Wetlands Ecol Manage (2020) 28:495–507
https://doi.org/10.1007/s11273-020-09727-y

ORIGINAL PAPER

Verification of empirical equations describing subsidence rate of peatland in Central Poland

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Received: 8 January 2020 / Accepted: 27 April 2020 / Published online: 9 May 2020

Abstract Currently, due to prolonged soil drought, dehydrated peat soils are particularly exposed to subsidence and, as a consequence, even to disappearance from the natural environment, in which they perform many important functions, e.g. storage of organic carbon and water retention. Therefore, predicting of settlement and disappearance processes of these soils is very important issue. This study was conducted to: (1) determine the degree and rate of subsidence of a drained peatland over 40 years, (2) establish the effect of subsidence on the depth of ditches and a watercourse, (3) verify empirical equations describing the subsidence based on field measurements. The work was carried out on fen in Central Poland which was managed as a grassland until around 2000, and then its use was discontinued. Subsidence rate was estimated from measurements of the peat deposit thickness taken in 11 locations in 1978 and 2018. Fourteen empirical equations used for estimating subsidence rate of drained peatlands were selected to verify the calculations against field data. The average subsidence rate of the studied peatland was relativity low (0.62 cm year^{-1}), which may be associated with abandoning of agricultural use for the last 20 years. Loss of peat thickness varied from 5 to 41% and depended rather on drainage intensity than on its initial depth. In general, six from the verified empirical equations were useful in estimating average subsidence rate. Four equations seemed to be the most useful for deeply drained sites. Estimation of the subsidence solely on the basis of time since drainage may be biased.

Keywords Peatland subsidence · Empirical equations of subsidence · Drained peatland

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Introduction

The main reasons for peat soil surface lowering in the first years after drainage involve disappearance of water buoyancy and pressure of the drained layers on the underlying layers (Ostromęcki 1971). Lowering groundwater table by 1 cm increases the load by approx. 0.01 kPa (Wösten et al. 1997). Dehydration of surface layers decreases their humidity, initiates shrinking and finally compaction of organic soil (Hendriks 2004; Peng and Horn 2007; Gebhard et al. 2009, 2012; Oleszczuk 2011; Ilnicki and Szajdak 2016). These physical phenomena are the main reasons for surface lowering of drained peatlands. In natural conditions, this results in considerable lowering of peatland surface reaching 5–10 cm year^{-1} (Ostromęcki 1956; Ilnicki 1973, 2002a; Schothorst 1982; Millete and Broughton 1984; Okruszko 1993; Wösten et al. 1997; Jurczuk 2000; Lipka et al. 2017), or even up to 20 cm year^{-1} (Hutchinson 1980). The process is called the first phase of subsidence and usually occurs up to 10 years after drainage (Ilnicki and Szajdak 2016). The subsidence rate in the first phase after drainage depends mainly on the following factors: primary thickness of the peat deposit, its stratigraphy, type of peat, drainage intensity and physical properties (mainly the degree of organic matter decomposition and soil bulk density). Even when the groundwater table reaches a stable level, the subsidence continues and is called the second phase of subsidence—soil loss. The process involves mineralization of the organic matter, i.e. oxidation of the soil organic matter, reduction of organic carbon content and finally carbon dioxide emissions into the atmosphere and dissolved organic carbon cycling (Okruszko 1993; Ilnicki 2002b; Kechavarzi et al. 2007; Oleszczuk et al. 2008; Hribljan et al. 2014). The rate of peat deposit subsidence slows down considerably to about 1–3 cm year^{-1} (Ilnicki 1973; Lipka 1978; Kasimir-Klemedtsson et al. 1997; Jurczuk 2000; Dawson et al. 2010; Van den Akker et al. 2012; Deverel et al. 2016; Grzywna 2016, 2017; Lipka et al. 2017). In the second phase the main factors that affect subsidence are: drainage duration and depth, climate (primarily temperature, abundance and distribution of precipitation), chemical properties (mainly organic carbon and ash content) as well as the type and form of agricultural use (Ilnicki and Szajdak 2016). Research literature contains numerous equations describing the subsidence rate of peat soils, both in the first and second phase (e.g. Ostromęcki 1956; Segeberg 1960; Wertz 1967; Schothorst 1977; Querner et al. 2012 and other see Table 1). They account for different parameters, such as peat deposit thickness, its bulk density, depth, drainage duration and groundwater table level.

Most of the research to date have concerned selected areas or entire peatlands and have focused on determining the degree and rate of subsidence and disappearance of these soils. They involved peatlands in Poland (e.g. Ilnicki 1972; Jurczuk 2000; Chrzanowski and Szuniewicz 2002), Great Britain (e.g. Dawson et al. 2010), the Netherlands (e.g. Hoogland et al. 2012; Querner et al. 2012; Van den Hardeveld et al. 2017), Germany (e.g. Eggelsmann 1986), Sweden (e.g. Mc Afee 1985), Italy (e.g. Zanello et al. 2011), the USA (e.g. Stephens et al. 1984; Snyder 2005), Canada (e.g. Hillman 1997; Silins and Rothwell 1998), New Zealand (e.g. Schipper and McLeod 2002), or Indonesia (e.g. Hooijer et al. 2012). Much fewer studies concerned the effects of subsidence on ditches and watercourses crossing the drained peatlands (Oleszczuk et al. 2017). Papers on verification of the empirical equations describing the peatland subsidence are also few (Grzywna 2017). Nowadays, predicting the subsidence rate of drained peatlands is particularly important for estimating greenhouse gas emissions, i.e. in the context of climate change (e.g. Kasimir-Klemedtsson et al. 1997; Van den Akker et al. 2008; Couwenberg 2011).

The aim of the study was to: (1) determine the degree and rate of subsidence of a drained peatland over 40 years, (2) establish the effect of subsidence on the depth of ditches and a watercourse, (3) verify empirical equations describing the subsidence based on field measurements.

Materials and methods

Study area

Solec peatland (Fig. 1a) is located within the Warsaw Plain, near the village of Solec, Masovia region, Poland (52° 02′ 39″ N 21° 06′ 17″ E). It covers about 220 ha and contains quaternary deposits with thickness exceeding even 50 m. The top of deposit is composed of fen peats with thickness ranging from about 0.5 to 1.8 m, mainly sedge (*Cariceti*) and sedge-reed (*Cariceto-Phragmiteti*) of medium and high degree of decomposition and underlain with loose sand (Kaca 1981). Geological drilling within section F5 of the investigated peatland revealed the following peat sequence: down to ca. 50–70 cm—sapric peat, transformed as a result of moorshing (Okruszko 1993), 70–80 cm—sedge-reed peat (*Cariceto-Phragmiteti*), 80–90 cm—moss peat (*Bryaleti*), 90–120 cm—

Table 1 Empirical equations for peat surface subsidence by various authors

Site (source)	Equation (number)		Explanations of symbols acc. to sources
Noteć River valley, fen (reed) (Ilnicki 1972)	$h = 0.14H + 0.33t + 0.005L - 0.53$	(1)	h—surface subsidence (m) H—initial depth of peatland (m) t—depth of ditches (m) L—time (years)
Noteć River Valley; drainage intensity of peatlands			y—surface subsidence (cm) x—initial depth of deposit (cm)
Low (0.4–0.6 m)	$y = 0.051x + 8.6$	(2)	
Medium (0.6–1.0 m)	$y = 0.05x + 18$	(3)	
High (1.0–1.2 m)	$y = 0.082x + 34.6$	(4)	
Total (Ilnicki 1972)	$y = 0.101x + 9.5$	(5)	
Noteć River Valley; drainage intensity of peatlands			y—surface subsidence (cm year^{-1}) x—initial depth of deposit (cm)
Low* (0.4–0.6 m)	–		
Medium (0.6–1.0 m)	$y = 0.00107x + 0.34$	(6)	
High (1.0–1.2 m)	$y = 0.00228x + 0.47$	(7)	
Total (Ilnicki 1972)	$y = 0.0021x + 0.17$	(8)	
Peatlands in Central Europe (Ilnicki 1972)	$y = 0.12x + 23$	(9)	y—surface subsidence (cm) x—initial depth of deposit (cm)
Peatland of Moscow Reaserch Station (Stankiewicz and Karelin 1965 after Ilnicki 1972)	$y = 0.156x + 19.2$	(10)	y – surface subsidence (cm) x—initial depth of deposit (cm)
Biebrza River Valley; Kuwasy I fen (Krzywonos 1974)	$y = 0.099x + 2.9$	(11)	y—surface subsidence (cm) x—initial depth of deposit (cm)
Stary Borek fen (Jurczuk 2000)	$S = 1.88H^{0.204} \cdot t^{0.6}$	(12)	S—subsidence (cm) H—initial depth of deposit (cm) t—years after drainage
Stepnica and Góra 3 fens (Jurczuk 1991)	$h = a \cdot x^b$	(13)	h—surface subsidence (cm) x—time since drainage (years) a, b—empirical coefficients
Varied peatlands (Maslov et al. 1996 after Ilnicki 2000a)	$S = 5.9 \cdot 0.91^y + 2.1$	(14)	S—subsidence (cm year^{-1}) y—time (years)

*Statistically non- significant

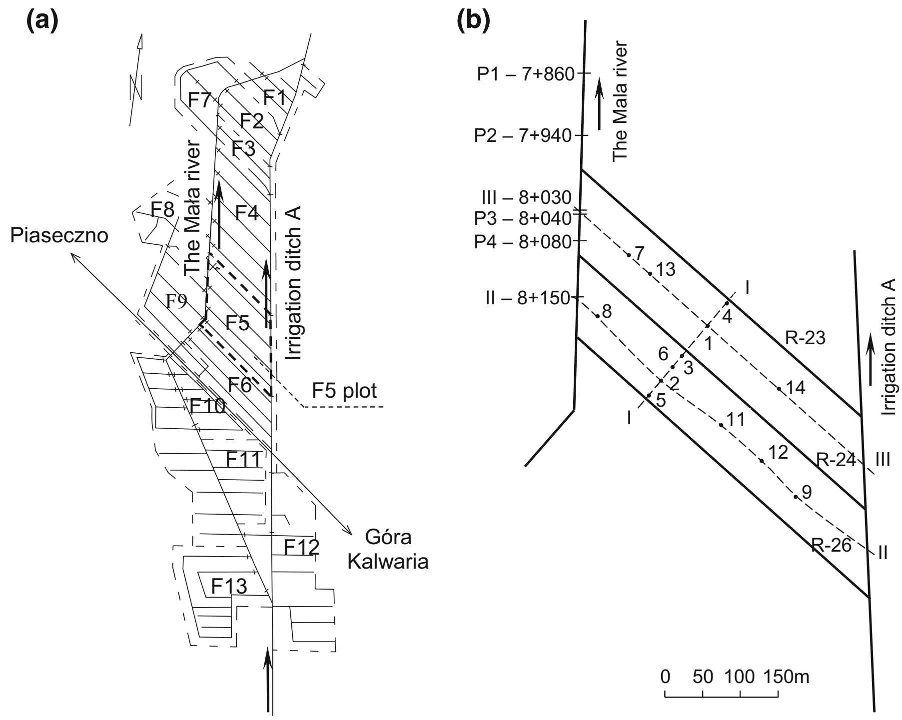


Fig. 1 The map of the Solec peatland (**a**) and location of measurement points, transects and cross-sections on the Mała river on F5 section (**b**)

sedge-moss peat (*Cariceto-Bryaleti*). According to WRB system, the soils were classified as Rheic Hemic Histosols (Drainic) (IUSS Working Group WRB 2014).

The first drainage works at the Solec peatland began in 1941–1943 (Brożek 1967). They involved a design of a main network of drainage ditches and a construction of a few dams. In 1967 a project was developed to modernize the grassland improvement system and it was implemented in the years 1968–1971 by dividing the area into 13 sections (F1–F13, Fig. 1a). Drainage and irrigation ditches were designed with spacing between 90 and 130 m and average designed depth of 100 cm. There are currently no water management activities in place over the entire site. In the summer, the ditches are usually dry. The area was managed as a grassland and pasture until around 2000, and then its use was discontinued. The peatland is crossed by the Mała river (Fig. 1a), the bed of which was reconstructed in the years 1941–1943 and improved for draining purposes in the years 1968–1971. The river runs via the drained peatland for 3.2 km. Dimensions of the cross section of the designed river bed in 1967 were as follows: bottom width 1.50–2.00 m, depth 2.00–2.50 m, embankment slope 1:1.5 (Brożek 1967).

Field survey

Having access to the archived project for the modernization of the drainage system (Brożek 1967), which includes, among others, a topographic map (scale 1: 2000) and cross sections of the riverbed (scale 1: 100), we designed our investigation of the peatland condition within F5 section. The measurements of the ordinates of the Mała banks along its entire length at the Solec site were performed in 1967. The studies on the peat deposit thickness, ditch depth and the Mała river carried out in 1978 involved only the F5 section. The section area between the Mała and the measurement points 4, 1 and 11 is covered mainly with common nettle (*Urtica dioica*), and further towards the supply ditch A it is overgrown with bushes and trees that made the subsidence measurements impossible (Fig. 1b). We took into account the results of peat deposit thickness measurements taken in 1978 for 11 measurement points of this section (Fig. 1b; Kaca 1981), and the outcomes of leveling measurements of the soil surface along three measurement transects (I-I, II-II—km 8 + 150, III-III—km 8 + 030) (Fig. 1b; Kaca 1981). The measurements were repeated for the same points after 40 years, i.e. in 2018. To stabilize the measurement points and observe the groundwater table level, we installed observation wells at each of the thirteen points. Deposit thickness was measured with a soil sampler (five repetitions within 2 × 2 m area) six times in 2018 (May, June, July, August, September and December). No measurements were performed for points No. 9 and 12 due to limited access (dense bushes). Leveling measurement of the peatland surface along three transects was carried out in September 2018 using a leveling instrument (Carl Zeiss Jena NI 050) and accounting for the existing network of repers. Measurement outcomes from 1978 and 2018 enabled us to compare peat thickness and the level of land surface within the span of 40 years.

We used the drainage network modernization project (Brożek 1967) to investigate current geometry of the Mała bed in four cross sections (P1, P2, P3, P4) located along a 220 m long section. In September 2018, we carried out leveling measurements for individual river cross sections: km 7 + 860 (P1), 7 + 940 (P2), 8 + 040 (P3) and 8 + 080 (P4). The altitude of individual cross section elements was calculated using a temporary benchmark of 100.60 m a.s.l. located at a culvert-weir in a ditch R-24 near the Mała (Fig. 1b). On the left bank of the cross sections P1–P4 we also measured the peat deposit thickness (in some sections of the right bank green biomass obtained during embankment mowing was deposited).

Verification of the empirical equations for estimating the peatland subsidence

Having in mind that data from continuous peatland monitoring, e.g. groundwater level are often missing, we selected for verification only equations that require very basic information about investigated site. Fourteen empirical equations (Table 1) selected for verification enabled us to calculate the degree and rate of the peatland subsidence, mainly based on the data on the original deposit thickness (Eqs. 1–12), depth of the ditches (Eq. 1) and time since drainage (Eqs. 1, 12–14). Equations 13 and 14 are estimates and only require the time since drainage.

After gathering the required input data for individual empirical equations, we attempted to estimate the peat deposit subsidence in the second phase and to compare the computation results with field measurements of the Solec peatland. We assumed a good match for the measurements and calculations for a difference of ± 30%, and very good for a difference of ± 15%. The following values of initial parameters were adopted for calculations (1978): original peat thickness at individual measurement points—Table 2, time of drainage—40 years (second phase of subsidence), ditch depth—Table 3. For measurement points 7 and 8 located near the Mała, we assumed that the subsidence rate was affected by draining influence of the river, so our calculations also accounted for the river bed depth (Table 3). Empirical coefficients of $a = 9.0$ and $b = 0.346$ for 150 cm deep deposit determined by Jurczuk (1991) were adopted for Eq. 13.

Results

Peatland subsidence

In 1978 peat thickness at eleven measurement points was usually similar (except for point 14) and ranged from about 110 cm to 170 cm (median 140 cm). Despite comparable peat thickness and identical climatic conditions, a significant variation in the peatland subsidence, ranging from 9 cm (point 13) to 58 cm (point 7) was noted over 40 years (Table 2). The largest percentage decrease in peat deposit thickness occurred for points 7 (41%), 4 (30%) and 8 (26%), of which points 7 and 8 are located near the Mała bed, and point 4 is in the immediate vicinity of R-23 drainage ditch. At most points the annual rate of peatland subsidence was relatively low (< 1 cm $year^{-1}$), and only exceeded 1 cm $year^{-1}$ for points 4 and 7. Average rate of peatland subsidence for section F5 was 0.62 cm $year^{-1}$ (Table 2). The leveling measurements along transects I-III (Fig. 2) showed the greatest subsidence rate of 0.73 cm $year^{-1}$ along II-II transect, slightly lower (0.61 cm $year^{-1}$) along III-III transect, and the lowest (0.55 cm $year^{-1}$) for I-I transect.

The measurements for the three transects also revealed lowering of the banks and shallowing of the drainage ditches (R-26, R-24, R-23) and the Mała bed (Table 3; Fig. 2). Over 40 years, altitude of the ditch and river banks lowered by 0.15–0.40 m due to subsidence and peat disappearance. At the same time, we witnessed a slight drop (by 0.02–0.05 m) or a rise (by 0.07–0.40 m), probably caused by silting, of the bottom altitude in individual ditches and the river. Bank subsidence and simultaneous bottom rise caused

Table 2 Groundwater level and peat depth loss rate of the Solec peatland in measurement points (1–14) in the years 1978–2018

No.	Mean (± SD) groundwater level (m b.g.l.)	Mean (± SD) depth of peat (cm) in the years		Peat depth loss in 40 years		Peat depth loss rate
	2018	1978	2018	cm	%	cm year^{-1}
1	39.0 (± 17.1)	150	131 (± 1.2)	19	13	0.48
2	37.8 (± 20.0)	150	127 (± 0.9)	23	15	0.58
3	48.8 (± 23.7)	130	120 (± 1.0)	10	8	0.25
4	62.2 (± 15.6)	160	111 (± 2.4)	48	30	1.20
5	32.5 (± 17.4)	150	131 (± 1.7)	19	13	0.48
6	28.2 (± 19.8)	130	119 (± 2.4)	11	9	0.28
7	41.0 (± 11.9)	140	82 (± 2.4)	58	41	1.45
8	44.5 (± 10.5)	140	103 (± 0.8)	37	26	0.93
11	46.2 (± 17.2)	110	83 (± 4.4)	27	25	0.68
13	42.8 (± 13.1)	170	161 (± 2.4)	9	5	0.23
14	38.0 (± 11.8)	70	60 (± 2.3)	10	14	0.25
Total	41.9 (± 16.2)	136	112 (± 2.0)	24	18	0.62

Table 3 Ordinates of ditches and the Mała river banks and bottoms in measurement transects in the years 1978–2018

Year	Ordinates (m a.s.l.)		Depth (m)
	bank	bottom	
	Ditch D-26—transect I-I		
1978	100.45	99.35	1.10
2018	100.20	99.50	0.70
1978–2018 (m)	− 0.25	0.15	− 0.40
	Ditch D-24—transect I-I		
1978	100.40	99.35	1.05
2018	100.25	99.75	0.50
1978–2018 (m)	− 0.15	0.40	− 0.55
	Ditch D-23—transect I-I		
1978	100.55	99.45	1.10
2018	100.30	99.40	0.90
1978–2018 (m)	– 0.25	– 0.05	– 0.20
	Mała river—transect II-II		
1978	100.40	98.52	1.88
2018	100.14	98.50	1.64
1978–2018 (m)	− 0.26	− 0.02	− 0.24
	Mała river—transect III-III		
1978	100.40	98.25	2.15
2018	100.00	98.32	1.68
1978–2018 (m)	− 0.40	0.07	− 0.47

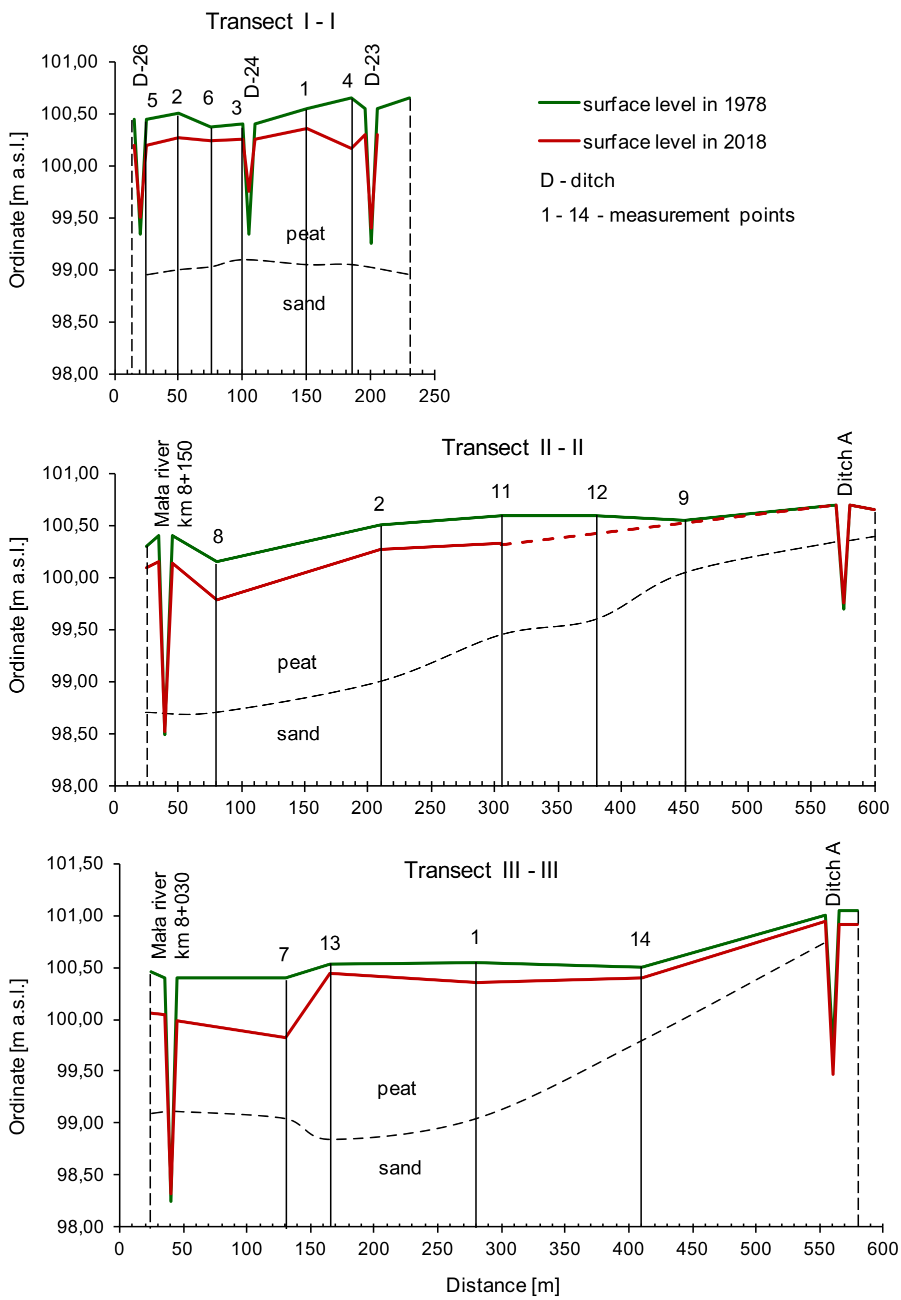
shallowing of the ditches and the river. The greatest changes in the Mała depth occurred within the transect III-III, where over the studied period the bed depth decreased from 2.15 m to 1.68 m, i.e. by 0.47 m. Ditch depth has decreased over 40 years (1978–2018) by on average 0.20–0.55 m as compared to their depth measured in 1978.

Changes in the altitude of the Mała banks for four cross sections P1-P2-P3-P4 were determined from a long-time perspective of 51 years (1967–2018). P1 section demonstrated the greatest lowering of its left bank (by 45 cm) (Table 4), where the land surface reached the mineral layer level (Fig. 3). The least pronounced lowering of the left bank (0.27 m) was observed for the cross section P4 (Table 4; Fig. 3). In short, the average river bank subsidence rate was 0.74 cm year^{-1}. The subsidence degree of the right bank was considerably lower, and this may be caused by depositing there the green matter obtained during embankment mowing (on average every 5 years).

Verification of the empirical equations for estimating the peatland subsidence

Field measurements of the degree and rate of the Solec peatland subsidence in the second phase were compared with the estimation values yielded by fourteen selected empirical equations (Table 5). The most similar results (± 30% difference) were obtained for

Fig. 2 Measurement transects (I-I, II-II, III-III) across part of the Solec peatland



four measurement points and the Eqs. 1, 2, 5,8 and 11, and for three points for the Eqs. 4, 6, 10 and 12. Verification with the Eqs. 3, 7 and 9 provided the weakest match with the field data. Calculations with Eq. 1 included two variants for the initial and current depth of drainage ditches. The results for the initial depth of the ditches were most similar to the field data. Very good match of field and theoretical data (± 15%) on the average peatland subsidence was achieved for three Equations: 1, 3, 5 and good (± 30%) for six of them: 1, 3, 5, 6, 7, 8. The Eqs. 4, 10 and 12 (three points) and the Eq. 9 (two points) were the best match for the points with the greatest subsidence rate (4, 7, 8).

Table 4 Ordinates of the Mała river banks in years 1967 and 2018 in cross-sections

Year	Bank	Ordinates in cross-sections (m a.s.l.)			
		P-1	P-2	P-3	P-4
1967	Left	100.19	99.99	100.39	100.61
2018	Left	99.74	99.59	100.01	100.34
1967–2018 (m)		0.45	0.40	0.38	0.27
1967	Right	99.99	100.09	100.36	100.47
2018	Right	99.81	99.67	100.03	100.10
1967–2018 (m)		0.18	0.42	0.33	0.37

Discussion

Subsidence of the peatland surface and drainage network

Average lowering of the Solec peatland surface over 40 years (1978–2018) reached 24 cm, and average subsidence rate was 0.62 cm year^{-1}. When compared with the literature data for grasslands, this value came out relatively small. Ilnicki and Szajdak (2016) claimed that in Poland the subsidence rate of the deposits composed of reed peats reached 0.33 cm year^{-1}, 0.58 cm year^{-1} and 1.12 cm year^{-1} for low, medium and high drainage depth, respectively. According to Szuniewicz (1996), these values reach 0.7 cm year^{-1} for medium and 1.35 cm year^{-1} for deep drainage. Lipka (1978) and Lipka et al. (2005) reported subsidence values of 1.11–1.35 cm year^{-1}, and Okruszko (1991) of 1.34 cm year^{-1}. For instance, in the Netherlands, grassland subsidence reaches 0.3–2.2 cm year^{-1} (Van den Akker et al. 2012), and in Sweden 0.5 cm year^{-1} for extensive pastures and 1.0 cm year^{-1} for managed grasslands (Berglund and Berglund 2010).

Percentage loss of the Solec peat deposit in the years 1978–2018 ranged from 5 to 41%. It did not correlate with the initial thickness of the deposit, as it was pretty similar at all tested points (except for point 14). The greatest peat deposit loss occurred at the points directly adjacent to the Mała and ditch R-23 (point 7–41%, point 4–30%, point 8–26%). The draining nature of the Mała was previously advocated by Gąsowska (2017), who determined the range of a depression curve on the right side of the river bed (section F5) to be 150 m. This covers the points 7 and 8. Peatland lowering within this belt of ca. 150 m was the greatest and amounted to on average 1.19 cm year^{-1}.

Over the last 20 years the Solec peatland was not managed as a grassland and the drainage ditches were not maintained. This may have translated into lower rate of its subsidence. Ditch shallowing in this period reached 38 cm, i.e. about 36% of their initial depth. The abandonment could have limited mineralization of the organic matter and peatland disappearance, which should be deemed positive from the ecological perspective and the role of grasslands on peat soils in water and climate regulation and preservation of biodiversity (Deru et al. 2018). In Dublany peatland in Ukraine, cessation of grassland use and lack of drainage system maintenance over 17 years reduced the rate of its subsidence from on average 7.0 cm year^{-1} to 0.6 cm year^{-1} (Lipka et al. 2017), that is to the same rate as at the investigated Solec peatland.

Subsidence of the Solec peatland results in lowering the altitude of the ditch and the river banks. Furthermore, lack of maintenance leads to their silting and bottom altitude elevation. The final outcome of these processes manifested itself in shallowing the ditches and the river bed. Similar alterations were reported by Oleszczuk et al. (2017), who demonstrated a decrease in the depth of other ditches within the peatland by 1.0 m to 0.3–0.7 m over 46 years. The greatest rate of ditch bank subsidence occurred near their opening into the Mała (1.7–2.6 cm year^{-1}). A study of longitudinal profiles of the ditches at the same peatland (Gąsowska 2017) yielded similar results. Research on changes in cross-sectional area and depth of the Mała were conducted by Oleszczuk et al. (2014) and Urbański et al. (2018) for four selected measurement sections. They showed a slightly higher subsidence rate of the river banks visible in the cross Sections (1.09 cm year^{-1}) than in our study, and by 40–50% smaller area of the cross section than in 1967.

Verification of the empirical equations for estimating the peatland subsidence

Verification of the empirical equations developed by different authors against the field measurements at the Solec peatland identified the Eqs. 1, 3 and 5, and also 6, 7 and 8 developed by Ilnicki (1972) as the most accurate for estimating the average subsidence rate. It is recommended to use initial and not current ditch

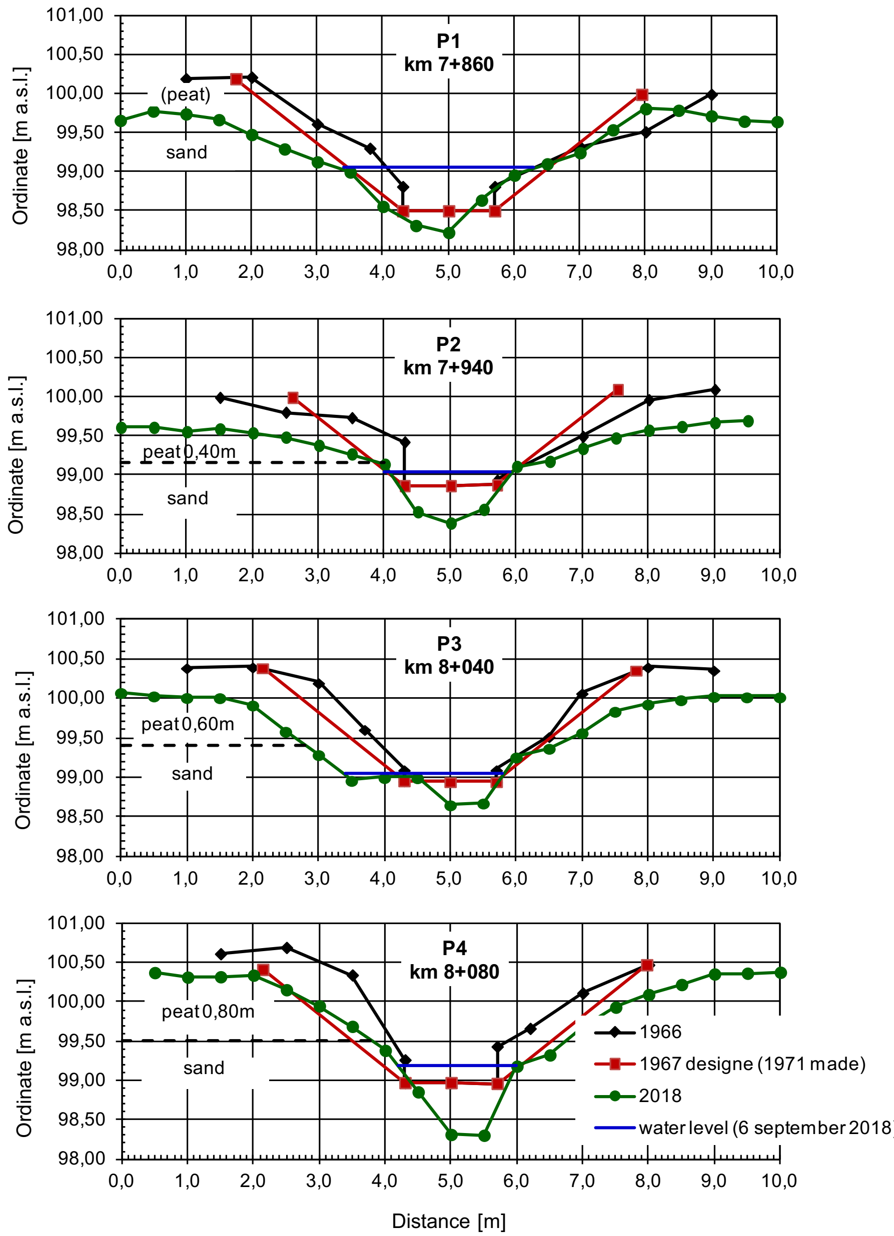


Fig. 3 Cross-sections of the Mała river: ordinates measured before melioration works in 1966; ordinates according to melioration plan developed in 1967; ordinates measured in 2018

depth in the equations that require ditch depth parameter. The Eqs. 4 (Ilnicki 1972), 10 (Stankiewicz and Karelin 1965), 12 (Jurczuk 2000) and 9 (Ilnicki 1972) seem the most useful for calculating subsidence at deeply drained sites, as demonstrated for points 4, 7 and 8 of the investigated peatland. Estimation of the subsidence solely on the basis of time since drainage, as for the Eqs. 13 (Jurczuk 1991) and 14 (Maslov et al. 1996) may be biased, while introducing additional parameters, as in the Eqs. 12 developed by Jurczuk (2000) and 1 developed by Ilnicki (1972), improves estimation results and makes the equations useful in further predictions.

Grzywna (2017) verified empirical equations describing the subsidence rate of peat soils in eastern Poland drained for over 38 years. The verification included the equations developed by Ostromęcki (1956), Segeberg (1960), Wertz (1967) and Jurczuk (2000), which apart from initial deposit thickness and time since drainage require data on groundwater level,

Table 5 Measured from peat thickness and calculated rates of subsidence of the Solec peatland in the years 1978–2018. Values in bold indicate a difference of ± 30%

Point no.	Measured rate of subsidence (cm year^{-1})	Rate of subsidence (cm year^{-1}) according to empirical equations no 1–14 (see Table 1)													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.48	**0.61**	**0.41***	0.64	1.17	**0.62**	**0.50***	0.81	**0.49***	1.03	1.07	**0.44***	1.19	0.89**	0.03
2	0.58	**0.61***	**0.41**	**0.64***	1.17	**0.62***	**0.50***	0.81	**0.49**	1.03	1.07	**0.44**	1.19		
3	0.25	0.54	0.38	0.61	1.13	0.57	0.48	0.77	0.44	0.97	0.99	0.39	1.16		
4	1.20	0.64	0.42	0.65	**1.19***	0.64	0.51	0.83	0.51	**1.06***	**1.10***	0.47	**1.21***		
5	0.48	**0.61**	**0.41***	0.64	1.17	**0.62**	**0.50***	0.81	**0.49***	1.03	1.07	**0.44***	1.19		
6	0.28	0.54	0.38	0.61	1.13	0.57	0.48	0.77	0.44	0.97	0.99	0.39	1.16		
7	1.45	**1.44***	0.39	0.63	**1.15**	0.59	0.49	0.79	0.46	1.00	**1.03**	0.42	**1.18**		
8	0.93	1.22	0.39	0.63	**1.15**	0.59	0.49	**0.79***	0.46	**1.00***	**1.03***	0.42	**1.18**		
11	0.68	0.47	0.36	**0.59***	1.09	**0.52**	0.46	**0.72***	0.40	0.91	0.91	0.34	1.12		
13	0.23	0.68	0.43	0.66	1.21	0.67	0.52	0.86	0.53	1.09	1.14	0.49	1.23		
14	0.25	0.33	**0.30**	0.54	1.01	0.41	0.41	0.63	**0.32**	0.79	0.75	**0.25***	1.02		
M	0.62	**0.70***	0.39	**0.62***	1.14	**0.58***	**0.49**	**0.78**	**0.46**	0.98	1.01	0.41	1.17		

M mean

*Difference between measured and calculated rate of subsidence of ± 15%; ** for empirical coefficients of a = 9.0 i b = 0.346

and for Jurczuk's Equations (2000) also on bulk density. Grzywna (2017) reported considerable match between field and theoretical results, particularly for Jurczuk's Equation (2000). However, practical experience shows that data from continuous groundwater level monitoring are often lacking, which makes the use of these equations difficult.

Conclusions

Over 40 years, the small area of the Solec peatland (section F5), featuring similar initial deposit thickness, experienced considerable differences in the subsidence rate ranging from 0.23 to 1.45 cm year^{-1}. However, average subsidence rate was relativity low (0.62 cm year^{-1}), which may be associated with abandoning of agricultural use of the area and lack of drainage ditch maintenance for the last 20 years. Percentage loss of the peat deposit thickness in the years 1978–2018 varied from 5 to 41% and did not depend on its initial thickness but rather on the drainage intensity. Subsidence of the peatland resulted in lowering the altitude of the ditch and the Mała banks and bed. Moreover, lack of maintenance contributed to their silting and elevation of the bottom altitude. This finally caused shallowing of the ditches and the river bed. Over the 40 years, altitude of the ditch and river banks lowered by 0.15–0.40 m, river bed depth dropped by a maximum of 0.47 m, and ditch depth by 0.20 to 0.55 m.

Verification of the empirical equations against the field data for the Solec peatland showed that particularly Eqs. 1, 3 and 5 developed by Ilnicki (1972) but also Eqs. 6, 7 and 8 are useful in estimating average subsidence rate for this area. It is recommended to use initial and not current ditch depth in the equations that require this parameter. The equations developed by Ilnicki (1972) (No. 4), Stankiewicz and Karelin (1965), Jurczuk (2000), and Ilnicki (1972) (No. 9) seem the most useful in calculating the subsidence at deeply drained sites. Estimation of the subsidence solely on the basis of time since drainage (equations by Jurczuk (1991) and Maslov et al. (1996)) may be biased, while introducing additional parameters to the equations developed by Jurczuk (2000) and Ilnicki (1972) (No. 1), improved estimation results making the equations useful in further predictions.

Acknowledgements This research was carried out within Projects and DS-505-20-0527-00-Q00519-99 and DS-3331/KMIKŚ financed from a research grant allocated by the Polish Ministry of Science and Higher Education.

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