1-1-2005

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Recommended Citation

Booth, Robert K.; Hotchkiss, S. C.; and Wilcox, Douglas A., "Discoloration of Polyvinyl Chloride (PVC) Tape as a Proxy for Water-Table Depth in Peatlands: Validation and Assessment of Seasonal Variability" (2005). *Environmental Science and Biology Faculty Publications.* Paper 41.
http://digitalcommons.brockport.edu/env_facpub/41

Functional Ecology 2005

Discoloration of polyvinyl chloride (PVC) tape as a proxy for water-table depth in peatlands: validation and assessment of seasonal variability

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Summary

1. Discoloration of polyvinyl chloride (PVC) tape has been used in peatland ecological and hydrological studies as an inexpensive way to monitor changes in water-table depth and reducing conditions.

2. We investigated the relationship between depth of PVC tape discoloration and measured water-table depth at monthly time steps during the growing season within nine kettle peatlands of northern Wisconsin. Our specific objectives were to: (1) determine if PVC discoloration is an accurate method of inferring water-table depth in *Sphagnum*-dominated kettle peatlands of the region; (2) assess seasonal variability in the accuracy of the method; and (3) determine if systematic differences in accuracy occurred among microhabitats, PVC tape colour and peatlands.

3. Our results indicated that PVC tape discoloration can be used to describe gradients of water-table depth in kettle peatlands. However, accuracy differed among the peatlands studied, and was systematically biased in early spring and late summer/autumn. Regardless of the month when the tape was installed, the highest elevations of PVC tape discoloration showed the strongest correlation with midsummer (around July) water-table depth and average water-table depth during the growing season.

4. The PVC tape discoloration method should be used cautiously when precise estimates are needed of seasonal changes in the water-table.

Key-words: hydrological indicator, reducing conditions, water depth, wetlands

Functional Ecology (2005)
doi: 10.1111/j.1365-2435.2005.01048.x

Introduction

The depth of the water-table is an important ecological determinant in wetlands, influencing the structure, function and spatial patterning of biota at multiple temporal and spatial scales (Andrus 1986; van der Valk 1994; Runhaar, Witte & Verburg 1997; Mitch & Gosselink 2000; Charman 2002; Asada, Warner & Pojar 2003). A variety of techniques have been used to measure the temporal and spatial variability of water-table depth in wetlands, including the installation of dip wells and mechanical maximum–minimum recorders (Boggie 1977; Bragg *et al*. 1994). However, most of these methods are prohibitively expensive or time-consuming for studies requiring long-term monitoring of water-table depth at numerous sites. Recently, a relatively inexpensive method of water-table depth monitoring in peatlands has been proposed, based on the observation that polyvinyl chloride (PVC) changes colour when exposed to reducing conditions (Bragazza 1996; Belyea 1999). The colour change occurs within 3–7 days of exposure to reducing conditions, and probably results from a reaction with hydrogen sulphide (Clymo 1965; Stephenson *et al*. 1994; Belyea 1999; Navrátilová & Hájek 2005). As reducing conditions are generally correlated with water-table depth, the method can be used to monitor water-table depth changes indirectly (Belyea 1999; Charman 2002).

A strong correlation between depth of PVC discoloration and the water-table has been demonstrated for sites within an ombrotrophic peatland (Ellergower Moss) in south-western Scotland (Belyea 1999) and within several minerotrophic peatlands of the Czech Republic (Navrátilová & Hájek 2005). The method has also been applied in ecological studies (Lachance & Lavoie 2004). However, validation of the method is still needed in other regions and peatland types, especially as redox potential has been shown to vary with pH and peatland type (Ross 1995; De Mars & Wassen 1999). At Ellergower

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Moss, PVC tape was applied to wooden stakes, inserted into the peat in a variety of microhabitats, and left for 15 months (Belyea 1999). Depth to the water-table was measured in dip wells at each site several times during the year. The highest elevation of PVC tape discoloration and the elevation of complete PVC tape discoloration were strongly correlated with the highest and lowest measured water-table elevations, respectively ($r = 0{\cdot}98$ and 0·96). However, there was a systematic bias, with PVC-inferred water-table elevations typically slightly lower than measurements of water-table depth. Belyea (1999) suggested that this overestimation of water-table depth may have resulted from a time lag in the chemical reaction with PVC, or an imperfect correspondence between the depth of the water-table and the presence of reducing conditions. In sites with standing water, the lack of an exact correspondence between water-table elevation and reducing conditions was particularly likely because of the availability of dissolved oxygen in these habitats (Belyea 1999). The depths of the water-table and of reducing conditions also vary seasonally, and potential temporal changes in the accuracy of the method at different times of year need to be assessed more fully.

In this study we investigated the accuracy of PVC tape in recording monthly changes in water-table depth from late April to October in nine *Sphagnum*-dominated kettle peatlands of northern Wisconsin. Our specific objectives were to determine if: (1) PVC discoloration is an accurate method of inferring water-table depth in *Sphagnum*-dominated kettle peatlands of the region; (2) seasonal variability in the accuracy of the method exists, and (3) systematic differences in the accuracy of the method occur among microhabitats, PVC tape colours, and peatlands distributed along a well characterized landscape and hydrological gradient.

Materials and methods

STUDY SITES

The study sites included nine *Sphagnum*-dominated kettle peatlands in the Northern Highlands Lake District of Wisconsin (Fig. 1; Table 1). Small kettle lakes and peatlands are common landscape features of the region. Surface materials are characterized by sandy till deposits overlying granitic bedrock. The nine peatlands are within a well characterized groundwater-flow system (Okwueze 1983; Anderson & Cheng 1993; Fig. 1) and have been the subject of previous hydrological and ecological investigations (Kratz & DeWitt 1986; Kratz & Medland 1989; Marin, Kratz & Bowser 1990). Water chemistry is relatively similar among the nine peatlands studied (Kratz & Medland 1989). Estimates have also been made of the relative contribution of groundwater to each of the nine peatlands, suggesting substantial variability in the relative influence of groundwater among the peatlands (Kratz & Medland 1989; Table 1). Vegetation is similar among the peatlands and is characterized by *Sphagnum*, *Chamaedaphne calyculata* (L.) Moench, *Andromeda glaucophylla* Link, *Carex oligosperma* Michaux, *Larix laricina* (DuRoi) K. Koch, and *Picea mariana* (Miller) BSP. However, peatlands low in the watershed tend to be more densely forested than peatlands high in the watershed.

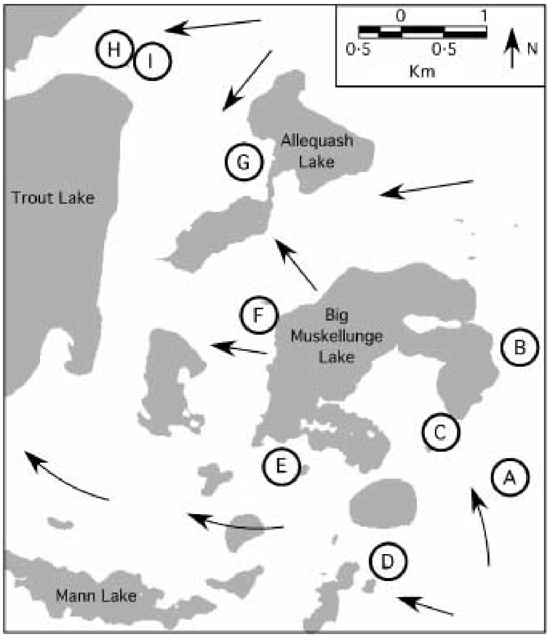

Fig. 1. Location of peatlands studied (A–I) in the Northern Highlands Lake District of northern Wisconsin. Arrows indicate the general direction of groundwater flow (modified from Okwueze 1983; Kratz & Medland 1989).

METHODS

Before initiating this study, we conducted a preliminary test of several brands and colours of PVC tape, and found that PVC tape advertised as 'weatherproof' or 'waterproof' failed to change colour. All other types tested had prominent and similar colour changes.

We mounted PVC tape along the entire length of 1-m-long wooden stakes and inserted the stakes into the peat at 97 locations within the nine peatlands. Four tape colours were used (white, yellow, green, red); only one colour was used on each stake, and colours were not chosen systematically. Although systematic placement of colours within peatlands and microhabitats would have been preferable, the amount of each colour that was available varied unexpectedly each month, so this was not feasible. Each stake was inserted to the same depth relative to the surface of the peatland, with 15 cm of each stake left above the peatland surface. Sites were chosen along a transect within each peatland in an effort to sample the full range of topographic variability, including pools, hollows and hummocks. At peatlands containing a central pond, the transect extended from the peatland edge to the pond. Sites were classified qualitatively as floating, pool/hollow, hummock, or intermediate in topography. Floating sites

Table 1. Characteristics of the studied peatlands, with peatlands arranged from highest (A) to lowest (I) in the watershed (see Figure 1). Negative water-table depths indicate standing water

						Range of water-table depths sampled in each month (cm)						
Peatland	*n*	Location	pH	Conductivity	Ground-water input (%)*	May	Jun	Jul	Aug	Sep	Oct	Brief description
A	14	46°00′11″N 89°35′37″W	3·89–4·25	81·0–180·1	4 (3–13)	20 to −25	37 to −12	50 to 11	58 to 15	68 to 18	59 to 14	Open, *Sphagnum*-dominated peatland.
B	10	46°01′09″N 89°35′18″W	3·68–4·69	35·1–100·0	35 (12–71)	37 to −19	47 to −16	60 to 0	63 to 4	71 to 7	67 to 7	Open, *Sphagnum*-dominated peatland with prominent hummock-hollow topography and central pond.
C	13	46°00′27″N 89°36′20″W	3·73–3·95	58·4–135·2	6 (3–17)	41 to −11	47 to −2	59 to 10	65 to 12	67 to 12	62 to 13	Mostly open, *Sphagnum*-dominated peatland with central pond.
D	15	45°59′42″N 89°36′52″W	3·52–4·26	31·0–192·4	5 (3–16)	25 to −16	38 to −6	44 to 8	47 to 6	59 to 13	51 to 10	Open, *Sphagnum*-dominated peatland with central pond.
E	10	46°00′17″N 89°37′39″W	3·87–4·08	60·3–133·0	3 (3–10)	31 to −14	45 to −1	57 to 14	57 to 20	68 to 26	58 to 13	Mostly open, *Sphagnum*-dominated peatland.
F	9	46°01′20″N 89°37′58″W	3·71–3·92	70·5–129·4	3 (3–10)	19 to −12	26 to −1	43 to 18	48 to 28	64 to 32	58 to 30	*Sphagnum*-dominated peatland with moderate amounts of black spruce.
G	8	46°02′16″N 89°38′09″W	3·70–4·06	75·2–113·0	54 (16–95)	29 to −4	39 to 0	58 to 12	59 to 17	54 to 21	57 to 18	*Sphagnum*-dominated peatland with abundant *Picea mariana*.
H	8	46°02′51″N 89°39′03″W	3·57–4·23	41·1–61·6	48 (15–88)	17 to −18	22 to −8	36 to 4	36 to 2	45 to 2	42 to 1	*Sphagnum*-dominated peatland with abundant *Picea mariana* and a central pond.
I	10	46°02′48″N 89°38′55″W	3·91–4·20	62·8–107·8	12 (5–32)	24 to −8	26 to −3	35 to 7	42 to 13	46 to 17	40 to 18	*Sphagnum*-dominated peatland with abundant *Picea mariana*.

*Estimated percentage of annual water budget that comes from ground water and error range (from Kratz and Medland, 1989).

Table 2. Time of installation and collection of PVC-lined stakes and water-table depth measurements at the 97 sites

Sampling 'month' discussed in text	Actual dates of measurement/ collection	Length of time stakes were installed (days)	Number of PVC-lined stakes that failed to change color
May	23–25 April 2004		
June	5–7 June 2004	~43 days	0
July	10–13 July 2004	~36 days	6
August	9–11 August 2004	~31 days	1
September	3–5 September 2004	~23 days	11
October	9–10 October 2004	~36 days	8

were variable in topography. PVC-lined stakes were installed and removed every month during the growing season, starting in the week following snowmelt in late April 2004 (Table 2). Depth to the water-table was measured from the holes left by the stakes, allowing approximately 30 min for the water level in the hole to reach equilibrium with the surrounding peat. New stakes were installed within 15 cm of previous stakes. We discuss our data in monthly time steps from May to October, although the actual dates of water-table depth measurement and the installation and collection of stakes are listed in Table 2.

Depth to first sign of PVC tape discoloration was measured on each stake. Although Belyea (1999) also measured depth to full PVC discoloration, we found this was a very difficult and often subjective decision. Much of the PVC discoloration was mottled, and the lack of an obvious area of full discoloration may be because stakes were not left in the peatland for long enough. Belyea (1999) left stakes in a peatland for 15 months and also noted some difficulty in determining the highest point of full discoloration.

We measured pH and conductivity of water at each site in July. Measurements were made on water squeezed from *Sphagnum* and on water collected from the depth of the water-table. Differences in peat bulk density might affect the depth of reducing conditions and perhaps the relationship between reducing conditions and water-table depth, so we also collected two peat samples from each peatland in October for bulk density calculations. Samples were collected from hollows within 20 m of the sample transect in each peatland, by carefully inserting and collecting a volumetric sample of peat in a 30-cm-long PVC tube (10·2 cm diameter). Samples were weighed, dried at ≈100 °C, and reweighed. Data on ionic concentrations for these peatlands were obtained from Kratz & Medland (1989).

Results and discussion

The highest level of PVC tape discoloration was obvious on most stakes, although for a few stakes the colour change was somewhat gradual over a few centimetres. However, the tape on a few stakes did not change colour (Table 2). The reasons for this are unclear, but may be at least partially related to chemical variability in different types of PVC tape. For example, at least eight of the PVC-lined stakes that did not change colour were lined with tape from two particular rolls, suggesting that something unique about those rolls inhibited the colour change. However, PVC tape from other rolls of the same brand and colour worked well. Testing multiple brands and types of tape before using the method in hydrological and ecohydrological studies is clearly advisable.

PVC discoloration is an accurate method of inferring water-table depth in *Sphagnum*-dominated kettle peatlands of the region, particularly along a relative water-table depth gradient (Fig. 2). The measured water-table depths and the highest points of PVC tape discoloration show the strongest correspondence for the stakes installed between July and August (Fig. 2). The method was least accurate in early spring, but correlations were still strong (Fig. 2). Although these results suggest that the method can be used to infer water-table depths along a relative gradient at all times during the growing season, precise reconstructions are problematic in early spring and autumn. PVC-inferred water-table depths were typically deeper than actual measurements in early spring, and shallower than measurements in late autumn (Figs 2 and 3). However, regardless of the month when stakes were inserted into the peat, a good correspondence was found between the highest point of PVC tape discoloration and midsummer (around July) water-table depth (Fig. 3). In fact, PVC tape discoloration on stakes inserted in early spring and autumn correlates better with July water-table depth than with water-table depth measurements made during the months when stakes were installed (Fig. 3).

The strong correspondence between PVC discoloration and midsummer water-table depth, along with the consistent pattern of water-table depth overestimation in the spring and underestimation in the autumn, suggests that the depth of reducing conditions varies much less than the water-table depth during the growing season. The average position of PVC tape discoloration varied very little across the season compared with water-table depths (Fig. 4). Early in spring, conditions were relatively cold, biological activity was low and water levels were high. Water in the peatlands was probably relatively oxygen-rich, and reducing conditions were present only well below the actual water-table depth.

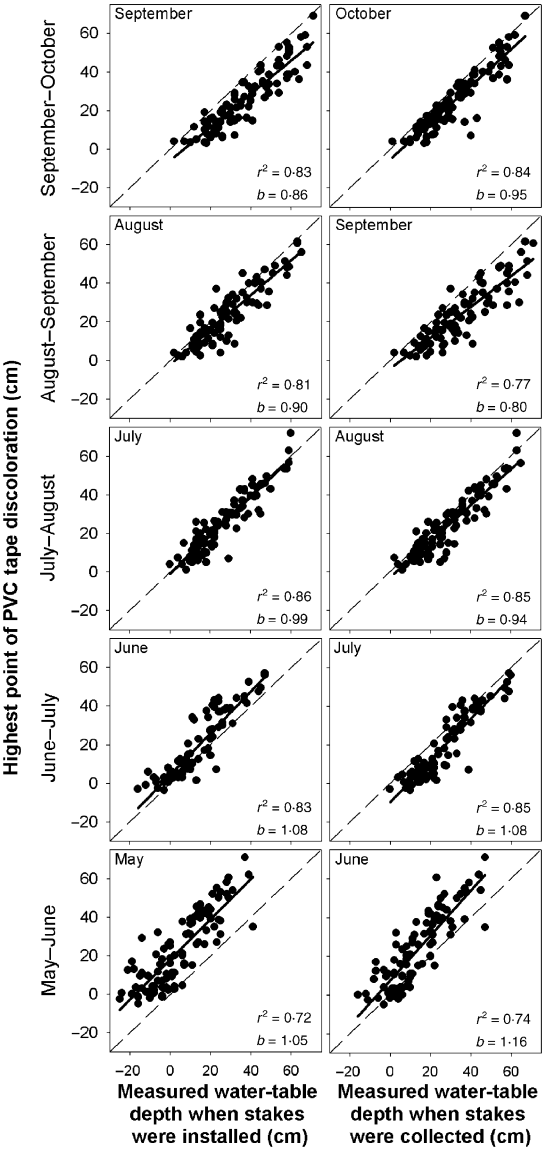

Fig. 2. Relationships between measured and PVC-inferred water-table depth for each ≈1-month period from late April (May) to October. Relationships between highest point of PVC tape discoloration and water-table depths measured when each group of stakes was installed (first column) and collected (second column). Negative water-table depths indicate standing water above the surface of the peatland. Solid lines, regression lines; dashed lines, 1 : 1 lines. The PVC discoloration method can accurately predict water-table depths along the hydrological gradient sampled, although there are systematic biases from a 1 : 1 relationship.

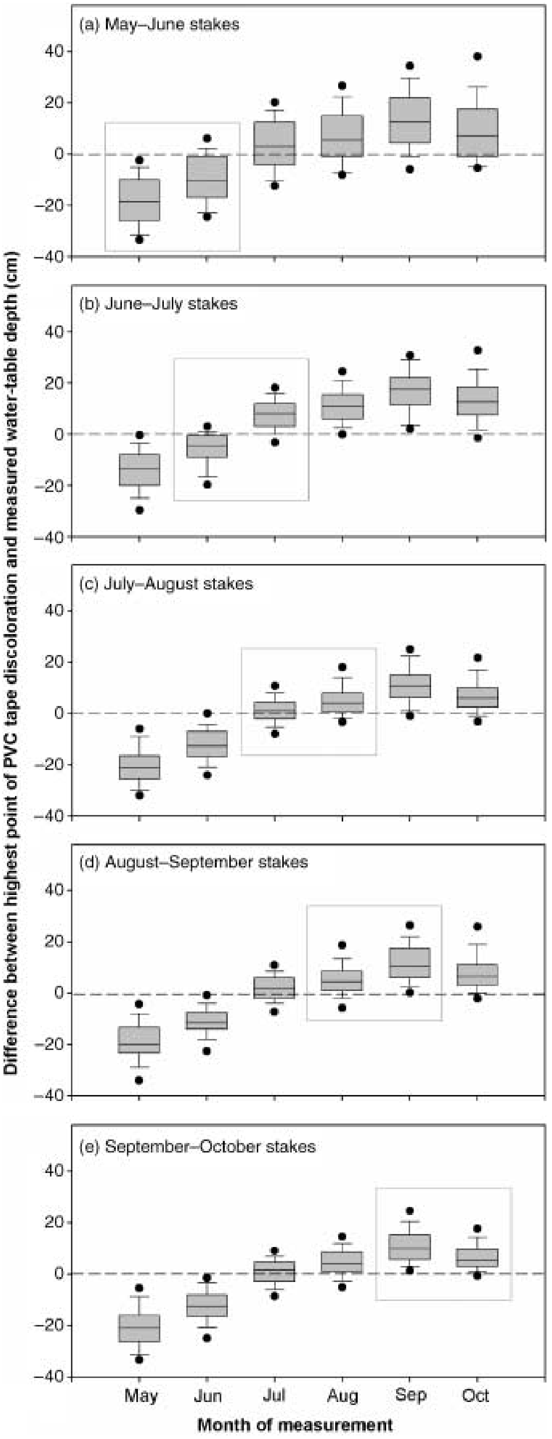

Fig. 3. Box plots showing the difference between measured water-table for each month and elevation of PVC tape discoloration for stakes in peatlands from (a) May–June; (b) June–July; (c) July–August; (d) August–September; (e) September–October. Box plots show median (line), 50% (box), 75% (lines) and 95% (dots) of distribution. Rectangles highlight the period when each group of stakes was installed. Negative values indicate that PVC tape discoloration tended to occur below the water-table depth; positive values indicate PVC tape discoloration above the water-table depth. Differences are shown even for months when stakes were not installed. Regardless of when the PVC tape was installed, the highest point of PVC discoloration corresponds most closely with the position of the water-table in midsummer (typically July), suggesting that the depth of reducing conditions does not track water-table depth precisely.

By midsummer, warming temperatures and increased biological activity led to increased evapotranspiration and lowering of water-tables. In the present study the depth of water-tables and the highest position of reducing conditions were essentially equal in midsummer. In late summer water levels continued to drop, but the inferred depth of reducing conditions did not.

Several possibilities might explain the discoloration of PVC tape above the elevation of the water-table in late summer and autumn. First, water levels may have

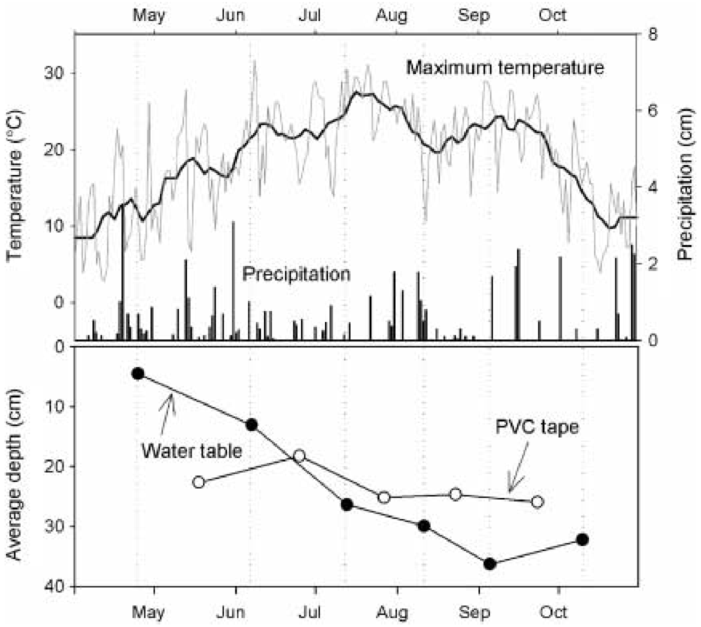

Fig. 4. Temperature (daily maximum and running average) and precipitation during the 2004 growing season (from nearest weather station in Minocqua, WI) plotted against average water-table depth and highest point of PVC tape discoloration. Vertical dotted lines highlight sampling times. Water-table depth varied substantially across the season, whereas the elevation of highest PVC tape discoloration (highest depth of reducing conditions) varied considerably less.

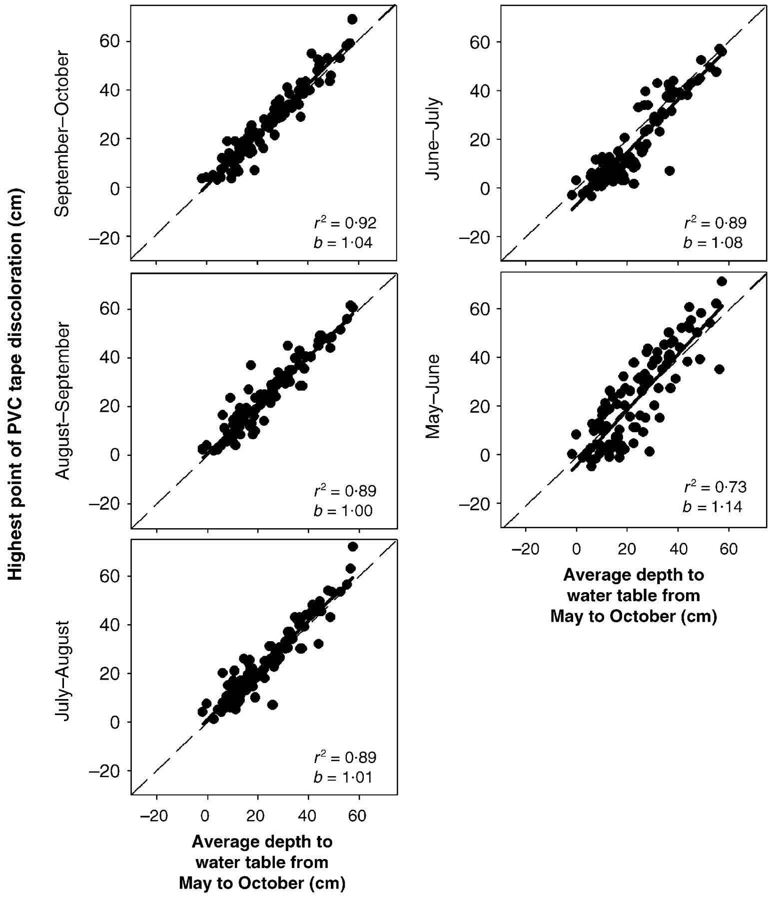

Fig. 5. Relationships between average measured water-table depth from May to October, and PVC-inferred water-table depth for each ≈1-month period. Negative water-table depths indicate standing water above the surface of the peatland. Solid lines, regression lines; dashed lines, 1 : 1 lines.

risen between sampling intervals and were not detected by our monthly sampling. However, a comparison of temperature, precipitation and water-level measurements suggests that this is unlikely, particularly as the higher water levels would have to have been maintained for the 3–7 days required to cause the PVC tape to change colour (Fig. 4). For example, measurements in August were made during a several-day interval of heavy precipitation and cool temperatures, when conditions would have been expected to be as wet as at any time earlier in the month (Fig. 4), yet PVC tape discoloration still occurred above the level of the measured water-table. Similarly, during the relatively dry month preceding the September measurements, it is unlikely that the water-table would have risen at any time (Fig. 4). Another possible explanation for the difference between measured water-table depths and PVC tape discoloration in the late summer/autumn is that our measurements of water-table depth were inaccurate, perhaps because we did not allow sufficient time for water levels in the hole to equilibrate with the surrounding peat. However, the amount of time allowed for equilibration was approximately the same for each month, so this seems unlikely. In our opinion, the most likely explanation for the underestimation of water-table depth is that peat even somewhat above the water-table remained sufficiently wet and oxygen-depleted in the late summer and autumn to allow the continued production of hydrogen sulphide. The low porosity and relatively high moisture content of the peat may have inhibited downward oxygen diffusion, allowing the continued presence of reducing conditions.

Midsummer water-table depths are very similar to average water-table depths during the growing season in the nine peatlands, suggesting that PVC tape discoloration may be closely related to the average annual water-table depth. Our data indicate strong relationships between the average water-table depth during the growing season and the height of PVC tape discoloration (Fig. 5). In fact, the highest point of PVC tape discoloration generally corresponds better to average water-tables than to midsummer water-tables, suggesting that the method works better at estimating the mean water-table depth. The strong relationship between the mean positions of the water-table and reducing conditions may be related to the vertical position of microbes that are important in mediating redox conditions. These microbes may be more frequent at the position of the average annual water-table depth. However, studies are needed to test this hypothesis. Clearly, the PVC tape discoloration method should be used cautiously when precise estimates of seasonal changes in water-table depth are needed.

The accuracy of the PVC tape discoloration method of inferring water-table depth was also significantly different between some of the peatlands, although no significant differences were found among microhabitats or PVC tape colours (Fig. 6). It is unclear why differences occurred among some of the peatlands, but they may be related to variability in peat composition and

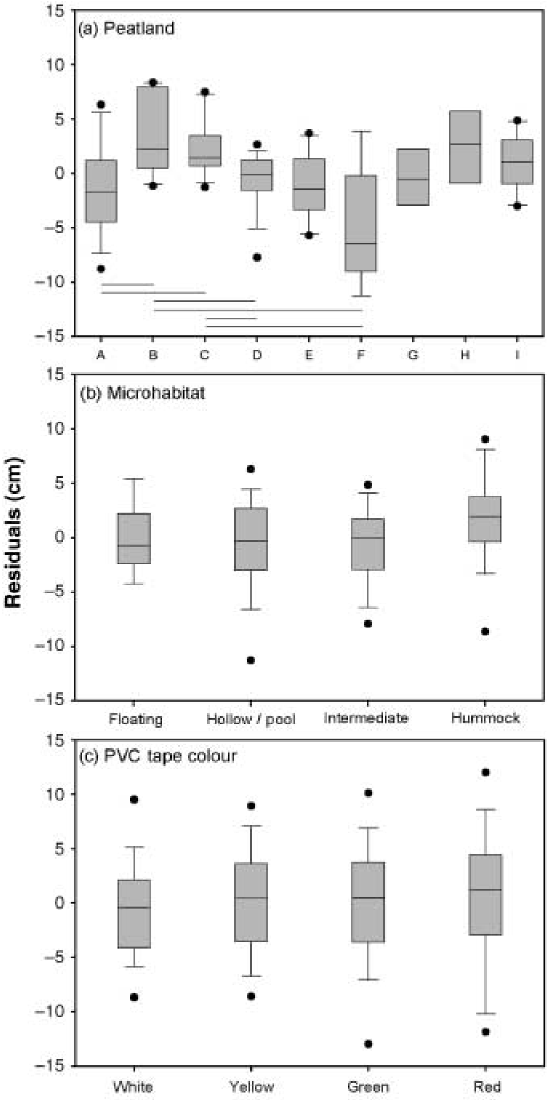

Fig. 6. Box plots of residuals for regressions between highest point of PVC tape discoloration and measured water-table depth (symbols as in Fig. 3). For comparisons by (a) peatland and (b) microhabitat, the measured water-table depth at installation and collection of each group of stakes was averaged and then regressed against the highest point of PVC tape discoloration for each month. Residuals were then averaged for all months. For comparison of (c) PVC tape colour, the average water-table depth at installation and collection of stakes was regressed against the highest point of PVC tape discoloration for each month, and all regression residuals for each tape colour were compared. Significant differences were found between some peatlands, indicated by horizontal lines ($P < 0{\cdot}01$, *t*-test).

water chemistry, which can affect redox conditions. For example, sulphate reduction has been shown to occur at different redox potentials depending on pH (Ross 1995; Charman 2002), and redox potential also varies in different peatland types (De Mars & Wassen 1999). However, we did not find a significant correlation between differences in the accuracy of the method among peatlands and the environmental variables that we measured (Table 3), although our sample size for these comparisons was relatively low ($n = 9$).

Table 3. Correlations between some characteristics of each peatland and average residuals for the regressions between average water-table depths and the highest points of PVC-tape discoloration. No correlations were statistically significant ($P < 0{\cdot}01$)

Variable	Correlation coefficient (*r*)
Bulk density†	−0·47
Ca‡	−0·47
Cl‡	0·32
Conductivity (water squeezed from *Sphagnum*)†	−0·20
Conductivity (water from depth of water table)†	−0·59
Estimated groundwater influence (% of net water budget)‡	0·50
K‡	0·16
Mg‡	0·00
Na‡	0·23
pH (water squeezed from *Sphagnum*)†	−0·14
pH (water from depth)†	0·55
SiO_2-Si‡	0·57
SD_4-S‡	−0·16

†Measured in this study.
‡Measured in Kratz and Medland (1989).

In summary, PVC tape discoloration can be used to describe gradients of water-table depth accurately in kettle peatlands of northern Wisconsin. However, the accuracy of the method differed among the peatlands studied, and may be related to complex relationships among trophic status, groundwater and redox potential. Additional research is needed to understand these relationships. The precision of the method in early spring and late summer/autumn was systematically biased, with water-table depths over- and underestimated, respectively. However, regardless of the month during the growing season that the PVC tape was installed, the highest elevations of PVC tape discoloration were strongly correlated with midsummer (around July) water-table depths and average water-table depths during the growing season. Our results suggest that the depth of reducing conditions is much less seasonally variable than water-table depth in kettle peatlands of the region, although more work is needed to test this hypothesis. Therefore the PVC tape discoloration method should be used cautiously when precise estimates are needed of seasonal changes in water-table depth.

Acknowledgements

The present study was partially funded by a co-operative agreement between the University of Wisconsin and the US Geological Survey – Great Lakes Science Center under USGS agreement #4ERAG0048, and collaborative research grants from the Ecology and Earth System History programs of the National Science Foundation. We thank the Climate, People, and Environment Program at the University of Wisconsin's Center for Climatic Research for providing additional support.

A. L. Beaudet provided considerable field and laboratory assistance, and the study benefited from discussions with T. Kratz. Michele Woodford helped draft Fig. 1.

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Received 10 June 2005; revised 5 August 2005; accepted 8 August 2005