Formation and Development of Floating Peat Mats in a European Eutrophic Lake: A Case Study

Henning Günther[1], Dresden University of Applied Sciences, Dresden, Germany and Rüdiger Knösche, Potsdam University (retired), Potsdam, Germany

ABSTRACT

In a case study, we analyzed the development of a spatially extended eutrophic floating marsh in a mid-European river floodplain lake. Such buoyant fringe marshes occur occasionally in lakes or river floodplain waters which have accumulated considerable amounts of very soft organic sediments. There are two hypotheses about their formation: 1) diverse helophytes, among them *Cicuta virosa* and *Carex pseudocyperus*, colonize floating-leaf plant communities or floating plant residues washed ashore, and 2) normal reed stands detach from the soft lake bottom which then float up caused by their rhizome aerenchyma and by marsh gas accumulation. The following questions were pursued: 1) How did these floating peat mats develop and do they grow horizontally on the water surface? and 2) How will they develop in future? Our study is mainly based on the analysis of historical maps, aerial photographs, and the zonation of the riparian vegetation. In the first half of the 20th century, the formation of floating swamps began on the waterside edge of large reeds that had developed on huge mud banks. The succession proceeded at this edge to alder carr without substantial expansion toward the open water. This and other findings led us to the conclusion that the floating mat formation proceeds according to the second hypothesis. Since there is no significant horizontal growth of these floating marshes, the riparian vegetation belt of the lake will only spread by repeating the entire process.

INTRODUCTION

Eutrophic floating peat mats (floating islands, floating marshes, 'Schwingmoore' or 'Schwingriede' in Germany, 'Plaur or Plav' in Danube Delta, floating sudds in Africa, 'matupá' in Brasilia) are worldwide in distribution (Gore 1983; Van Duzer 2004; Tiner 2009). They are stands of helophytes growing on several decimeters and sometimes up to 2 m thick layers of rhizome networks, interspersed with peat, floating on water surface or on extremely liquid mud predominantly in front of the normal reed belt. Wind and wave action occasionally detach pieces from these mats which then drift over the lake, run aground on mud banks, or run ashore. The growth time for such mats depends on the productivity of their vegetation and can take up to 100 years for a 60 cm thick *Typha* mat (Hogg and Wein 1988a). Eutrophic floating marshes occasionally seem to mark the terminal stage of the limnic phase of lakes (Pokorný and Jankovská 2000; Tallis 1983) and therefore, their developmental dynamics are of interest for comprehensive understanding of terrestrialization (i.e., filling of the lake by sedimentation and accumulation of organic matter that converts open water to a habitat dominated by woody vegetation) as well as for lake management (Mallison et al. 2001). Moreover, in nature conservation this type of emergent vegetation that often forms great belts around lakes is of higher interest, due to its structure. Floating peat mats are characterized by a relatively low vegetation height, relatively high plant species diversity, and interspersed small water areas providing special habitats for water birds (Burgess and Hirons 1992; Dunlop et al. 1991; Sjörs 1983). Occasionally, floating mats are also of economic interest because detached mat pieces can block waterways and outflows (Mallison and Hujik 1999; Mallison et al. 2001, 2010).

For understanding the origin and development of floating eutrophic marshes, it must be stated in principle that many helophytes are more or less able to float due to their gas-filled lacunar system (aerenchyma) in the corm (Crawford 1983). However, most of them cannot survive floating on water surface in an upright position without anchorage in a solid ground. In order to explain origin and development of floating peat mats in Central Europe the following hypotheses have been suggested (Boer 1942; Hejný 1971; Sculthorpe 1985):

> 1a. Floating-leaf plants, e.g., *Nymphaea* and *Nuphar,* and floating communities of *Stratiotes aloides* or *Hydrocharis morsus-ranae* serve together with entrapped floating organic matter in stagnant lake bays as substratum for establishment of the plant community *Cicuto-Caricetum pseudocyperi* with the characteristic species *Cicuta virosa* and *Carex pseudocyperus*. These initials become more and more solidified by plant roots and by incorporated organic matter (Freitag et al. 1958; van Donselaar 1961; den Held et al. 1992).

1. Corresponding author: henning.guenther@htw-dresden.de.

1b. A similar hypothesis is the assumption of colonization of organic residues by helophytic plants that have been washed ashore providing a suitable substratum for growth of diverse helophytic plants. Here species such as *Cicuta virosa*, *Carex pseudocyperus*, and *Thelypteris palustris* may be very effective (Krausch 1965). *Cicuta virosa* and *Carex pseudocyperus* are specially adapted to grow on wet, little decomposed plant litter (Hejný 1960).

2. *Typha* or *Phragmites* stands anchored in very soft mud detach from the bottom at rising water level, sometimes additionally promoted by wind and wave action, and begin to float due to their aerenchyma and accumulated marsh-gas bubbles. These floating reeds will then be invaded by a range of lower growing helophytes, such as *Cicuta virosa, Carex pseudocyperus, Mentha aquatica, Lycopus europaeus,* and *Thelypteris palustris* (Pallis 1916; van Donselaar-Ten Bokkel Huinik 1961; Rodewald-Rudescu 1974; Hogg and Wein 1987; Krusi and Wein 1988; Lieffers 1984; Mallik 1989; Tomassen et al. 2004; Volkova 2010). Rodewald-Rudescu (1974) in describing floating mats in the Danube Delta estimated that this way of floating mat formation was the rule in that water system.

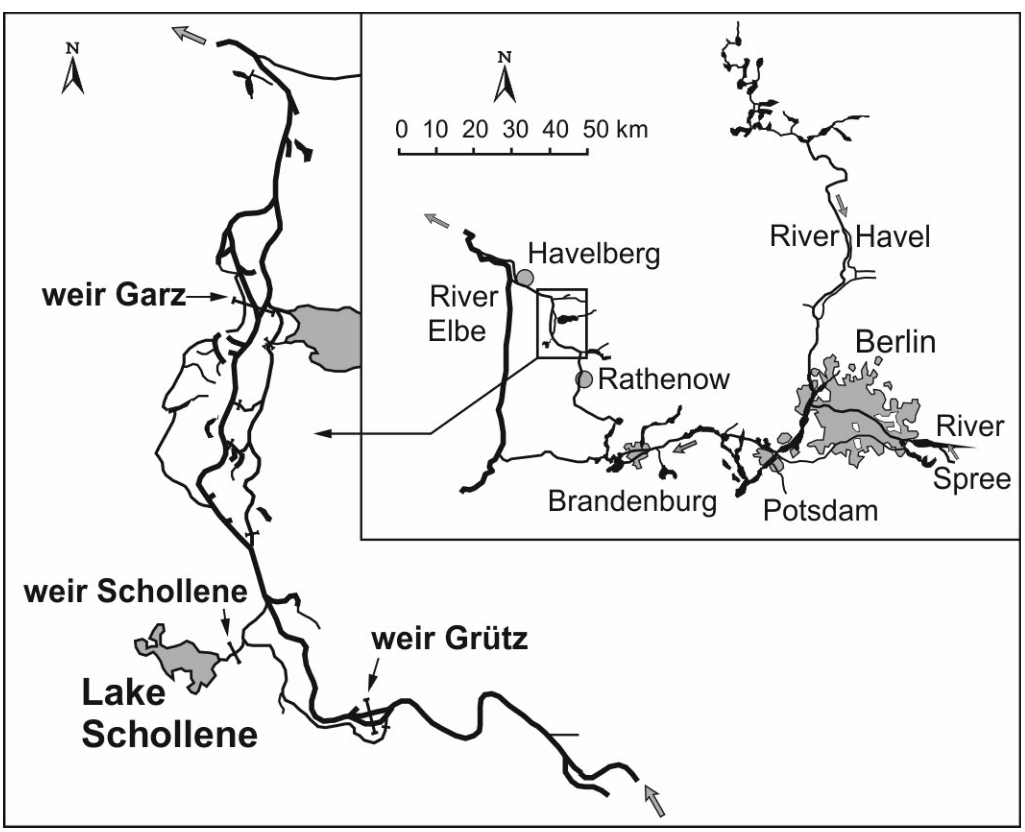
Although most scientists tend favor the second hypothesis, it is not yet clear whether both pathways occur in Central European waters, and if so, which way is more important or for which types of waters these ways are characteristic. Especially for larger lakes, it is not easy to understand how such vegetation initials on loose organic matter can survive wind and wave action for long periods. In the case of colonization of *Stratiotes* carpets, the carrying vegetation even sinks to the bottom at winter time. Furthermore, small isolated waters cannot accumulate substantial amounts of loose organic matter on the shore.

We had the opportunity to investigate Lake Schollene within the Havel River floodplain in NE Germany - which is characterized by extensive floating vegetation mats and was described relatively well in an older study (Potonié 1937). This enabled us to conduct a case study on the long-term development of eutrophic floating peat mats. For this, we addressed two questions: 1) How did these floating peat mats develop and do they grow significantly laterally on the water surface? and 2) How will they develop under human influence in future?

STUDY AREA

Lake Schollene, located in the floodplain of the lower section of River Havel (Brandenburg, NE Germany), is a medium-sized shallow lake covering 240 ha including reeds and the floating peatland belt. The zone of reeds and floating marshes is exceptionally large so that the open water occupies only 39% (94.6 ha) of the total area (Rutter et al. 1994; Figure 1). The original depth to the mineral substrate was approximately 12 m (Potonié 1937), but the lake has filled with organic sediment up to an average free water depth of 0.75 m and a maximum depth of 2.1 m, measured at summertime (Fisch und Umwelt 2005). The water catchment area of the lake has an area of 3100 ha, from which a high proportion of the water seeps diffusely into the lake. During flooding phases, water flows from the Havel River into the lake via a connecting ditch - Seestrang Ditch, and at low river water levels in summer, the lake is impounded by a weir to

FIGURE 1. Map showing the position of Lake Schollene within the lower Havel River floodplain.



ensure a minimum level (e.g., 24.40–25.13 m a.s.l. in 1996). Without this weir one third of the open water area would fall dry (be exposed) during summer (Hilbig and Reichhoff 1974; Kummer et al. 1973). The productivity of the lake can be classified as polytrophic (Knösche 2008).

METHODS

Historical Water Surface Areas

For analysis of the water surface areas of Lake Schollene, historical maps were superimposed using GIS with the help of three road crossings. We used historical topographic maps of 1767-1787 (Schmettau's map series at 1:50.000), of 1843 (Prussian Base Mapping 1830-1865, ordinance survey map of Schollene surveyed by Techow in 1843, the first reliable topographic map at 1:25.000), of 1877-1915 (Prussian New Land Survey 1877-1915 at 1:25.000), and of 1985 (topographic maps at 1:25,000).

Historical Water Levels

In addition to the water surface area, we estimated the historical water levels in the River Havel at the mouth of Seestrang Ditch. That was possible using historical water level data recorded at the gauges Rathenow and Havelberg between 1900 and August 1945 as well as at the gauges Grütz and Garz since August 1945 provided by the Water and Shipping Administration of the Federal Government, Federal Institute for Water Sciences. Water levels at the mouth of Seestrang Ditch were interpolated, assuming a constant flow gradient, by using the ratio of distances between this point and the weir Rathenow (after 1913 the weir at Grütz) as well as the whole distance between Rathenow (Grütz) and Havelberg for the period 1900–1945. These water levels correspond during the winter with those of Lake Schollene. For the period after August 1945 the gauges of weirs Grütz and Garz (built between 1906 and 1912) were used. The interpolated water levels have been validated on the basis of measured winter water levels since 1996 to 2015 at a gauge in the ditch which corresponds with the water level of Lake Schollene during winter and spring ('gauge' in Figure 2). Interpolated data from 1913 to 1945 were additionally corrected by a factor derived from comparison of current interpolated data on the basis of the gauges in Havelberg/Rathenow and Grütz/Garz. That is the time period from which the water level data of Grütz/Garz were lost (i.e., burned) at the end of the Second World War.

Vegetation

For analysis of the vegetation development, we used a vegetation map based on an aerial photograph published by Potonié (1937), as well as original aerial photographs from May 31, 1944 (film No. 0066-44), the summer of 1953 (film No. 1953, picture 679), May 25, 1995 (film No. 10-95, picture 107), and April 17, 2003 (film No. 25-03, picture 475) obtained from the Office of Land-surveying and Geoinformation Brandenburg. The use of the aerial photographs was permitted by this Institution in accordance with Agreement Geobasisdaten © GeoBasis-DE/LGB, GB 05/19.

The emergent vegetation was surveyed in detail only at the lakeward side. In the winter 2005/06, we systematically surveyed 70 transects (4 m wide, 10–30 m long) beginning at the lakeward vegetation boundary to assess the distribution and spatial sequences of the floating vegetation types. The ice cover allowed us to enter the reed stands. Transects were arranged equidistantly every 100 m. Most of the helophytic species could also be determined in winter so that the assignment to plant associations was possible.

The assignment of communities was based on a geobotanical study in this lake by Zank (1997, unpublished). Four vegetation types were identified, with vegetation types 1, 2, and 3 being mostly described as floating marshes in the literature.

1. A community regularly characterized by *Carex pseudocyperus* occurs nearly exclusively at the lakeward edge of the emergent vegetation. It is rich in helophytes of lower stature like *Thelypteris palustris, Rumex hydrolapathum, Lycopus europaeus, Mentha aquatica, Lythrum salicaria, Peucedanum palustre, Epilobium* sp., and is sparsely interspersed with *Phragmites australis* or *Typha* species. This phytocoenosis has been described as *Cicuto virosae-Caricetum pseudocyperi* Boer et Siss. 1942 by Boer (1942), as *Cicuta* type by Den Held et al. (1992), or as 'water hemlock-sedge fen' by Succow and Joosten (2001, pp. 146-148 and 152). *Cicuta* is often absent in this type of vegetation, yet many authors assign such communities to the *Cicuto-Caricetum*, as they are similar in structure, physiognomy and function (Philippi 1973; Hilbig and Reichhoff 1974).

2. A community like the *Cicuto-Caricetum pseudocyperi* is extensively dominated by *Carex paniculata*. It has been termed as *Cicuto-Caricetum paniculatae* Succ 1970 (Jeschke and Müther 1978), *Cicuto-Caricetum pseudocyperi* variant of *Carex paniculata* (Timmermann 1993), *Caricetum paniculatae* (Krausch 1964; Westhoff and Den Held 1969; Pott 1992), *Rumici hydrolapathi-Caricetum paniculatae* Succ. 1988 (Schubert et al. 1995), or as *Carex paniculata* type (Den Held et al. 1992). To distinguish this community from the *Caricetum paniculatae* Wangerin 1916 ap. v. Rochow 1951 on wet terrestrial sites where Rumex hydrolapathum is usually absent, we use the name *Rumici hydrolapathi-Caricetum paniculatae*.

3. This type is nearly up to 100% covered by *Thelypteris palustris. Phragmites* or *Typha* are moderately frequent interspersed and the other helophytes of the *Cicuto-Caricetum* are absent or scarce. This phytocoenosis has been described as *Thelypteridi-Phragmitetum* Kuiper 1957 (Kuiper 1957; Tomaszewicz 1977).

4. The last type - alder carr termed as *Carici elongatae-Alnetum glutinosae* Tx. 1931, is dominated by *Alnus glutinosa*, moderately colonized by *Carex paniculata*, with scattered *Carex elongata*. This type is the driest of the lake's wetland plant communities.

Sampling of Peat Cores

Common peat corers were not suitable for sampling peat due to the very coarse and compressible substrate of the peat mats. Consequently, we used a long knife to cut out a 20 x 20 cm peat block which was then carefully excavated. From the upper peat layer, we cut three blocks (7-10 cm in diameter and 20 cm long, measured precisely) and one block from the sublayer. Blocks were taken to the lab, dried at 70°C in a drying oven for one week and then weighed.

RESULTS

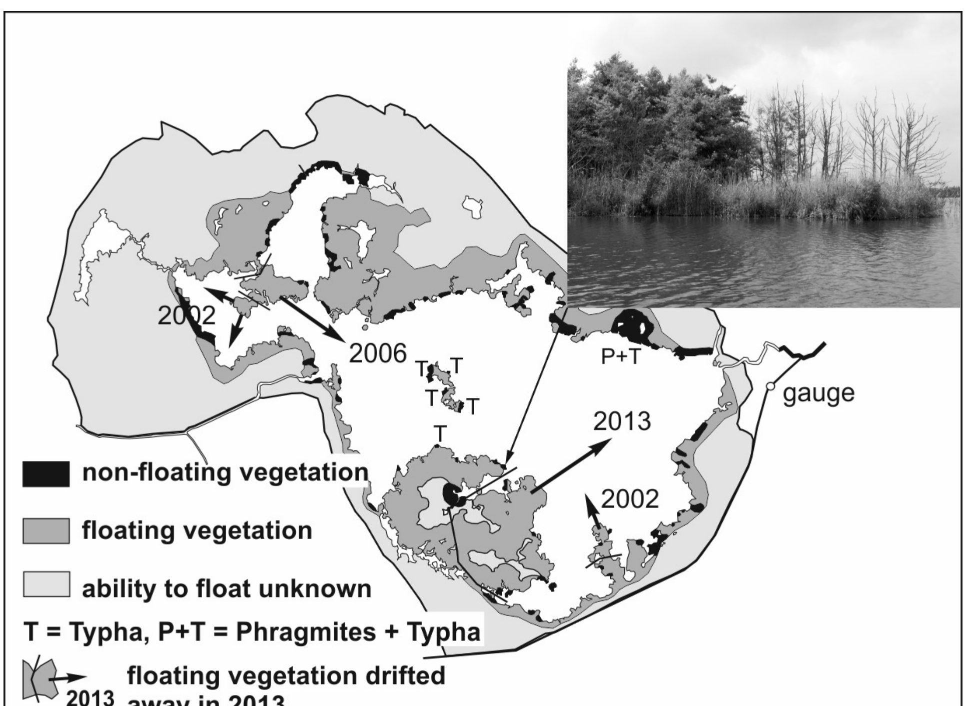
Floatability of Emergent Vegetation in Lake Schollene

The floatability of large areas of emergent vegetation in this lake has been achieved in different ways. During the flood events of 2002, 2006, and 2013, large islands detached from the emergent vegetation belt forming the lakeshore and then drifted over the lake (Figure 2). The extreme summer flood 2002 left highly visible flood marks on alder trunks and reed plants rooted in the substrate. Floatable vegetation did not show any flood marks while non-buoyant vegetation carried such marks at a height corresponding to the water level rise. Further, non-buoyant alder trees suffered from submergence of their trunk bases, having their leaves turn yellow (i.e., evidence of chlorosis) or having lost their foliage. This happens due to a decrease of oxygen supply to the roots via lenticels located predominantly at the trunk bases when inundated during the growing season (Ellenberg and Leuschner 2010, p. 467). On this basis, we mapped the buoyant and non-buoyant vegetation as far as it could be viewed from water. At longer distances, the yellow-leaved or dead alder trees indicated non-floating vegetation. The landward boundary of the floatability, however, was only estimated (Figure 2). We found non-buoyant vegetation in the center of the southern island and as small patches at the water side periphery of the emergent vegetation which anchor the large floating peat mats at their position. Sometimes these patches originated from former floating peat mats already carrying alder trees which lost their buoyancy (Figure 2 and 3) while in other cases, they may be formed by reeds that did not get buoyant.

Hydrology and Water Level of Lake Schollene

As noted earlier, this lake is part of the Havel River floodplain and is connected by a ~1.5 km long ditch called "Seestrang" (Figure 1). Between 1980 and 2015 the lake's water level ranged from 24.85 m to 26.31 m a.s.l. (mean: 24.95 m). The minimum water level is controlled by a weir in Seestrang Ditch that is closed during the summer when the river water level goes down. If the water level in the river exceeds about 25 m a.s.l., the surrounding fen areas of the lake will increasingly be flooded until the lake level corresponds with that of the river. This weir existed before the Second World War but had almost completely disintegrated by the end of 1960s. It was reconstructed in the 1970s but the exact construction time was not documented (personal information from the authorities for nature conservation). Before the reconstruction, the water level in the lake was from time to time lowered so far that larger peripheral areas of the lake were exposed to air (personal observations from local fishermen, aerial photograph from summer 1953 – Figure 6, and Kummer et al. 1973). Unfortunately, that was not documented in a manner we could use for analysis.

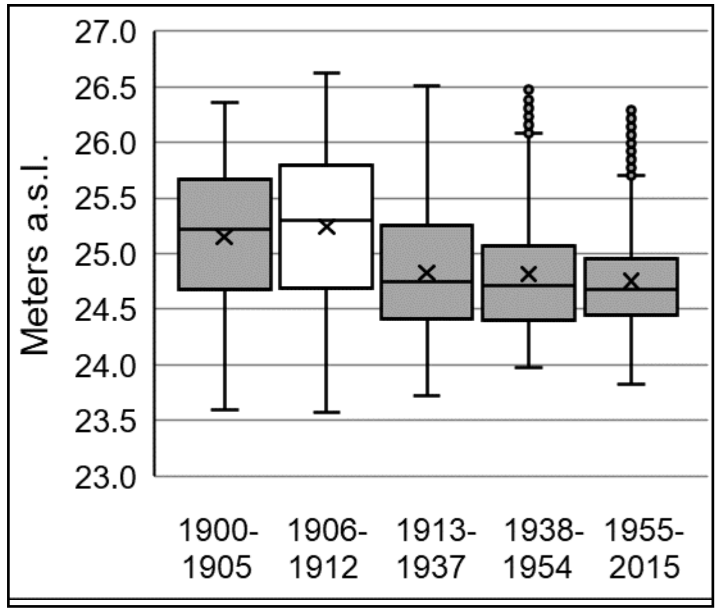
FIGURE 2. Floatability of the emergent vegetation mapped on the basis of flood marks on alder trunks and on dead emergent plant parts after the extreme Elbe River flood in the summer of 2002. The inserted photograph shows a non-floating part (dead alders) at the northern shore line of the southern large island. The arrows indicate the direction of movement of detached floating mats in 2002, 2006, and 2013. The use of the underlying map is permitted by Geobasisdaten © GeoBasis-DE/LGB, GB 05/19.



From 1900 to today, some important actions were taken for river regulation. Between 1906 and 1912 two new weirs were constructed between Rathenow and Havelberg at Grütz and Garz. The Weir Neuwerben in the north of Havelberg which ensures minimum water levels in the Havel River was set into operation in 1954 (Nabu 2017).

Water levels in the Havel River at the mouth of Seestrang Ditch correspond during the winter with those of Lake Schollene. The water levels responded clearly to the river regulation measures from 1906 to 1912: they were lowered by about 0.5 m (Figure 4). Simultaneously, the lowest water levels increased slightly (better water retention in the river). Since then, the river's water level often fell below 25 m a.s.l. (mean water level of Lake Schollene). Consequently, large peripheral areas of the lake would fall dry in summer if the weir in Seestrang Ditch was not closed. According to the bathymetric map of Fisch und Umwelt (2005), a 15–60 m wide peripheral strip of the lake would be exposed when the water level drops below 24.5 m while about 80% of the lake area would be dewatered at a level of 24 m.

FIGURE 4. Estimated water levels of River Havel at the mouth of Seestrang Ditch during different time periods. White box: Period of the construction of the Weirs Grütz and Garz, these data are somewhat unreliable because it is not known when the weirs became fully operational. Boxes: 25%-quantile to 75%-quantile with the median (line) and mean value (cross).



In-filling History of Lake Schollene since the Late 1700s

The oldest available map of Lake Schollene is that of Schmettau (1767-1787). Unfortunately, it was rather difficult to fit this map to modern maps due to the generalized land survey techniques used at that time. Thus, the exact dimensions of the lake remained unreliable, only the shape of the lake could be fairly reliably assessed. Another problem was the appraisal of the silting-up vegetation. This vegetation was usually not mapped by the land surveyors because

FIGURE 5. Comparison of historical maps (1843, 1880, and 1985) of Lake Schollene showing the recent development of emergent vegetation and floating marshes: a: 1880 map vs. 1843 map (grey background map) and b: 1985 map vs. 1880 map. The maps were fitted using the crossroads 1, 2, and 3 as well as the inflow ditch in the west.

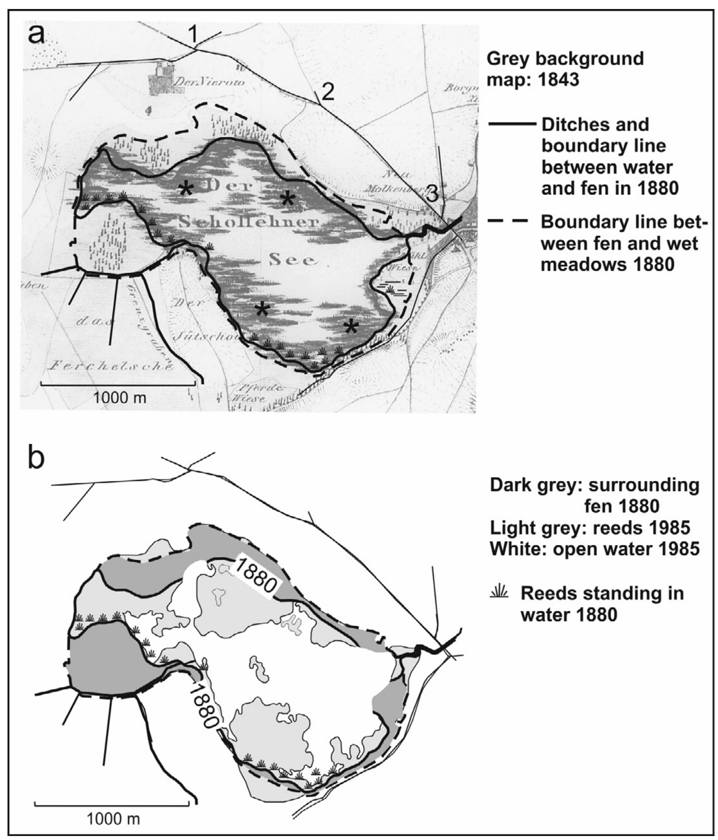
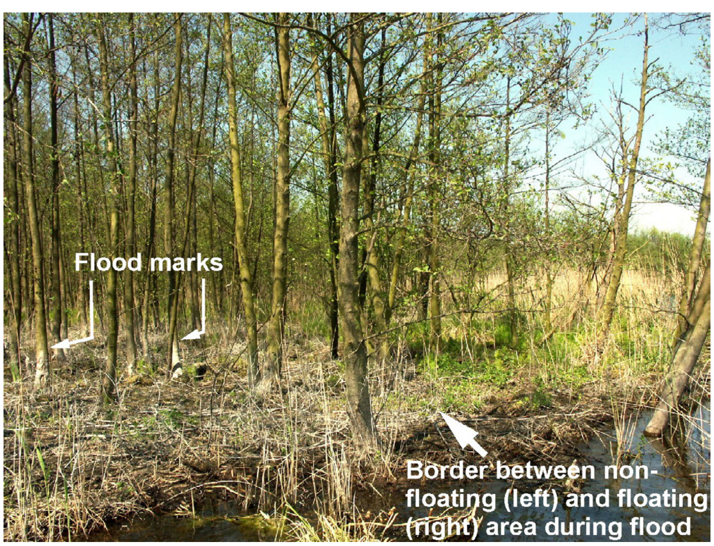


FIGURE 3. Flood marks: Non-floating section within a floating alder carr after the 2006 spring flood. The area inundated during the flood then exhibited dead epigeal marsh vegetation and flood traces on alder trunks (dried lake detritus) while the surrounding buoyant area remained fresh and green.



it was of little interest at that time and difficult to survey. The first information about the occurrence of wetlands in the lake appears on Techow's map of 1843 (Figure 5A, grey background map). This map shows a water area that almost perfectly corresponds with that from 1880 (continuous line in Figure 5a and b). Within this boundary line, Techow symbolized relatively large areas of vegetation standing in water, as it was marked by reed symbols over horizontal blue brush strokes (asterisks in Figure 5A). These areas roughly resembled those of the emergent vegetation on the map of 1985 (light grey in Figure 5B). In the map of 1880, some reed symbols are inserted in these areas, indicating that reeds grew in water. But, at that time, reeds were only mapped very roughly.

Outside of the 1880 shoreline, Techow mapped alder carrs (small vertical dashes) within the border of wet meadows which have been farmed since 1880 (dashed line in Figure 5a and b). In the terrestrial area within this dashed line, Rutter et al. (1994) found lake sediments in soil cores, but not outside this zone. The historical maps suggest that the area of open water including reeds standing in water decreased by about 65% very rapidly from the middle of the 18th century to the first third of the 20th century and then remained fairly constant (Table 1). However, it should be emphasized that Schmettau's maps of 1767-1787 were not very accurate.

The development of the emergent vegetation and floating marshes inside the lake from 1936 onwards is well documented by aerial photographs. Besides the fairly constant area of open water, the structure of the emergent vegetation changed occasionally. In 1936 and 1953 the lake was dotted with many small reed islands, sometimes free floating and sometimes anchored in the ground (Potonié 1937; Figure 6). That was the period when the lake occasionally fell partially dry (Kummer et al. 1973). These islands occurred exclusively within the shallower lake zones and were mainly

TABLE 1. Estimated development of the non-terrestrialized lake area from 1767 to 1880 (grey, area of reeds standing in water unclear) and the area of open water from 1936 to 2015 (white). Note that the areas from 1767 and 1812 are not very reliable because the land survey at that time was not as accurate as it was since the Prussian Base Mapping (1830-1865).

Year	1767	1812	1843	1880	1936	1953	1995	2003	2015
Area of open water (ha)	270	228	168	168	95.1	83.8	95.0	95.7	93.7

FIGURE 6. Development of the emergent and floating vegetation areas between 1936 and 2015 drawn from the vegetation map of Potonié (1937) and from aerial photographs of 1953, 1995, and 2015. Dark grey: emergent and floating vegetation, light grey: open water table, and white: bare lake bottom. A large section of marsh in the lower left of the 1995 image floated (dotted hatching) away and relocated to the lower right in 2015.

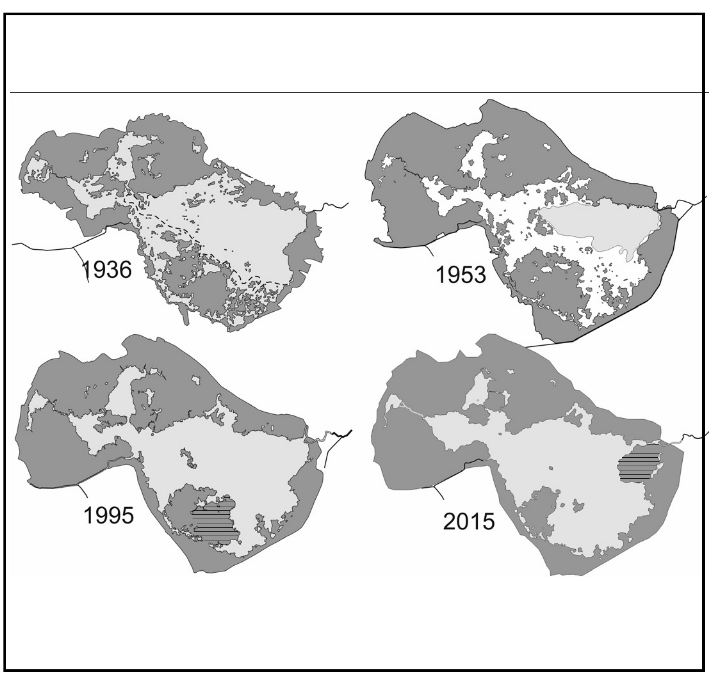
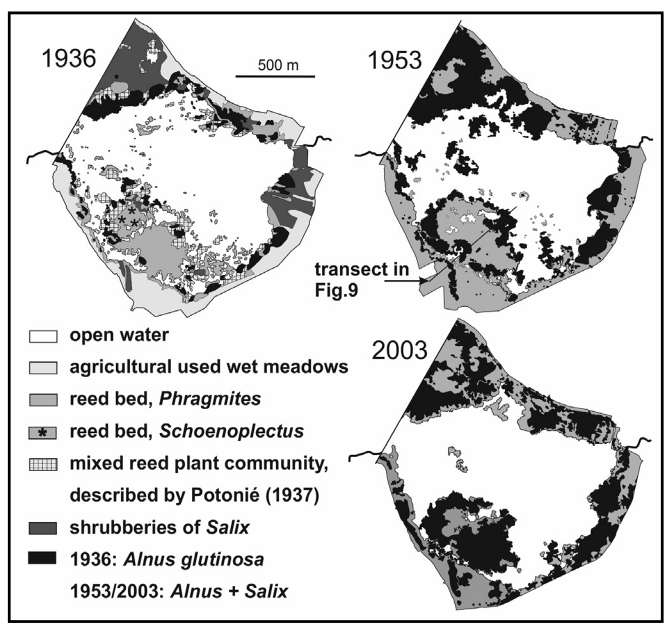


FIGURE 7. Development of floating marshes shown for the eastern part (main basin) of the lake, drawn from aerial photographs. The mixed reed plant community is very similar to the *Cicuto-Caricetum pseudocyperi* according to the reported species by Potonié (1937) although he did not mention this association. The wooded areas increased from 27.8 ha in 1936 (11.4 ha *Alnus glutinosa* and 16.4 ha Salix sp.) to 40.7 ha in 1953 and to 43.8 ha in 2003. However, the differentiation into willow and alder groves was not done for 1953 and 2003 because this was not reliably possible on the existing aerial photographs.



Typha patches (documented in some photographs from that time, H. Krüger, Rathenow 1955-60, unpublished personal communication). The structure of the lake remained constant for four decades after 1953 until very high water levels caused considerable rearrangements of reed beds in 2002, 2006 and 2013 (Figures 2 and 6). Floating mats carrying alder forests drifted over the lake driven by wind and attached to other locations on the lakeshore.

Development of the Floating Marshes since 1936

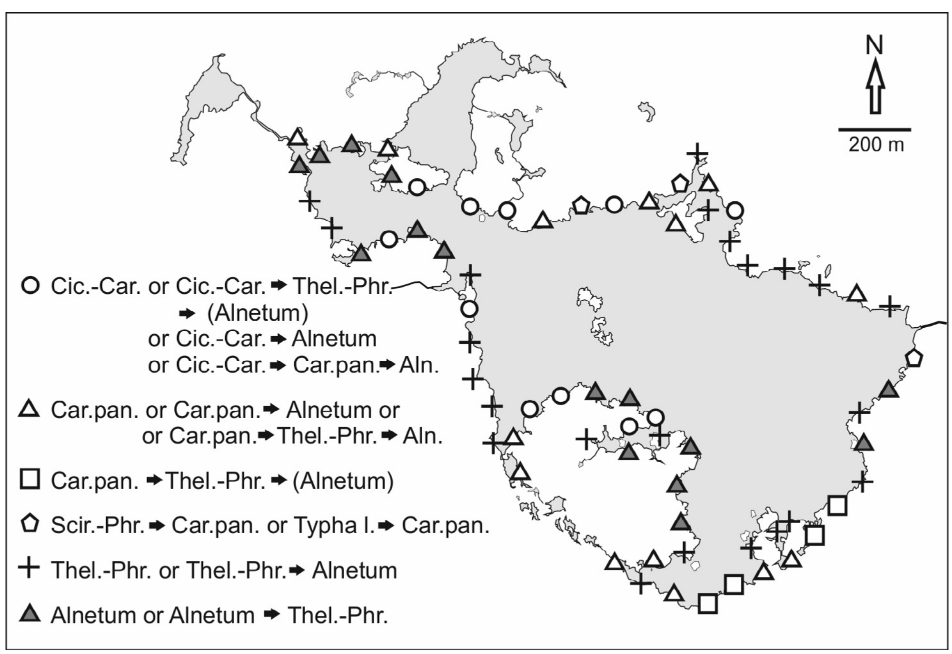
The formation of floating marshes was documented using the vegetation map of Potonié (1937) and two aerial photographs, one from 1953 and the other from 2003. The main purpose was to record the spread of alder trees because they mark the end point of the succession of emergent vegetation in waters. On the aerial images of 1953 and 2003, it was impossible to differentiate reliably between willow bushes and alder carrs, so we classified both willows and alders simply as woody plants. The northwestern part of the lake was excluded from our analysis, because the differentiation between reeds and woody plants on the photographs was not always possible there.

From 1936 to 2003, the areal extent of the emergent vegetation did not appear to change as the reported water area was nearly constant (Table 1). Some changes in the areal structure did occur. The large southern island showed its basic structure already in 1936 which, however, got more compact until 2003 (Figure 7). This island revealed the development of the emergent vegetation best. At the first stage in 1936, the island consisted mainly of *Phragmites* and *Schoenoplectus* reeds surrounded by a helophytic plant community characterized by *Cicuta virosa*, *Rumex hydrolapathum*, *Thelypteris palustris, Iris pseudacorus* and *Symphytum officinale*, and interspersed with reed species - it was called "Röhricht-Pflanzen-Gemeinschaft, gemischt" (mixed reed plant community) by Potonié (1937). Nearly exclusively within this community, small alder bushes developed (Figure 7). These alder patches enlarged centripetally as well as centrifugally and reached the lakeward shoreline in most places. This development could also be observed at the other shores of the lake. The residual of the central reed stand in the island is today well anchored in the ground and does not contain *Thelypteris palustris*. A further conspicuous change is that the great number of small islands in the shallow portion of the lake have disappeared.

The Vegetation of the Floating Marshes

The sequence of the four vegetation types was surveyed along transects during the winter 2005/06. The observed vegetation sequences were almost variable. In 19% of the transects, the *Cicuto-Caricetum pseudocyperi* occurred at the water side and was followed by the *Rumici hydrolapathi-Caricetum paniculatae* or/and the *Thelypteridi-Phragmitetum* and then by the *Carici elongatae-Alnetum glutinosae*. Sometimes the *Cicuto-Caricetum* was directly followed by an *Alnetum* (Figure 7). In Lake Schollene, *Cicuta virosa* is currently absent but we nevertheless assigned this phytocoenosis to the *Cicuto-Caricetum* as has been done by many geobotanists (e.g., Krausch 1964; Fabiszewski and Faliński 1967; Philippi 1973; Hilbig and Reichhoff 1974; Fischer 1999). This community formed a 1–9 m wide (median = 3 m) vegetation belt. In transects where the *Cicuto-Caricetum* was absent, the *Rumici hydrolapathi-Caricetum paniculatae* (26%) or the *Thelypteridi-Phragmitetum* (33%) adjoined the open water. In 20% of the transects alder carr bordered directly on the open water. At two sites, a 2 m wide stand of *Typha latifolia* rooting in the lake bottom was situated in front of the *Cicuto-Caricetum* (Figure 7).

FIGURE 8. The sequence of plant associations in 70 radial oriented and equidistant (100 m) arranged transects beginning at the open water/emergent vegetation edge. Cic.-Car. = *Cicuto-Caricetum pseudocyperi* without *Cicuta virosa*, Car. pan. = *Rumici hydrolapathi-Caricetum paniculatae*, Thel.-Phr. = *Thelypteridi-Phragmitetum*, Scir.-Phr. = *Scirpo-Phragmitetum*, Alnetum = *Carici elongatae-Alnetum glutinosae*. Parentheses mean that the community is sometimes present and sometimes not. The survey was made in January 2006. Two basins in the northwest were inaccessible due to ice conditions.



The Structure of the Floating Peat Mats

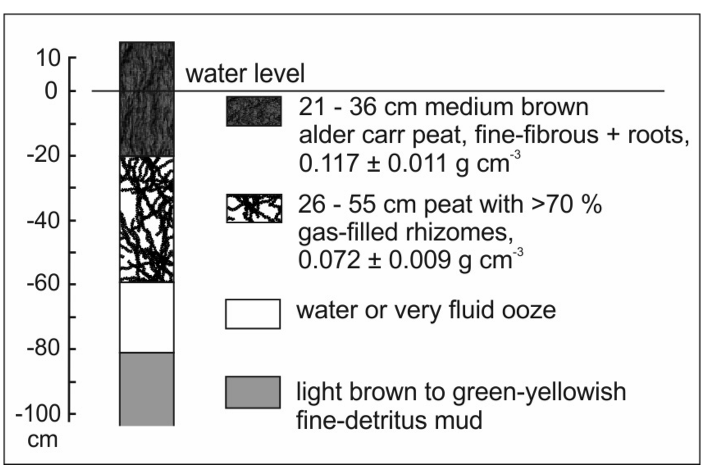
Four peat cores were excavated from the island that drifted away in 2013, two from the fringe zone (about 5–10 m from the peat mat edge) and two from the inner zone of the island (about 30–35 m from the edge). The fringe carried a largely open alder carr with a lot of dead trees (only about 10% cover by living trees) while the inner zone contained a more closed and vital alder carr (about 60% tree cover). Total mat thickness was 70 and 76 cm in the fringe and 62 and 66 cm in the inner area. The upper substrate layer was a brown peat mass intertwined by roots from the alder trees and below this layer a network of old dead rhizomes from a reed vegetation (rhizome diameter up to 2 cm) was found. The dry mass density ranged from 0.07 to 0.12 g cm^{-3} and excavated pieces from both layers were very buoyant (Figure 9).

DISCUSSION

Recent Development of the In-filling Zone

The open water area of the lake was presumably never larger than marked by the dashed line in Figure 5 since Rutter et al. (1994) did not find any lake sediments outside this border line and areas inside are much wetter than the farmed meadows outside. As noted earlier, the area of open water appeared to decrease very rapidly from the middle of the 18th century to the first third of the 20th century - by about 65% and remained fairly constant thereafter (Table 1). Besides the accumulation rate of organic sediments, the speed of terrestrialization depends on changes of the water level. A decreasing water level promotes the progression of the reed stands towards the open water area and vice versa, whereby the regression of the reed is slower and often not complete (van der Valk and Davis 1979; Wallsten and Forsgren 1989; Coops et al. 2004). Unfortunately, we have no information about the lake water levels before 1900. However, at the beginning of the 20th century the lowering of the mean water level in the Havel River by about 0.5 m (Figure 4), occasionally in combination with years in which the lake fell partially dry, may have promoted the repeated colonization of the exposed lake bottom or of very shallow water areas by reed stands, often in the form of small patches and islands (Figure 6). An aerial photograph from 1945, which is difficult to evaluate due to its poor quality, also shows a great number of reed islands. Thus, it is striking that the reed island formation only occurred during the time of unstable minimum water levels before the reconstruction of the outflow weir. Remarkably, no new reed stands have emerged after that.

FIGURE 9. The vertical profile of the floating peat mats, compiled from the results of 4 peat cores taken from the island drifted away in 2013 (see Figure 2)



The Structure and Floatability of the Peat Mats

The structure and thickness of Lake Schollene's floating peat mats correspond with those reported from the Mississippi River Delta (two-layered and about 50 cm thick; Sasser et al. 1991, 1995a, 1996; Swarzenski et al. 1991), but the sublayer of those mats was described as loose peat consisting of more decomposed organic material. The floating *Phragmites* marshes in the Danube Delta are different (Rodewald-Rudescu 1974). They are three-layered, 50–200 cm thick, with two sublayers consisting mainly of more horizontal (deepest layer) or more vertical (middle layer) *Phragmites* rhizomes. These differences in the structure of the peat mats may be due to the morphology of *Phragmites australis*. The floating mats of Lake Schollene originated from *Phragmites* or *Typha* stands (rhizomes of the sublayer, Figure 9) but were later successively colonized by stands of herbaceous helophytes and alders (see below). *Typha* and *Phragmites* rhizomes have large aerenchyma that contribute to their buoyancy (Hogg and Wein 1988a, b). However, the most important contribution to the buoyancy comes presumably from marsh gas entrapped within the peat (Canadian flooded fen: Hogg and Wein 1988b; Mississippi Delta: Sasser et al. 1996). Unfortunately, we have not done any similar investigations to confirm this for Lake Schollene peat mats. The strong dependence of the buoyancy on trapped marsh gas means that the floating mats may lose their buoyancy when subjected to strong wave action and/or due to the increased weight of the alder trees. Strong wave action may further loosen the peat body so that it may lose marsh gas while introducing oxygen into and under the peat mats that may slow marsh gas production. Observations of a local dieback of alders on peripheral zones of the floating marshes (Figure 2) seems to suggest loss of buoyancy. These sites can be colonized by willows which are more flood-tolerant than alders (Hilbig and Reichhoff 1974).

Besides the degree of marsh gas accumulation, buoyancy depends on the density of the peat (fresh mass per volume) (Hogg and Wein 1988b; Sasser et al. 1995a, 1996). Since measuring the density of fresh peat is a challenge as marsh gas bubbles and water are lost immediately during excavation of the cores, authors have used the dry peat weight per unit volume as an important metric. Tomassen et al. (2004) estimated a bulk density of dried peat of about 0.075 g cm^{-3} in Dutch floating oligotrophic bogs. Similar results and a density for non-floating peat ranging between 0.105 and 0.16 g cm^{-3} were reported by Sasser et al. 1991, 1995a, 1996 and Swarzenski et al. 1991 from eutrophic floating mats in the Mississippi Delta. For Lake Schollene peat mats we found 0.11 g cm^{-3} in the upper layer and 0.07 g cm^{-3} in the sublayer, which are more at or above the limit for buoyancy. It is difficult to assess why bulk densities in Lake Schollene are slightly higher. It may be that the higher root content and possibly the better degradability of alder litter, partly promoted under the influence of oxygen, leads to denser peat. Due to the high nitrogen content of alder litter and the correlation of the litter decomposability with the C/N ratio, the decomposition rate of alder litter is about 25 times higher than that of Phragmites or Typha (Enriquez et al. 1993). We have carefully tried to exclude a compression of the peat by our sampling method but the leakage of marsh gas during the excavation of the sample could not completely be prevented. It may be that in such old peat mats, carrying alder trees, especially the top layer is more compressed by the own weight.

The Process of Floating Mat Formation in Lake Schollene

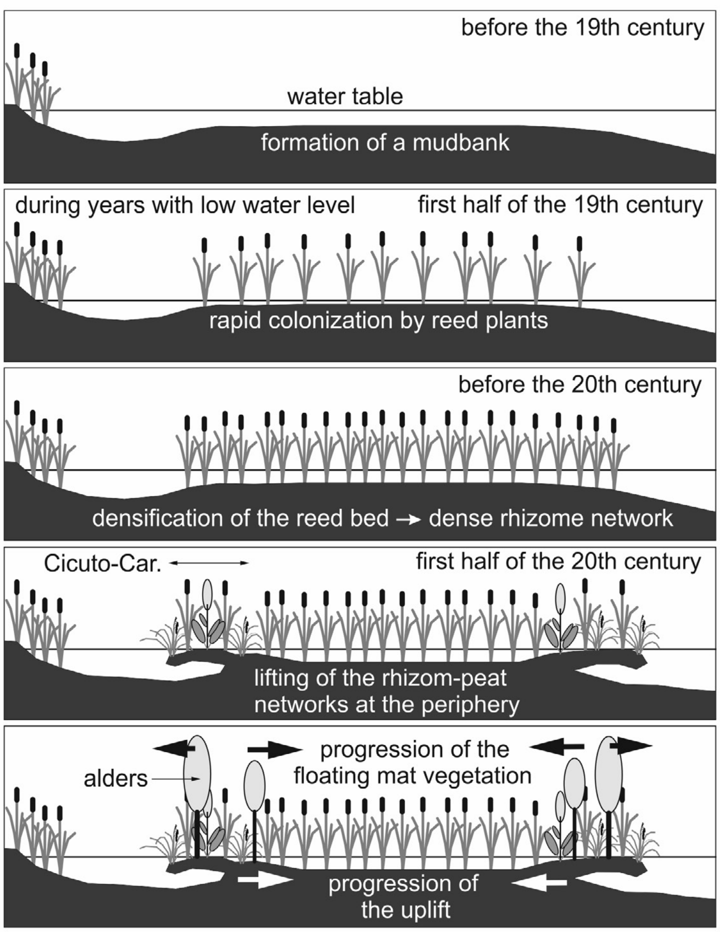
If floating mat formation in Lake Schollene came through colonization of pleustophytic vegetation (i.e., free floating plants) or of accumulated organic matter (first hypothesis, see Introduction), one would expect to see substantial lateral growth of the floating mats. However, such lateral growth has not been observed in this lake. Consequently, development of the emergent vegetation in Lake Schollene more likely supports the second hypothesis (detachment of reed stands from the lake bottom and subsequent floating-up). At the latest, in the first third of the 20th century, the emergent vegetation began to float on water or on extremely liquid mud (Potonié 1937). Potonié's map indicates that at the beginning of the 20th century the in-filling process had progressed so far that suitable conditions for floating peat mat formation arose: 1) up to 12 m accumulated organic sediment distributed over the whole lake area, 2) free water depth ≤ 2 m, 3) possibility of wind-induced redistribution of the lake mud, and 4) formation of very soft mud banks. His map shows very large areas with water depths ≤ 25 cm in the northwestern and southwestern parts of the lake - areas located nearest to the prevailing wind direction and therefore most sheltered from wind by the shore and its vegetation. Here large quantities of redistributed very soft organic sediments have accumulated, accelerating the spread of reed-bed vegetation (Horst et al. 1966; Figure 5). However, the very soft consistency of the redistributed organic matter allowed for only a poor anchoring of plants in the sediment. The preferential formation of floating marshes on very thick and soft mud layers has also been highlighted by many authors (Pallis 1916; Boer 1942; van Donselaar 1961; Jeschke 1963; Bernatowicz and Zachwieja 1966; Schmidt 1981; Hogg and Wein 1988a; Bunting and Warner 1998; Fischer 1999).

As the map comparison suggests, the formation of floating peat mats likely began at places with typical reeds standing in water (Figure 5). To explain the formation of floating mats in detail we focus on the southern big island because the process is best visible there. This island was located in the same place until 2013 - the map of 1843 shows reeds most likely standing in water (Figure 5), and later Potonié (1937) mapped normal *Phragmites* stands on approximately 75% of the central island area. The formation of floating mats started at the periphery of the island with a community called by Potonié as "mixed reed plant community" (Figure 7), occupied by species that do not grow in deep water and are characteristic for the *Cicuto-Caricetum pseudocyperi*. Among these species, *Cicuta virosa* clearly prefers floating marshes (Shin et al. 2013, 2015). Moreover, the floatability is evident, because the first small alder groves, which would not be able to survive submergence at summertime (Ellenberg and Leuschner 2010), colonized these peripheral communities. These alder groves spread then towards the periphery of the island, so that they often border directly to the water body (Figure 10). But the most conspicuous spread of the alder carr occurred centripetally, indicating the progression of floatability (Figure 7). All this development took place without any substantial expansion of that island, meaning that the formation and further development of the floating marshes occurred at one and the same site. Consequently, an enlargement of the total area of the floating mats seems only be possible after reeds colonized the lake bottom followed by the whole process of floating up due to a rise in lake levels. On old floating mats, the alders can then accumulate so much organic matter that they touch down on more stable layers of the lake sediment. The described process of floating mat formation is illustrated in Figure 11 and applies in principle to the other shores of the lake (Figure 7).

The mode of floating mat formation, as described for Lake Schollene, was discussed by the most scientists who have studied eutrophic lakes in the temperate climatic zone (Pallis 1916; Rodewald-Rudescu 1974; Hogg and Wein

FIGURE 10. Non-floating section with dead alder trees within a floating alder carr after the spring flood in 2006. This photo was taken in July 2006 and therefore shows recovering marsh vegetation.

FIGURE 11. Schematic representation of the hypothesized origin and development of the floating marshes in Lake Schollene. The scheme represents, for instance, a NE to SW transect through the southern island shown in Figure 7.



1987; Hogg and Wein 1988a; Krusi and Wein 1988; Mallik 1989; Somodi and Botta-Dukat 2004; Volkova 2010). Hogg and Wein (1987) directly observed this process in a Canadian lake in the temperate zone after a rise in water levels. Some of the studies assumed lateral growth of these floating peat mats (Bernatowicz et al. 1966; Hogg and Wein 1988a; Krusi and Wein 1988; Somodi and Botta-Dukat 2004; Volkova 2010) but clear evidence for this assumption were not reported. Sasser et al. (1995b) even found a net area loss of the floating peat mats by about 4% on the basis of aerial photographs within a 47-year period in a lake in the Mississippi River Delta.

The floating *Sphagnum* mats in oligotrophic bog lakes can generally grow centripetally along the water surface. In contrast to eutrophic systems, the pioneer species in such bogs (e.g., *Menyanthes trifoliata*, *Carex limosa*, *Carex lasiocarpa*, *Chamaedaphne calyculata*, and *Kalmia polifolia*) are low-growing herbaceous species or shrubs with long rhizomes or horizontal growing shoots (Dansereau and Segadas-Vianna 1952; Larsen 1982; Taylor 1983; Kratz and DeWitt 1986; Zimmerli 1988). Their large aerenchyma provide a strong buoyancy and they do not need anchoring in the ground due to their low stature. These pioneers are then colonized behind the floating mat edge by *Sphagnum* mosses and other bog species (Larsen 1982). The average rate of lateral growth is about 1 cm/year up to a maximum of 5 cm/year (Larsen 1982; Schwintzer and Williams 1974).

The question if floating mats were formed on pleustophytic vegetation (e.g., *Stratiotes aloides*) in Lake Schollene, as suggested by van Donselaar-ten Bokkel Huinink (1961) and Den Held et al. (1992), could not be investigated today because such communities have disappeared. This assumption is merely based on the frequently observed occurrence of floating marshes in the neighborhood of *Stratiotes*. When initials of the floating mat vegetation are found directly on *Stratiotes* carpets, the question arises as to how they can survive the wintertime when *Stratiotes* is submerged. In tropical waters where the floating mat formation on pleustophytes (e.g., *Eichhornia crassipes*, *Salvinia molesta*, and *Pistia stratiotes*) was clearly observed we have a different situation. Here the growth is considerably faster and without any interruption during the whole year. After accumulation of some organic matter within the pleustophyte carpets, very fast-growing rhizomatous sedges or grasses like *Cyperus papyrus*, *Scirpus cubensis*, or *Leersia hexandra* interlacing each other allow colonization of these carpets. Owing to the uninterrupted rapid growth in tropical regions, these colonizers can successively replace the pleustophytes during a short time (Trivedy et al. 1978; Gore 1983; Hill et al. 1987; Ellery et al. 1990; Wolf 1990; Junk 1997; Adams et al. 2002; Azza et al. 2006).

Regarding the formation of floating marshes on dead organic matter washed ashore, we did not find any evidence of this in Lake Schollene but we cannot exclude this process, as it is generally possible. Perhaps, this way of floating mat formation is better suited for old river branches where large amounts of dead organic matter can accumulate permanently transported in the river. These river branches are often wind-sheltered enough so that wave action will not so easily destroy the accumulations (Freitag et al. 1958; Lieffers 1984).

The role of the communities with the dominant species *Phragmites australis* and *Thelypteris palustris* on floating peat mats is almost unclear. Tomaszewicz (1977) described such communities as *Thelypteridi-Phragmitetum* Kuiper 1957 and found often them on floating peat mats in very shallow lakes. However, we do not know whether this community represents a specific way of floating marsh formation or whether the increased dominance of *Thelypteris* simply indicates succession on an existing floating mat. Zank (1997) pointed out on the basis of publications of Horst et al. (1966) and Hilbig and Reichhoff (1974) that *Thelypteris* in Lake Schollene probably became more dominant from 1954 to the time of his own investigations. The *Thelypteridi-Phragmitetum* may be a specific vegetation type or a later developmental stage of the buoyant peat mats because it could often be found in deep inner areas of the floating marshes. At these sites, the up-floating reed stands remain mostly intact and dense so that only the slightly shade-resistant, runner-forming fern is able to occupy these sites.

The willow shrubberies in the north and east of the lake, which were mapped on the land side by Potonié (Figure 7) and which were later partly colonized by alders, indicate a younger stage of development than the alder stands, according to the normal sequence of terrestrialization in lakes. Willow groves were much more widespread until the 1950s and have since declined (Hilbig and Reichhoff 1974).

The floating marsh formation marks the last limnic phase of Lake Schollene due to the accumulation of very fluid organic sediments nearly up to the water surface. A palynologic study of Pokorný and Janovská (2000) seems to support this view. In a fossil lake which was almost similar to Lake Schollene, they found at the transition from the limnic to the terrestric phase of lake development, a singular occurrence of *Cicuta virosa* together with *Carex pseudocyperus* and helophytes that are typical for the *Cicuto-Caricetum*.

Do the Floating Peat Mats Grow Laterally Along the Water Surface?

Based on our work, we believe that the floating peat mats in Lake Schollene are not able to grow substantially laterally. This view is supported by the following facts. First, during the eight decades after 1936 the open water area did not decrease substantially. The lower water area observed in 1953 promoted the formation of numerous reed islands during very low lake water levels. These islands disappeared nearly completely in years with normal water levels, especially after the reconstruction of the weir in the outflow (Seestrang) during the 1970s. Second, the succession of the vegetation progressed at one and the same place at the lakeward periphery from the first stage the *Cicuto-Caricetum pseudocyperi* (at the beginning even with *Cicuta virosa*; Potonié 1937; Horst et al. 1966), to the more solidified *Rumici hydrolapathi-Caricetum paniculatae*, partially with interspersed willows and young alder trees, to closed alder carr (Figure 7). The fact that mostly the *Cicuto-Caricetum* disappeared at the lakeward front and that it was often replaced by alder carr provides strong proof that lateral growth does not occur. *Cicuta virosa* has been seen as a pioneer species on less solidified floating peat mats (Shin et al. 2013, 2015); it often colonizes bare organic substrates and even dead wood (Hejný 1960, pp. 32-34 and 136-138; Demuth et al. 1992, p. 273). Third, besides small tillers of *Thelypteris palustris*, no species was observed that grows along the water surface. The almost heavy and tall helophytic species need to be anchored in the ground.

Nonetheless, we cannot exclude possibility that disrupted old rhizomes accumulated and compacted in small sheltered coves serve as substratum for the vegetation of the Cicuto-Caricetum pseudocyperi as it was hypothesized by Krausch (1965). This way of floating mat formation could have led to a filling of the many small indentations on the outer edge of the floating vegetation. Such *Cicuto-Caricetum pseudocyperi* initials were not observed on accumulated floating organic matter in Lake Schollene. A similar result may be reached by drifting floating mat islands disrupted on other sites, but this does not increase the whole area of floating mats or decrease the open water area.

Floating Mat Formation in Relation to the Lake Water Levels

Our examination of the formation of the floating mats in Lake Schollene has shown that their formation probably dates back into the first half of the 20th century. This was the period from the construction of the two weirs Grütz and Garz until the reconstruction of the weir in the outflow (Seestrang). It was characterized by lower lake water levels (Figure 4) and some summers with a partially dry (exposed) lake bottom. The bare lake bottom during the growing season provided suitable substrate for the establishment and rapid expansion of new reed stands (van der Valk and Davis 1979; van der Valk et al. 1994; Coops et al. 2004). The great number of reed islands in the shallow lake zones found in 1936 and 1953 (Figure 6) can be interpreted to support this. In years with higher water levels throughout the year, consolidated larger pieces of reed stands could then have accumulated enough swamp gas that they became buoyant and smaller ones were presumably disintegrated. After reconstruction of the weir in the lake outflow during the 1970s the minimum lake water level could be stabilized at about 24.85 m at summertime. Since then, no more reed islands have formed. We therefore believe that the formation of new areas of floating vegetation mats is now prevented and will be prevented as long as the current minimum water level is maintained or until such time as new organic matter banks are piled up to almost reach the water surface. Accordingly, the vegetation on the floating peat mats gives the impression of a very advanced succession stage: the absence of *Cicuta virosa*, a high percentage of *Carex paniculata* or a shift into a *Rumici hydrolapathi-Caricetum paniculatae*, and the spread of alder carr (Boer 1942; van Donselaar 1961; den Held et al. 1992). *Cicuta virosa* prefers to colonize bare organic matter in young floating peat mats or even in mats of pleustophytes (Boer 1942; van Donselaar-ten Bokkel Huinink 1961; Shin et al. 2013, 2015). Furthermore, the typical *Cicuto-Caricetum pseudocyperi* containing this species is regarded as the first stage of vegetation development on floating mats (Boer 1942; Kuiper 1957; Koerselman and Verhoeven 1992; Fischer 1999). We must conclude that the present state of the vegetation of the floating mats in the lake also indicates that any substantial new formation of floating mats is not occurring.

Expected Development at Different Water Level Regimes

While the current water level regime with variable maximum water levels during winter time and constant relatively high minimum water levels from year to year (Table 1, after 1980) persist, we expect that the area of the open water will decrease very slowly over a long time depending on a general or local rise of organic matter accumulation. In time, it is possible that more areas of non-floating, emergent vegetation may become buoyant and can later be colonized by alders. We expect that the floating peat mats will increase in thickness until they will rest on more solid layers of the underlying mud, forming non-floating, consolidated alder carr which directly borders on the open water (Kratz and DeWitt 1986). A temporary strong increase of the water level (extreme flood), however, would result in disintegration and/or disruption followed by a drifting away of floating mats. This new floating-mat formation in front of the existing vegetation would lead to a faster reduction of the open water surface than if more constant water levels are maintained as is the current situation. ■

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