amplitude	1.47	1.39	-	-
First quartile	1.00	1.14	1.09	1.60
Third quartile	1.46	1.52	2.37	2.63
Standard deviation	0.32	0.24	0.79	0.80

Table 2. Statistics related to groundwater depth in the marsh hydrozones in the monitoring points for 1999-2013

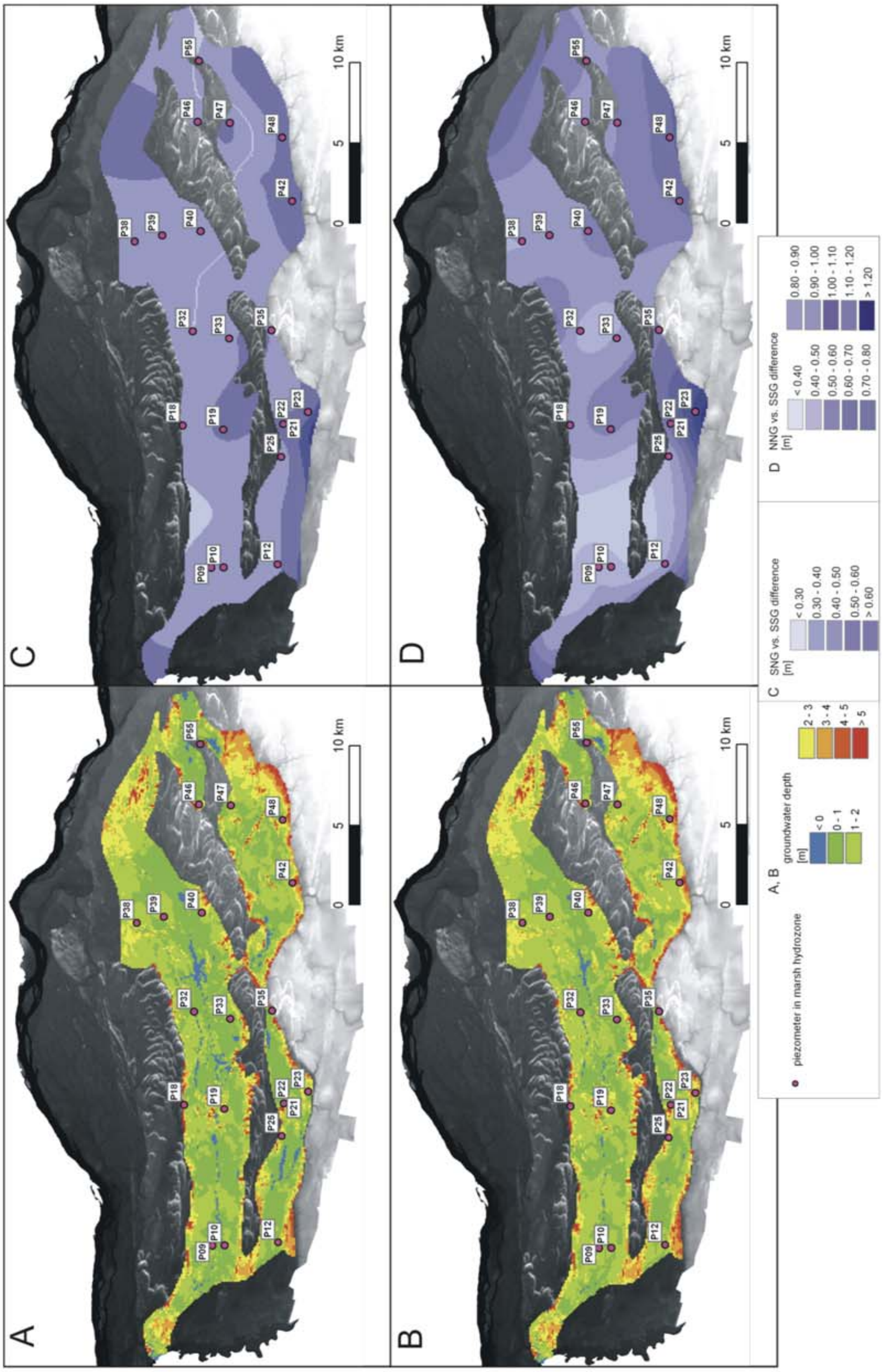
preparing a geostatistical distribution for the annual average levels determined according to hydrodynamic modelling (SSGm) (Gruszczyński and Krogulec 2011). The difference map between these two models (SSG vs SSGm) has indicated high reliability of the geostatistical methods. In 44% surface of the marsh hydrozones, accordance of the models was determined in the range of <|0.167| m, which corresponds to the average square error for hydrodynamic modelling.

SSG is characterized by the water table within 0–0.5 m in 29% surface of the GDE area for the northern marsh hydrozone. Within the southern marsh hydrozone, the most commonly occurring range is the depth above the surface (<0 m), which comprises 26% of its surface (Text-fig. 5). For SNG, both marsh hydrozones are characterized by depth intervals at 0.5–1.0 m – 27% of the surface in the northern hydrozone and 16% of the surface in the southern hydrozone. The difference between the SNG and SSG levels was less than 0.4 m on 46% of the surface and occurred mainly in the central part of the northern marsh hydrozone. Larger differences occurred in the southern marsh hydrozone, where the difference was between 0.40 and 0.50 m on 39% of the surface (Text-fig. 6).

For NNG levels, the largest areas are related to the presence of the water table at 1.0–1.5 m – 30% in the northern hydrozone, whereas in the southern hydrozone the range within 0.5–1.0 m prevails (17% of the surface). Differences between NNG and SSG levels reached from 0.36 m in the western part of both hydrozones to 1.24 m in the southern hydrozone. The most common intervals were: 0.50–0.60 m in the northern hy-



Text-fig. 5. Geostatistical spatial distribution of average groundwater level (SSG) in marsh hydrozones for 1999-2013: A – groundwater contour lines; B – groundwater depth; C – difference between SSGm (groundwater modelling) vs SSG (geostatistical modelling)



Text-fig. 6. Groundwater depth in marsh hydrozones: A – average low level (SNG); B – the lowest level (NNG) and differences between: C – SNG vs SSG; D – NNG vs SSG drozone, and 0.60–0.70 m in the southern hydrozone (Text-fig. 6).

Thus, analysis of the spatial distribution of particular characteristic levels indicates significant fluctuations of the water table in the vegetation period, characterized by the common occurrence of low levels. SNGs are usually slightly lower than SR and SSG, which points to the possibility of numerous decreases in groundwater retention.

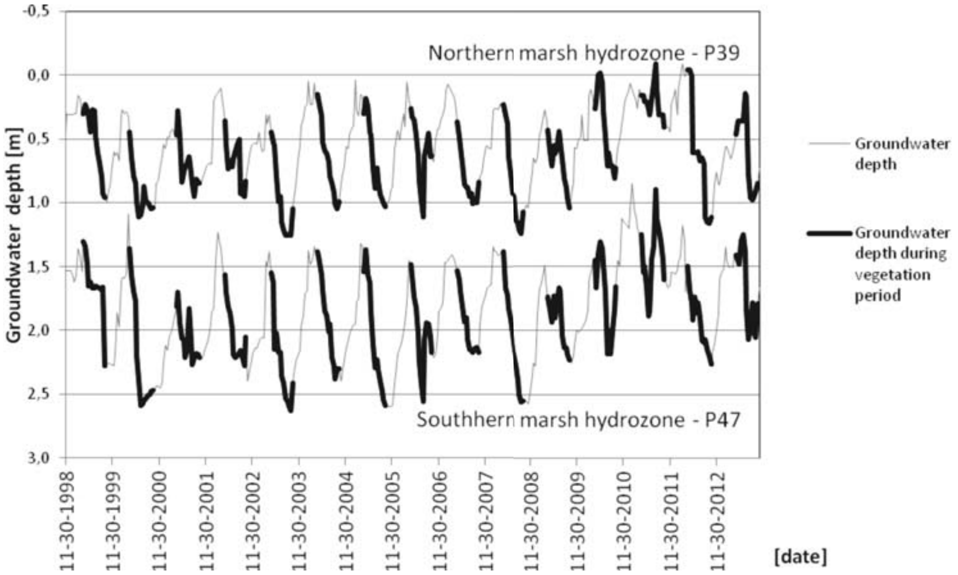
RETENTION

For an aquifer with a shallow water table, the basis for calculating the conditions of groundwater retention is the groundwater level in an observation site, determined as the depth to the water table in a piezometer related to the assumed reference level (basic condition) (Rasmussen and Andreasen 1959; Gerhard 1986; Hall and Risser 1993; Healy and Cook 2002; Pleczyński and Przybyłek 1974; Macioszczyk and Szestakow 1983; Krogulec 2004). According to this assumption, the piezometers in marsh hydrozones are located beyond the range of significant influence of anthropogenic factors, they capture shallow unconfined aquifer, and the aquifer horizon is recharged by rainfall infiltration. The retention conditions in the studied GDEs were determined based on hydrograms presenting the groundwater levels in particular piezometers of the monitoring network. For 1999-2013, the minimal level was observed for 2003 (NNG) and the maximal level was noted in 2011 in all observation sites (Text-fig. 7). Most vegetation periods in the analyzed interval were characterized by maximal groundwater retention at the beginning of the vegetation and minimal groundwater retention at the end of this interval. Analysis of hydrograms from all piezometers of the marsh hydrozones indicates gradual decrease of the water table during the vegetation period (Text-fig. 7); retention increase at the end of the vegetation intervals, temporal cease of this trend (in 2002 and 2005), or its reversal (in 2006) were observed only in a few years.

Detailed, seasonal analysis of the hydrograms in the vegetation period (Text-fig. 8) indicates registered, low retention conditions, close to the average low level (SNG). In the northern marsh hydrozone, average retention at the end of the vegetation period exceeded SNG by only 0.14 m, and in the southern marsh hydrozone it was even lower by 0.01 m from the SNG level.

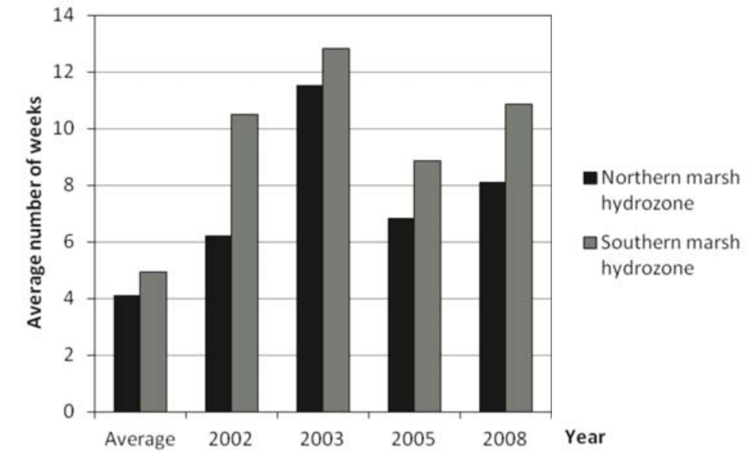
In 2003, representing a year with the lowest levels in the interval (SNG), retention was lower than the SNG through half of the vegetation period (from August), which corresponds to 11–13 weeks (Text-fig. 9). Slightly shorter low level periods than those of the SNG were noted also in 2002, 2005 and 2008. As a rule, these periods are shorter in the northern marsh hydrozone and last 2 to 4 weeks less.

In the entire observation interval, groundwater retention at the end of the vegetation period was lower that at its beginning. Decrease of groundwater retention takes place at an average rate of 0.04 m/2 weeks, maximally at 0.26–0.28 m/2 weeks. The average rate of changes for particular years was from 0.01 m/2 weeks (2001) to 0.08 m/2 weeks (2005). Temporal increase of retention is sporadic in the vegetation period, and the highest observed changes were at 0.28–0.41 m/2 weeks.



Text-fig. 7. Range of groundwater table changes in the P39 (northern marsh hydrozone) and P47 piezometer (southern marsh hydrozone)

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

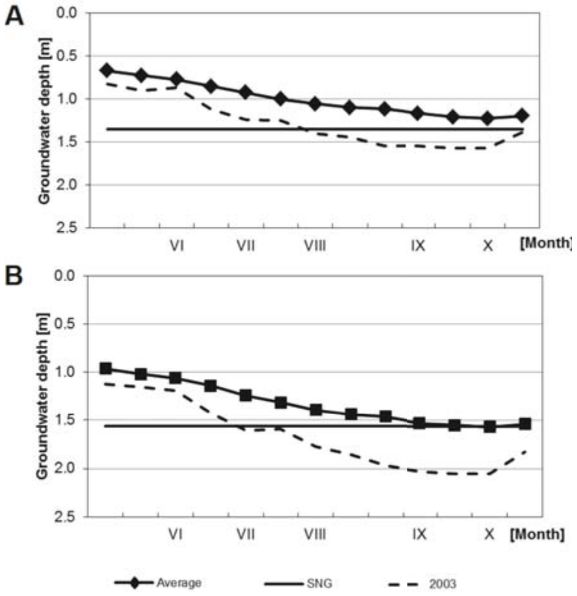


Text-fig. 8. Number of weeks with level lower than SNG in the vegetation period for 1999-2013 and for selected years with low groundwater retention

INFILTRATION RECHARGE

Infiltration recharge was determined using two independent methods. The recharge network with a discretization step at 100×100 m is an element of water balance obtained from hydrodynamic modeling (Gruszczyński and Krogulec 2011). The Water Table Fluctuation – WTF method was also applied; it refers directly to the observation of the water table rise in the piezometers, which assumes that in short term (2 weeks for the KNP monitoring network) this increase is caused directly by infiltration recharge (Healy and Cook 2002).

The values of average annual infiltration recharge determined by the WTF method for 1999–2013, at a storage coefficient $\mu=0.0826$ assumed for a shallow water table (Somorowska 2006), was 96 mm/year for the northern marsh hydrozone and 98 mm/year for the southern marsh hydrozone (Table 3). In particular piezometers this value ranged averagely from 66 to 133 mm/year, and reached from 75 mm/year in 2003 to 158 mm/year in 2006. Analysis of data from each piezometer gave results from 31 mm/year in 2000 to 263 mm/year in 2011.



Text-fig. 9. Changes of groundwater retention during vegetation period: A – northern marsh hydrozone; B – southern marsh hydrozone

Average recharge was determined also solely for the vegetation period. For the northern marsh hydrozone, average recharge was 32 mm/year, and for the southern marsh hydrozone – 31 mm/year (Text-fig. 10), and reached from 9 mm/year in 2004 to 62 mm/year in 2011. In some piezometers there was no recharge in the vegetation period (2008, 2009), and the maximal recharge reached 139 mm/year. The recharge period had a duration of 5 to 8 weeks, which is 21–33% of the length of the vegetation period, and an average for the study interval it lasted for 7 weeks, i.e. 27% of the length of the vegetation period.

During water table decrease, underground evaporation was estimated based on a hydrogram with application of the WTF method (Cuthbert 2010).

Average underground evaporation in the vegetation period determined by the WTF method was 76 mm/year for the northern marsh hydrozone and 80 mm/year for the southern marsh hydrozone. In particular piezometers it reached from 57 to 99 mm/year, and in particular years – from 16 mm/year in 2013 to 140 mm/year in 2005.

Recharge determined by the WTF method, with a correction for underground evaporation for marsh areas, was outrun by underground evaporation in the vegeta-

Piezometer	Average annual recharge [mm/year]	Average recharge during vegetation period [mm/year]	Corrected average recharge during vegetation period [mm/year]
	Northern marsh hydrozone		
P9	100	29	-50
P10	118	46	-39
P18	69	17	-39
P19	133	47	-50
P32	82	38	-25
P33	109	37	-55
P38	95	31	-47
P39	96	28	-52
P40	115	38	-52
P46	66	18	-40
P55	75	28	-34
Average	96	32	-44
	Southern marsh hydrozone		
P12	101	34	-47
P21	89	23	-46
P22	102	35	-50
P23	99	31	-42
P25	66	17	-40
P35	94	31	-54
P42	116	43	-56
P47	112	36	-59
P48	99	30	-45
Average	98	31	-49

Table 3. Average annual groundwater recharge and for vegetation period in the piezometers in the marsh hydrozones (WTF method)

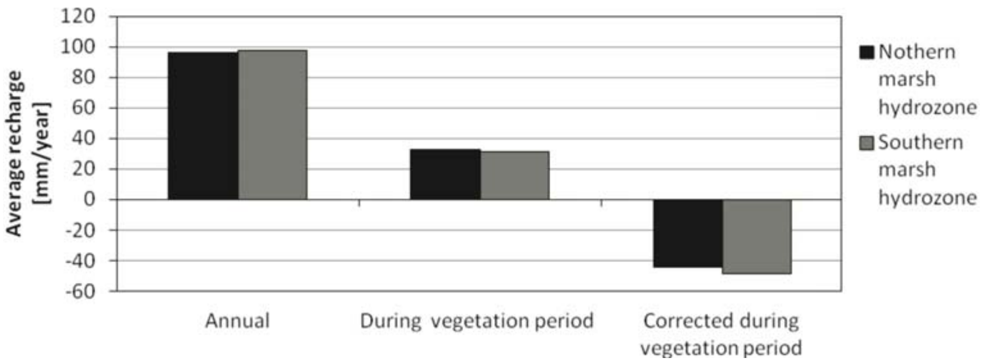
tion period, attaining negative values. For the piezometers these are values of -44 mm/year in the northern hydrozone and -49 mm/year in the southern hydrozone (Text-fig. 10), which are values close to the average values obtained for spatial data: -39 and -49 mm/year, respectively (Table 4). The prevailing values are in the range of -50 to -40 mm/year, which cover about 50% of the surface of both hydrozones.

Analogous results were also obtained for marsh areas using hydrodynamic modelling (Gruszczyński and Krogulec 2011), where the prevalence of underground evaporation over infiltration recharge is visible in an annual cycle, as a result of which average infiltration was - 13 mm/year in the northern hydrozone and -5 mm/year in the southern hydrozone.

DISCUSSION

Analysis of characteristic groundwater levels is the key factor allowing for determining the risk of ecosystem threat in conditions of non-availability of groundwater resources. The threat risk may be determined by comparison of groundwater depth for a specific groundwater level with the average depth of the root zone determined for a plant community. In order to define the magnitude of GDE threat risk, a spatial analysis was made, indicating areas, in which the average hydrodynamic level (SSG), average low level (SNG), and the lowest level (NNG) are lower than the average depth of the root zone (in Tab. 1 after Foxx *et al*. 1984) (Text-fig. 11). The vegetation type was also indicated for these areas (according to the general humidity requirements by Kucharski and Michalska-Hejduk 2003), which periodically could indicate humidity deficiencies in various intervals (Table 5A).

Due to the strict relationship between the humidity of the aeration zone with the groundwater levels (Somorowska 2006), capillary rise (from which plant intake may also take place) was assumed at 0.5 m; this height depends on the lithology of the aeration zone. The obtained results of the water table depth were re-



Text-fig. 10. Average recharge in the area of marsh hydrozones for 1999–2013 (based on WTF method in the piezometers)

stricted to areas, in which characteristic levels occur at least 0.5 m below the average depth of the root zone (Table 5B).

Using spatial characteristics, the depth of the root zones was compared with SNG levels dominating in the vegetation period. Areas, in which groundwater depth is at least 0.5 m below the average depth of the root zone at SNG levels, cover a total of about 39 km^2, that is 16% of the surface of the marsh areas (Text-fig. 11). At SNG levels, the most threatened plant communities are particularly valuable wet communities, including rare peatlands, occurring on a surface of 14.83 km^2. A total of about 2.04 km^2 of strictly protected areas are covered by the risk of unsatisfied water requirements for plants, directly resulting from the position of the water table.

SUMMARY

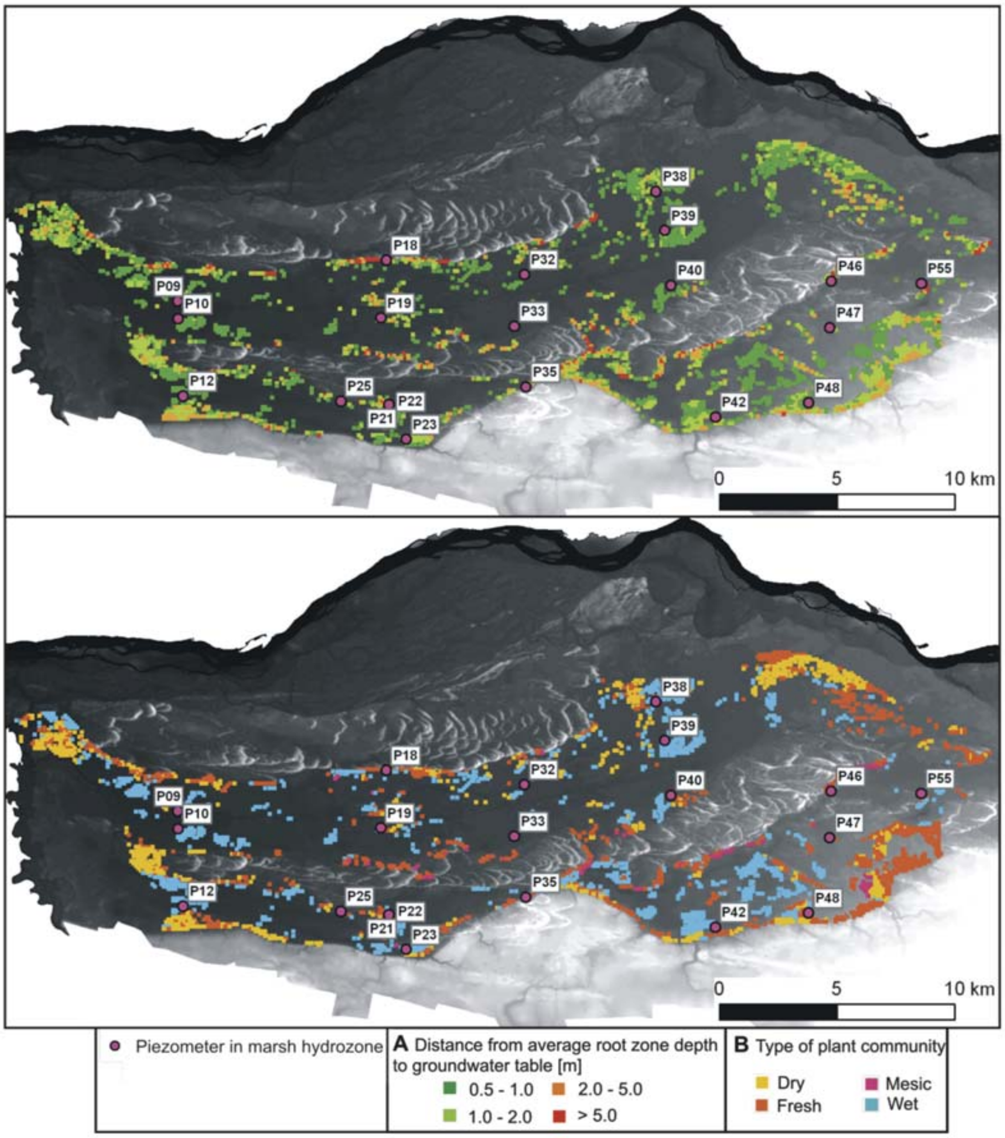
Analysis of groundwater levels in wetland areas of the Kampinos National Park, classified as GDEs, has indicated that the average depths of the groundwater levels for 1999–2013 are at about 1 m, and the range of level fluctuations results from the sequences of dry and humid years in relation to the average annual rainfall. A separate analysis was conducted for the vegetation pe-

Recharge [mm/year]	Recharge during vegetation period (WTF method)		Recharge corrected of evaporation during vegetation period (WTF method)		Annual recharge (groundwater modelling) (Gruszczyński and Krogulec 2011)	
	Northern marsh hydrozone	Southern marsh hydrozone	Northern marsh hydrozone	Southern marsh hydrozone	Northern marsh hydrozone	Southern marsh hydrozone
	area [%]					
< -60	-	-	-	5.4	8.79	10.10
-60 - -50	-	-	9.7	35.9	8.40	6.69
-50 - -40	-	-	46.8	54.8	9.72	7.07
-40 - -30	-	-	27.0	2.9	9.83	7.16
-30 - -20	-	-	13.5	1.0	10.26	7.34
-20 - -10	-	-	3.0	-	9.83	7.10
-10 - 0	-	-	-	-	9.41	7.34
0 - 10	-	0.0	-	-	7.86	8.18
10 - 20	6.4	3.5	-	-	5.53	6.24
20 - 30	47.0	49.1	-	-	4.91	7.58
30 – 40	43.7	46.1	-	-	4.40	8.22
> 40	2.9	1.3	-	-	11.04	16.98
Average recharge [mm/year]	29	29	-39	-49	-12	-5

Table 4. Spatial distribution of groundwater recharge in the marsh hydrozones using WTF method (for vegetation period) and groundwater modelling (annual) Recharge [mm/year]

riod, from mid-April to mid-October, during which the average depths slightly exceed the annual average values – the groundwater table is located below the average value by about 0.07–0.09 m. The obtained average values were compared with characteristic low levels: average low level (SNG) and the lowest level (NNG). Differences between the average level and the average lower level in most of GDE areas are at 0.30–0.40 m, which means that this level is relatively easy to accomplish at the lack of infiltration recharge in the vegetation period. The lowest level is characterized by the water table at 0.50–0.60 m below the average level, maximally at 1.24 m. Higher dynamics of the fluctuations are observed in the southern marsh hydrozone.

Analysis of retention fluctuations has indicated frequent occurrence of lower levels than SNG in the vegetation period, which lasted averagely about 4-5 weeks each year, and maximally had a duration of 13 weeks in 2003, when the lowest level also occurred (NNG). The lowest annual levels occurred at the end of the vegetation period, depending on the initial retention level before the vegetation period and the effectiveness of recharge in this interval. The beginning of the vegetation period was marked by levels close to annual maxima, resulting from the presence of meltwater recharge, after which gradual decrease of retention at about 0.04 m/2 weeks was observed, which sporadically is stopped (temporally, for several weeks) or reversed. Frequent decreases of retention below SNG levels occurred particularly in the second part of the vegetation period (from August).



Text-fig. 11. Threat of plant communities in GDE area during SNG level: A – distance from average root zone depth to groundwater table; B – type of plant community

A	Average annual level (SSG < root zone depth)	Average low level (SNG< root zone depth)	The lowest level (NNG< root zone depth)
Type of plant community	Area [km^2]		
Dry	10.91	15.61	18.87
Fresh	12.51	20.21	25.91
Mesic	0.67	1.38	1.73
Wet	21.28	29.76	38.30
Sum:	45.38	66.97	84.82
B	Average annual level (SSG < root zone depth)	Average low level (SNG< root zone depth)	The lowest level (NNG< root zone depth)
Type of plant community	Area [km^2]		
Dry	6.09	9.77	11.62
Fresh	7.93	13.03	15.97
Mesic	0.42	0.99	1.16
Wet	9.67	14.83	22.32
Sum:	24.11	38.62	51.07

Table 5. Area in the marsh hydrozones during SSG, SNG and NNG levels: A – lower than root zone depth; B – lower than 0.5 m from root zone depth

The value of infiltration recharge was determined using the WTF method, and its results were compared with the results of the hydrodynamic model. WTF results also indicate that for the vegetation period, similarly as in the annual balance, evaporation from a shallow water table caused the so-called negative recharge for most GDE areas, which means that evaporation losses exceed effective infiltration recharge. An average value is -39 mm/year for the northern marsh hydrozone and -49 mm/year for the southern marsh hydrozone. High evaporation from the groundwater table surface, as one of the elements of general evapotranspiration, is thus an important factor, restricting the availability of groundwater resources for plants and causing retention decrease in the vegetation period.

Types of plant communities occurring in the GDEs were also analyzed. At an average hydrodynamic level (SSG), on about 10% of the GDE surface, the water table is located below the average depth of the root zone, taking into account capillary rise depending on the lithology of the aeration zone. For average low levels (SNG), often reached in the vegetation period, these areas will cover about 39% of the surface. They will include mainly plant communities with wetland (i.e. peatland) vegetation, threatened by deficiencies of humidity from the groundwater table and zone of capillary rise.

A geostatistical tool was used to determine the regime of GDE areas, mainly to determine the spatial distribution of particular characteristic hydrodynamic levels. The usefulness of these tools was verified with regard to average levels (SSG) or infiltration recharge by comparison of the obtained results with the results of hydrodynamic modelling. Therefore, these tools may serve to recognize the elements of water balance of a hydrogeological unit with well-defined boundaries.

Acknowledgements

The comments by Professors Józef Chowaniec and Jacek Rożkowski, the journal referees, helped to improve the final version of this paper.

REFERENCES

Amezaga, J.M., Santamaría, L. and Green, A.J. 2002. Biotic wetland connectivity – supporting a new approach for wetland policy. *Acta Oecologica*, **23**, 213–222.

Andrzejewska, A. 2007. Porównanie terminów początku i końca okresu ewapotranspiracji z wód podziemnych z „meteorologicznymi" okresami wegetacyjnymi. Współczesne problemy hydrogeologii, **13**, 233–241.

Baraniecka, D.M. and Konecka-Betley, K. 1987. Fluvial sediments of the Vistulian and Holocene of the Warsaw basin. *Geographical Studies*, **4**, 151–170.

Bobbink, R., Beltman, B., Verhoeven, J.T.A. and Whigham D.F. (Eds) 2006. Wetlands: functioning, biodiversity, conservation and restoration, 315 p. [Series: Ecological studies, 191]. Springer; Berlin.

Booth, E.G. and Loheide II, S.P. 2012. Comparing surface effective saturation and depth-to-water-level as predictors of plant composition in a restored floodplain wetland. *Ecohydrology*, **5**, 637–647.

Boulton, A.J. 2005. Chances and challenges in the conservation of groundwaters and their dependent ecosystems. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **15**, 319–323.

Boulton, A.J., Fenwick, G.D., Hancock, P.J. and Harvey, M.S. 2008. Biodiversity, functional roles and ecosystem services of groundwater invertebrates. *Invertebrate Systematics*, **22**, 103–116.

Brönmark, C. and Hansson, L-A. 2002. Environmental issues in lakes and ponds: current state and perspectives. *Environmental Conservation*, **29**, 290–306.

Burgess, S.S.O., Adams, M.A., Turner, N.C. and White, D.A. 2001. Tree roots: conduits for deep recharge of soil water. *Oecologia*, **126**, 158–165.

Chmura, K., Chylińska, E., Dmowski, Z. and Nowak, L. 2009. Rola czynnika wodnego w kształtowaniu plonu wybranych roślin polowych. Infrastruktura i ekologia terenów wiejskich, Polska Akademia Nauk, Oddział w Krakowie, **9**, 33–44.

Clifton, R. and Evans C. 2001. Environmental water requirements of groundwater dependent ecosystems. Environmental Flows Initiative Technical Report no. 2. Commonwealth of Australia; Canberra.

Cuthbert, M. O. 2010. An improved time series approach for estimating groundwater recharge from groundwater level fluctuations. *Water Resources Research*, **46**, W09515, doi:10.1029/2009WR008572

Eamus, D., Froend, R., Loomes, R., Hose, G. and Murray, B. 2006. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. *Australian Journal of Botany*, **54**, 97–114.

Foster, S., Koundouri, P., Tuinhof, A., Kemper, K., Nanni, M. and Garduno, H. 2006. Groundwater dependent ecosystems: the challenge of balanced assessment and adequate conservation. GW Mate briefing note series, **15**. Washington, DC: World Bank.

Foxx, S.T., Tierney, D.G. and Williams, M.J. 1984. Rooting Depths of Plants Relative to Biological and Environmental Factors. Los Alamos National Laboratory Report, LA-10254-MS. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/16/061/16061888.pdf

Gerhart, J.M. 1986. Ground-water recharge and its effect on nitrate concentrations beneath a manured field site in Pennsylvania. *Ground Water*, **24**, 483–389.

Grant, R.F., Desai, A.R. and Sulman, B.N. 2012. Modelling contrasting responses of wetland productivity to changes in water table depth. *Biogeosciences*, **9**, 4215–4231.

Grimaldi, S., Orellana, F. and Daly E. 2015. Modelling the effects of soil type and root distribution on shallow groundwater resources. *Hydrological Processes*, **29**, 4457-4469.

Gruszczyński, T. and Krogulec, E. 2011. Numeryczny model pola filtracji w rejonie Kampinoskiego Parku Narodowego In: Okruszko, T. and Mioduszewski, W. and Kucharski L. (Eds), Ochrona i renaturyzacja mokradeł Kampinoskiego Parku Narodowego, pp. 73–92. Wydawnictwo SGGW; Warszawa.

Hall, D.W. and Risser, D.W. 1993. Effects of agricultural nutrient management on nitrogen fate and transport in Lancaster county, Pennsylvania. *Water Resources Bulletin*, **29,** 55–76.

Hatton, T. and Evans, R. 1998. Dependence of Australian ecosystems on groundwater. *Water*, **25**, 40–43.

Healy, R.W. and Cook, P.G. 2002. Using groundwater levels to estimate recharge. *Hydrogeology Journal*, **10**, 91–109.

Kelly, M., Tuxen, K.A. and Stralberg, D. 2011. Mapping changes to vegetation pattern in a restoring wetland: Finding pattern metrics that are consistent across spatial scale and time. *Ecological Indicators*, **11**, 263–273.

Kopeć, D., Michalska-Hejduk, D. and Krogulec, E. 2013. The relationship between vegetation and groundwater levels as an indicator of spontaneous wetland restoration. *Ecological Engineering,* **57***,* 242–251.

Krogulec, E. 2003. Hydrological conditions of the Kampinoski National Park (KNP) region. *Ecohydrology & Hydrobiology*, **3**, 257–266.

Krogulec, E. 2004. Ocena podatności wód podziemnych na zanieczyszczenia w dolinie rzecznej na podstawie przesłanek hydrodynamicznych. Uniwersytet Warszawski; Warszawa.

Krogulec, E. and Zabłocki, S. 2015. Relationship between the environmental and hydrogeological elements characterizing groundwater-dependent ecosystems in central Poland. *Hydrogeology Journal*, **23**, 1587–1602.

Kucharski, Ł. 2011. Narzędzie 5: Mapa roślinności i procesów dynamicznych KPN. In: Projekt - Opracowanie metod odtworzenia pierwotnych warunków wodnych Kampinoskiego Parku Narodowego w celu powstrzymania degradacji przyrodniczej i poprawienia stanu bioróżnorodności. http://kampinos.sggw.pl/assets/export/roslinnosc.rzeczywista. kpn.doc.pdf

Kucharski, L. and Michalska-Hejduk, D. 2003. Meadow and sward communities. In: Andrzejewski R. (Ed.), Nature of Kampinoski National Park, Kampinos National Park, pp. 339–360. Izabelin. [In Polish]

Le Maitre, D.C. Scott, D.F. and Colvin, C. 1999. A review of information on interactions between vegetation and groundwater, *Water SA*, **25**, 137–152.

Laurance, S.G.W. Baider, C. Florens, F.B.V. Ramrekha, S. Sevathian, J.-C. and Hammond D.S. 2012. Drivers of wetland disturbance and biodiversity impacts on a tropical oceanic Island. *Biological Conservation*, **149**, 136–142.

Macioszczyk, T. and Szestakow, W.M. 1983. Dynamika wód podziemnych – metody obliczeń. Wydawnictwa Geologiczne; Warszawa.

Mahoney, J. M. and Rood, S.B. 1991. A device for studying the influence of declining water table on poplar growth and survival. *Tree Physiology*, **8**, 305–314.

Muneepeerakul, C.P. Miralles-Wilhelm, F. Tamea, S. Rinaldo, A. and Rodriguez-Iturbe, I. 2008. Coupled hydrologic and vegetation dynamics in wetland ecosystems. *Water Resources Research*, **44**.

Murray, B.R. Hose, G.C. Eamus, D. and Licari, D. 2006. Valuation of groundwater-dependent ecosystems: a functional methodology incorporating ecosystem services. *Australian Journal of Botany*, **54**, 221–229.

Münch, Z. and Conrad, J. 2007. Remote sensing and GIS based determination of groundwater dependent ecosystems in the Western Cape, South Africa. *Hydrogeology Journal*, **15**, 19–28.

Okruszko, T. Mioduszewski, W. and Kucharski, L. (Eds) 2011. Ochrona i renaturyzacja mokradeł Kampinoskiego Parku Narodowego, 240 p. Wydawnictwo SGGW; Warszawa.

Orellana, F. Verma, P. Loheide, S.P. and Daly, E. 2012. Monitoring and modeling water-vegetation interactions in groundwater-dependent ecosystems. *Reviews of Geophysics*, **50**, RG3003, doi:10.1029/2011RG000383.

Pleczyński, J. and Przybyłek, J. 1974. The issue of the groundwater resources documenting in river valleys. Methodological study, 196 p. Wydawnictwa Geologiczne; Warszawa.

Puchalski, T. and Prusinkiewicz, Z. 1990. Ekologiczne podstawy siedliskoznawstwa leśnego, 618 p. Państwowe Wydawnictwo Rolnicze i Leśne.

Rashford, B.S. Bastian, C.T. and Cole, J.G. 2011 Agricultural Land-Use Change in Prairie Canada: Implications for Wetland and Waterfowl habitat Conservation. *Canadian Journal of Agricultural Economics*, **59**, 185-205.

Rasmussen, W.C. and Andreasen, G.E. 1959. Hydrologic budget of the Beaverdam Creek
Basin. *U.S. Geological Survey Water Supply Paper*, **1472**, 106 p.

Ridolfi, L. D'Odorico, P. and Laio, F. 2006. Effect of vegetation-water table feedbacks on the stability and resilience of plant ecosystems. *Water Resources* Research, **42**, W01201, doi:10.1029/2005WR004444.

Sarnacka, Z. 1992. Stratigraphy of Quaternary sediments in Warsaw and surrounding areas. *Prace Państwowego Instytutu Geologicznego*, **138**. [In Polish]

Schenk, H.J. and Jackson, B.R. 2002. Rooting depths, lateral root spreads and below-ground/above ground allometries of plants in water-limited ecosystems. *Journal of Ecology*, **90**, 480–494.

Solon, J. 1994. Mapa roślinności rzeczywistej - fotoindykacyjna ocena stosunków wodnych, w skali 1:25 000. Operat wodny Kampinoskiego Parku Narodowego. Ocena stosunków wodnych parku ze względu na potrzeby zbiorowisk roślinnych. Archiwum KPN; Izabelin.

Somorowska, U. 2006. Wpływ stanu retencji podziemnej na process odpływu w zlewni rzecznej. Wydawnictwa Uniwersytetu Warszawskiego; Warszawa.

Steube, C., Richter, S. and Griebler, C. 2009. First attempts towards an integrative concept for The ecological assessment of groundwater ecosystems. *Hydrogeology Journal*, **17,** 23–35.

Szajda, J. 1997. Roślinne i glebowo-wodne wskaźniki ewapotranspiracji łąki na glebie torfowomurszowej. Rozprawy habilitacyjne. IMUZ. Falenty. ISBN 83-85735-62-3.

Wang, P. Zhang, Y.C. Yu, J.J. Fu, G.B. and Ao, F. 2011. Vegetation dynamics induced by groundwater flucturations in the lower Heihe River Basin northwestern China. *Journal of Plant Ecology*, **4**, 77–90.

Manuscript submitted: 20th March 2016
Revised version accepted: 30th August 2016