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HYDROGEOLOGICAL EVALUATION OF A SOUTHERN ONTARIO KETTLE-HOLE PEATLAND AND ITS LINKAGE TO A REGIONAL AQUIFER

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Abstract: This paper examines a southern Ontario kettle-hole peatland (Spongy Lake) to determine its hydrogeological linkage with local and regional water tables. The water table in the peat deposit and lake are perched 6 m above the regional aquifer, and there are strong lateral and downward hydraulic gradients. The horizontal hydraulic gradient ($\Delta h/\Delta z$) measured at the edge of the peatland ranged between 0.15 and 0.23 and the vertical gradient reached -1.24 (i.e., downward flow). At depths less than 1.0 m, saturated hydraulic conductivity (K_s) ranged from 10^{-7} to 10^{-5} m s^{-1} and increased in magnitude with proximity to the peat surface. In an intermediate zone (1.0–4.0 m depth), K_s values ranged from 10^{-8} to 10^{-7} m s^{-1}, while deeper clay materials had K_s values ranging from 10^{-9} to 10^{-8} m s^{-1}. A clay layer directly below the deep peat limits downward seepage of water (one to two orders of magnitude less than evaporation). During periods of relatively high water, most seepage loss occurs laterally at the interface between mineral sediment and the peat. Spongy Lake is an important recharge zone for the regional aquifer, and the hydrologic and ecological integrity of the system should be protected.

Key Words: kettle, wetland, peatland, perched, ground water

INTRODUCTION

Kettle hole wetlands may be strongly linked to regional or local ground-water systems (Drexler et al. 1999, Fraser et al. 2001), and large-scale changes associated with regional aquifer hydrology may affect their ecological integrity. Reciprocally, disruption of the hydrologic function of kettle wetlands can have implications for the quantity and quality of water recharged to regional ground-water systems (Hayashi et al. 1998a, 1998b). Kettle-hole wetlands may also derive much of their water from adjacent landscapes, (e.g., from blowing snow (Woo and Rowsell 1993) or snowmelt runoff (Hayashi et al. 1998a)) and represent a zone of focused recharge to the regional aquifer (Lissey 1971). However, many such systems are set within, or overlie low permeability sediments that limit downward seepage (van der Kamp and Hayashi 1998). Consequently, ground-water losses may occur laterally and may increase where surrounding vascular or woody vegetation lowers the adjacent water table by evapotranspiration (Hayashi et al. 1998a).

Kettle wetlands may lack either surface inflows or outflows and may develop peat where open water bodies become filled by edge-bound organic material, succeeded by fen vegetation (Tallis 1983, Warner 1993). As peat accumulates, the surface rises and may become increasingly isolated from the surrounding mineral-rich ground water, following which, bog vegetation may colonize and grow (McNamara et al. 1992). In these systems, peat accumulates in the form of buoyant floating or quaking mats over open water (Warner et al. 1989, Warner 1993). These floating peat mats can cover the surface, leaving subsurface residual water pockets or lenses (Damman and French 1987), which may eventually become filled. This process of terrestrialization (Finlayson and Moser 1991) is strongly coupled to hydrologic processes, basin morphometry, and the influence of the accumulating peat and the floating, or buoyant mat (Kratz and DeWitt 1986, Wilcox and Simonir 1988, Campbell et al. 1997, Bunting and Warner 1998).

The hydrologic and biogeochemical functioning and

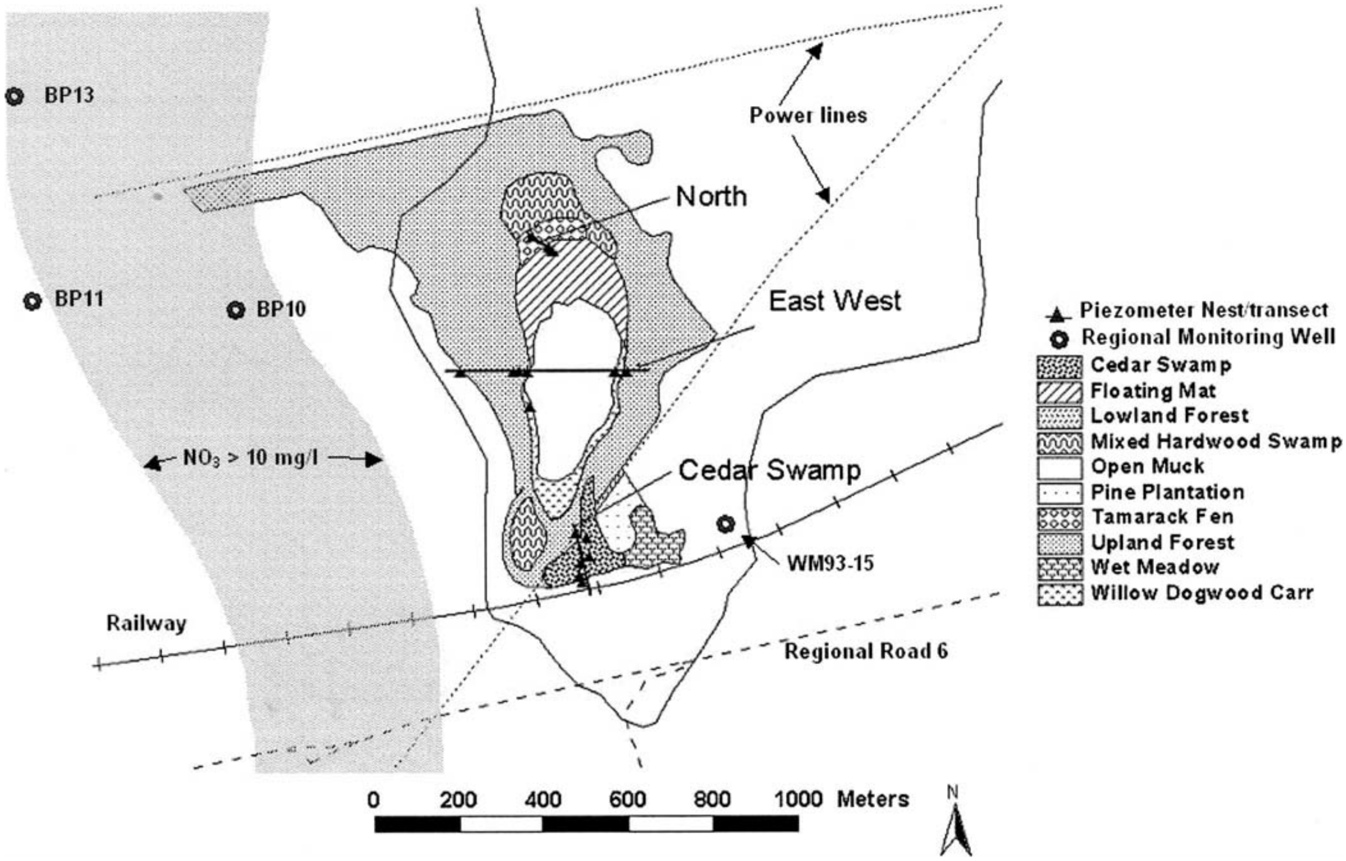

Figure 1. Setting of the Spongy Lake basin and the primary vegetation communities. BP 10, 11, 13, and WM93–15 are monitoring wells established by Terraqua (1996). Spongy Lake is located in southern Ontario, Canada (80° 61′, 43° 41′) and is part of the Waterloo Moraine recharge area.

development of peatlands are thus influenced by their specific hydrogeologic setting and linkages to local or regional ground water (Siegel 1981, Wilcox et al. 1986, Winter 1999). Because many peatland environments are maintained by ground-water exchanges (e.g., Hemond 1980, Koerselman 1989, McNamara et al. 1992, Gilvear et al. 1993), it is essential to understand ground-water flow through heterogeneous materials within the connected landscape and the peat itself (Hunt et al. 1996, Drexler et al. 1999).

The objective of the work reported in this paper was to determine the nature and magnitude of hydrogeologic linkages between a kettle peatland, the surrounding agricultural landscape, and regional aquifer.

STUDY SITE

Spongy Lake (Figure 1) is a 26-ha kettle-hole peatland located approximately 14 km west of Waterloo, Ontario, Canada (80° 61′, 43° 41′) in the Grand River watershed. It is situated in an ice-contact sand plain of the interlobate Waterloo moraine, which has a core of fine sand or sand and gravel capped by fine tills (Karrow 1993). The geological formations across Spongy Lake and surrounding areas shown in Figure 2 are based on bore-hole and well-log data (Terraqua 1996). The east and west margins of the kettle-hole depression have steep slopes. Gullies up to 1 m deep on the east slope formed due to surface water inflows during snowmelt or extreme rainfall events. Soils immediately surrounding Spongy Lake are loam, fine sandy loam, and silty clay loam (Presant and Wicklund 1971). A band of clay till underlies the southern half of the kettle (Figure 2). The underlying sand in which the ice block was trapped is exposed on the slopes below the till cap (Karrow 1993). Spongy Lake contains 4.9 m of gyttja-like peat, underlain by gray-brown clay of undetermined thickness (Karrow 1993).

Spongy Lake lies within a complex series of perched and regional aquifers within the uppermost hydrostratigraphic unit of the Waterloo Moraine aquifer complex, comprising primarily permeable sands and silts. Drinking water for nearby Baden and New Hamburg is supplied from the upper aquifer (Terraqua 1996), and pumping wells are located 1.5 km southwest of Spongy Lake. This recharge area is at high

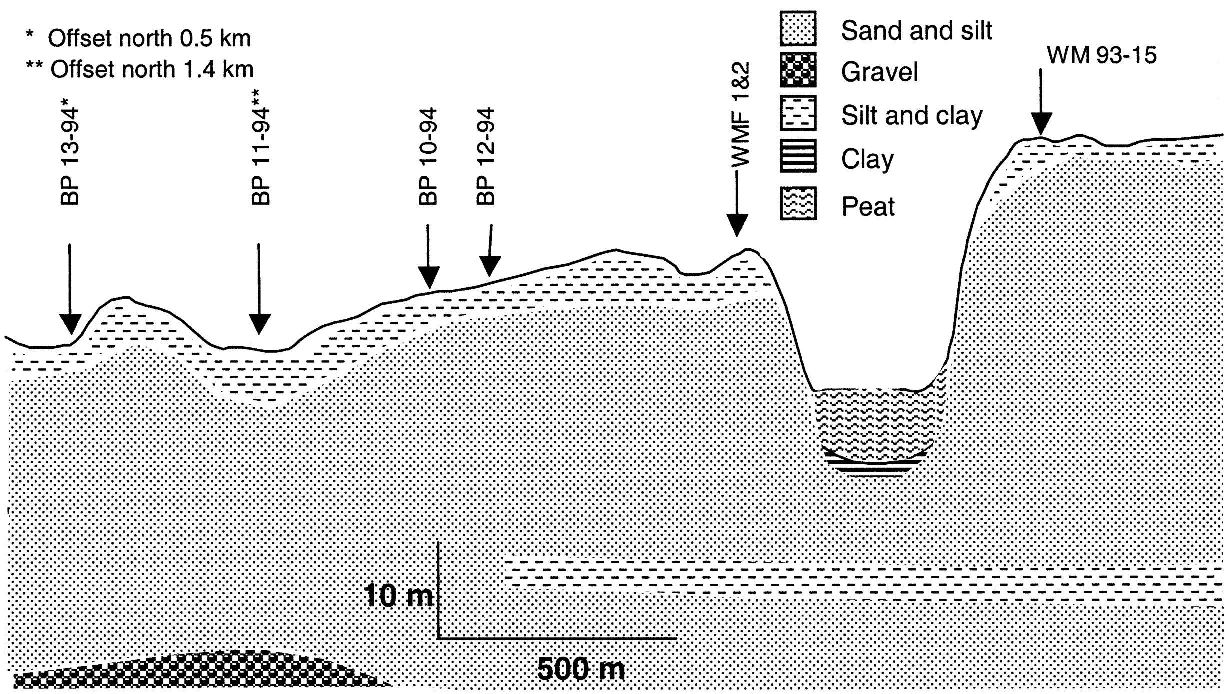

Figure 2. Hydrogeological cross section of the Spongy Lake area, indicating wells used in the municipalities' ''Wellhead Protection Study''. (Terraqua 1995, 1996)

risk of contamination with agricultural fertilizers and pesticides (Kerr-Upal et al. 1999), and nitrate concentrations range from 1.5 to 19.0 mg L^{-1} in monitoring wells (BP10, BP11, BP13) located less than 2 km west of Spongy (Figure 1). The annual pumping rate for the well field is 1370 to 2192 m^3d^{-1} (15.9 Ls^{-1} to 25.4 Ls^{-1}), and pumping tests indicate water-table drawdown of 20 to 40 cm in nearby wells (Terraqua 1996). The mean annual total precipitation is 908 mm, and mean January and July temperatures are −7.1 and 19.8 °C, respectively (Environment Canada 2003). Mean annual evapotranspiration is 540 mm (Sanderson 1998).

A buoyant mat of emergent vegetation covers the northern third of Spongy Lake (mostly sedges (*Carex* spp.) but with cattails (*Typha* spp.) closer to the eastern section, and interspersed with mosses (*Sphagnum* spp.), along with grasses (family *Poaceae*), marsh cinquefoil (*Potentilla palustris* (L.) Scop.), marsh fern (*Thelypteris palustris* Schott var. pubescens (Lawson) Fern.), water horehound (*Lycopus americanus* Muhl. ex Bartram), and leatherleaf (*Chamaedaphne calyculata* (L.) Moench). The rest of Spongy Lake is shallow open water. During the summers of 2000 and 2001 the lake dried out, exposing the peaty lake bed that is about 10–20 cm below the elevation of the buoyant mat. The peat is about 5 m thick. A cedar swamp (*Thuja occidentalis* L.) is located at the south part of Spongy Lake peatland and has a surface that rises about 40 cm above the lake bed. A margin of shrubs (*Alnus* spp. and *Salix* spp.) surrounds the mat, and the open water of the lake and on the east and west margins meet the lake (lake bed) directly. A variety of deciduous (mostly *Acer rubrum* L.) and coniferous trees (*Larix laricina* Du Roi) closer to the buoyant mat, exist in the kettle depression. Vegetation was identified and reported by Bloemen et al. (1979).

METHODS

In October 2002, eleven piezometer nests (28 piezometers) were installed along a north-south and a west-east transect across Spongy Lake. The west-east transect stretches from the western lip of the depression (piezometers WMF 1, WMF2) to the lake-bed. This transect does not include the central (inaccessible) part of the lake but begins again with piezometers on the lower east margin of the depression (Figure 3). The north-south transect extends from the hardwood swamp (HS) across the buoyant vegetation mat (BM), missing the central part of the lake, beginning again at the cedar swamp (CS) on the southern arm of the north-south transect (Figure 4).

Piezometers terminating in peat or clay were constructed of 20 mm and 25.4 mm (i.d.) PVC, with perforated intakes of 0.11 m and 0.14 m, and were installed at various depths (Figures 3 and 4). The narrower tubes were PVC drive-point piezometers and were mostly used in the cedar swamp where more roots were encountered. All piezometers were blocked

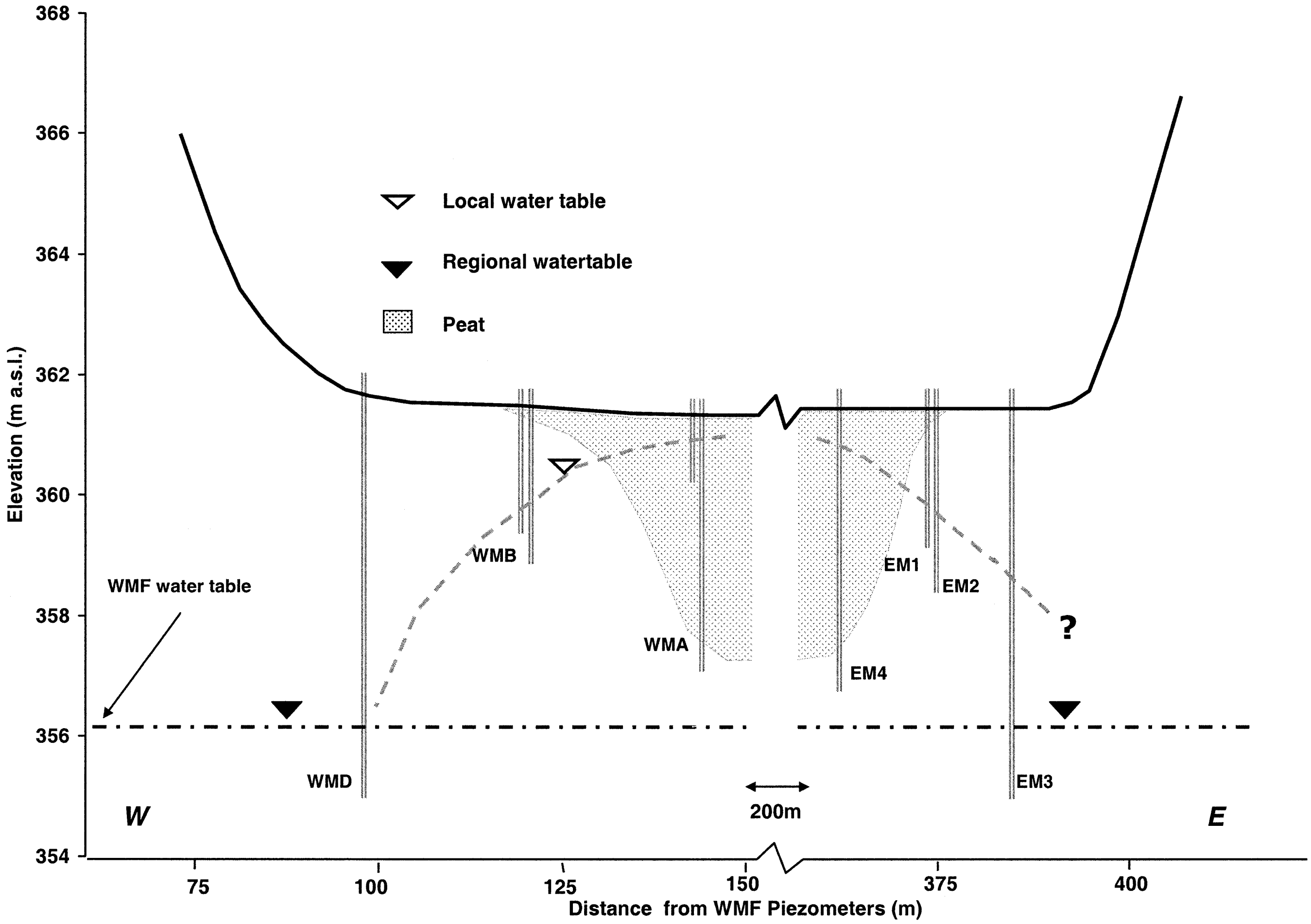

Figure 3. West-east transect across Spongy Lake.

at the end and drilled with 1-cm bit to make holes covering about 40% of the intake surface. Five steel drive point piezometers were situated at or below the interface of the peat layer and underlying mineral substrate (4–5 m depth). The intake of steel drive-point piezometers had about 20% of its surface covered with screened perforations (~1-cm holes). Existing piezometer nests from the wellhead study (Terraqua 1995) were incorporated in the transect. These included two steel drive-point piezometers (SP3, SP4) situated along the north-south transect at the margin of the bouyant mat. Piezometers WMF 1&2 (13-mm i.d.) are located on the west-east transect at the edge of the field on the western lip of the depression. These were 25.8 and 28.2 m below the surface, respectively. Water levels in the piezometers were measured weekly from October 2 to December 18, 2002. The water level was determined using an electronic sensor. The lower-than-expected water level in certain piezometers (e.g., the deepest piezometers at WMA, EM4, QM, CSM, and CSD) experienced a slow rise over the study period and never fully equilibrated (i.e., response time was too slow). They were not used to express hydraulic head but were interpreted to confirm the low hydraulic conductivity of those materials. Water-table data were supplemented by visual observations during the snowmelt period between March 24 and 29, 2003.

Elevations and locations of all piezometers were surveyed on December 11, 2002 using a Pentax Total Station (Model PTS 605). Hydraulic conductivity was determined in the field with bail tests using the method described by Hvorslev (1951). This method is based on the recovery rate of water in the piezometers, which were bailed with an open ended tube. The tube was lowered into the piezometer and withdrawn with the top end covered. Recovery rates in piezometers terminating in clay or deep peat ($\gg$150 cm) were slow, and only 5 to 45% recovery could be recorded. Recovery rates in the upper layers of peat were 75 to 99%. Response time of water levels of piezometers inserted into sedimentary materials with different hydraulic properties can vary significantly and thus result in time-lag errors (Hanschke and Baird 2001). Accordingly, values reported for piezometers situated in

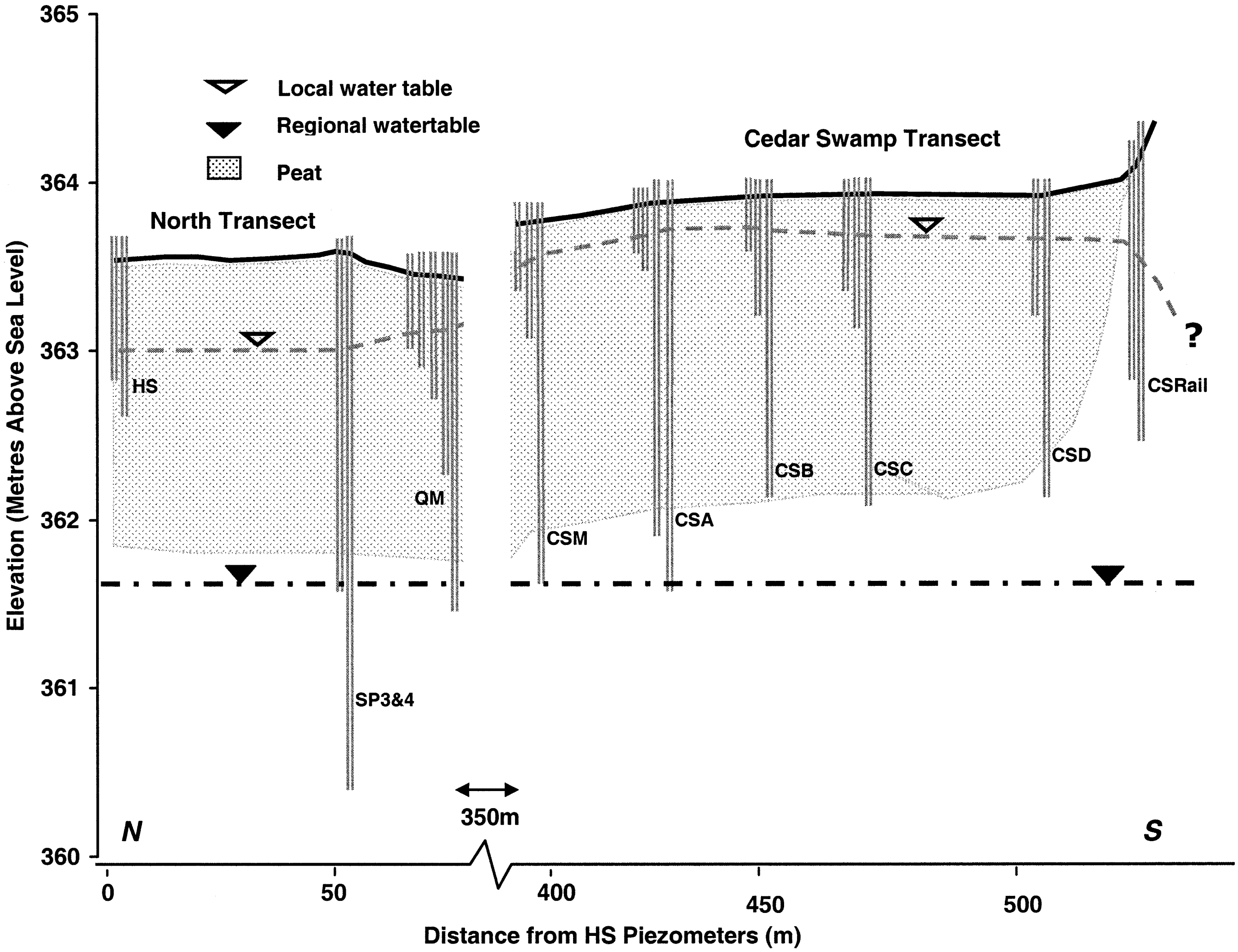

Figure 4. North-south transect across Spongy Lake.

clay and deep peat in Spongy Lake are approximate at best.

RESULTS

Spongy Lake was dry at the beginning of the study period following a dry summer, and the amorphous peat lake-bed was exposed. Beneath the buoyant vegetation mat at the north end, peat was sampled with a Russian corer and was continuous down to the mineral substrate at 5 m depth. The buoyant vegetation mat is supported weakly by deformable sediment (hence the name ''Spongy Lake''). Following rainfall, the surface of the mat rose. For example, a 37.6-mm rain event on November 10 raised the mat by 30 mm. This event covered the exposed lake sediments with a shallow (~8 cm at WMA) layer of water. Surface inflow was observed in springs located in the cedar swamp and may have entered through gullies draining agricultural land on the eastern slope.

Ground-water conditions in Figures 3 and 4 represent the relatively dry state of Spongy Lake before heavy November rains reflooded the lake. Piezometers on the margins of the west- east transect (WMD, EM3) suggest that the hydraulic head sloped steeply away from the lake (~361 m) (Figure 3). On the west side, the hydraulic head fell 4.07 m over a distance of less than 18 m, resulting in a strong horizontal hydraulic gradient ($\Delta h/\Delta x$) of 0.23. Hydraulic gradients were also steep on the east side. Horizontally, $\Delta h/\Delta x$ was 0.15 and vertically $h/\Delta z$ was -1.24 (at EM1/EM2). A deeper, regional water table was detected at approximately 356 m asl in piezometers terminating in sand below the base of Spongy Lake depression (EM3, WMD, WMF1, and WMF2), as well as in nearby monitoring well WM93–15 (Figure 2).

Hydrogeological conditions at the ends of the north-south transect suggested a similar pattern to those on the west-east transect. In all cases, the regional water table (as identified previously) was well below the local water table. On the north transect, there is some evidence (Figure 4) that the local water table sloped away from the lake and buoyant vegetation mat toward the hardwood swamp (HS), where the water table was consistently lower. The north transect did not extend to the peat-upland margin, so the extent or deflection of the local water table is unknown. On the south transect through the cedar swamp, the local water table was also high but dropped sharply just at the margin (Figure 4).

Spongy Lake had no surface outflow, but surface inflow occurred during the storm of November 10 and strong surface inflow occurred during snowmelt at the south and east margin between March 24 and 29, 2003. During the snowmelt period, surface-water inflow through a culvert beneath the railway bed flowed across the cedar swamp (Figure 1) and reformed into several bifurcated outlet streams. At two erosion gullies along the east margin, meltwater entered from swales on farmland to the northeast of the Spongy Lake depression. At the north of the lake, meltwater discharged onto the floating mat and hardwood swamp. No field measurements were made of surface-water flows, but it is clear that snowmelt generated outside the kettle-hole depression was a significant water input. The water level in Spongy Lake on March 27 was 20 cm above pre-melt levels, and strong surface water inflows were still occurring.

Estimated horizontal hydraulic conductivity (K_s) at depths less than 1.0 m, ranged from 10^{-7} to 10^{-5} m s^{-1} (n = 7), with a geometric mean of 1.3×10^{-6} m s^{-1}, and was greater near the peat surface. At an intermediate depth (1.0–4.0 m), K_s was 10^{-8} to 10^{-7} m s^{-1} (n = 6), with a geometric mean of 4.8×10^{-8} m s^{-1} (note that values reported for piezometers deeper than 1.5 m are generally based on less than 50% head recovery so may be partly in error). This material consisted of well-decomposed black peat with a von Post number (see Clymo 1983) > 8. Piezometers installed at depths greater than 4.0 m terminated at or below the clay/peat interface. The deepest of these were entirely within clay, and K_s values (n=3) were 2.0×10^{-9}, 4.0×10^{-9}, and 5.0×10^{-9} m s^{-1}. Two piezometers located at the clay-peat interface had hydraulic conductivities 2.6×10^{-7} and 4.0×10^{-8} m s^{-1}.

DISCUSSION

Spongy Lake is a kettle-hole depression partly filled with amorphous black peat. There are no data to determine the date of peat initiation in this system, although it is highly likely that the 5+ m of peat predates the land-clearance that began in the early 19th century. Warner (1989) suggested that a (probable) rise in the regional water table that followed conversion from woodland to farmland in southern Ontario may be responsible for the presence of floating mats on some kettle-hole depressions. However, in Spongy Lake, the regional water table lies about 6 m below the lake surface (Figures 3 and 4), so the development of a much higher local water table associated with peat development cannot be associated with the regional water table. Pumping of the regional aquifer at nearby municipal water-supply wells has lowered the regional water table near Spongy Lake by 20 to 40 cm (Terraqua 1996). This is unlikely to affect significantly the hydrologic conditions of Spongy Lake, as it has its own perched water table. Rather, the data indicate that Spongy Lake peatland exists independently of the regional aquifer, and its only connection is as a recharge zone.

The hydrogeological setting of kettle wetlands results in distinctively different hydrologic functions. Low elevation depression wetlands can have mostly ground-water inflow (Stewart and Kantrud 1972). Some studies found that kettle wetlands had a prominent recharge function (Meyboom 1966, Lissey 1971), some noting that recharge was the most important winter flux (Stewart and Kantrud 1971), others reporting mostly lateral flow (Hayashi et al. 1998), and yet others with little recharge or discharge (Hemond 1980). However, a detailed study (Drexler et al. 1999) showed that while discharge issued from springs at the wetland-upland interface, there were fine-scale variations (i.e., within several meters) in recharge and discharge function across the kettle peatland, and even these were transient and could reverse. Thus, while Eisenlohr (1972) describes kettle ponds as simply outcrops of the water table, it is apparent that the hydrologic relationship within kettle wetlands and between them and the mineral substrate are not easily characterized. In Spongy Lake peatland, the distinct separation of local and regional water table suggests that its hydrologic function is primarily a recharge one, although within the peatland, the fine-scale and transient behavior remains to be determined. Its relationship with the local aquifer can be ascertained with water budget data and ground-water-flow patterns.

Observations during the snowmelt in March 2003 indicate that Spongy Lake received snowmelt inputs originating from beyond the main depression itself. These inflows occurred only from the agricultural lands to the east of Spongy Lake and not at all from the extensive wooded northern section. In this respect, land clearance for farming may be an important factor that influences the current recharge function of Spongy Lake. However, intense snowmelt inputs occurred over a short period only (March 24 to 29). Thereafter, the Spongy Lake water inputs were restricted to direct precipitation, small seepage flows from the cedar swamp, and perhaps ephemeral surface flows during the largest storms. Outputs included evapotranspiration and seepage loss (downward and lateral). The annual total precipitation (P) averages 908 mm (Environment Canada 2003), while the average annual evapotranspiration in this region is 540 mm (Sanderson 1998). Evapotranspiration may occur closer to the potential rate (E_{POT}) in wetlands with open water (Price 1994), which in this region is about 590 mm (Sanderson 1998). Thus, on an annual basis, it is evident that the water inputs in this area far exceed the average annual loss by evapotranspiration. With no surface outflow from this system, the average annual water-seepage loss from Spongy Lake must therefore exceed 318 mm (P—E_{POT}). Given the importance of snowmelt input, the seepage loss may be considerably larger than this.

Piezometric data indicate strong lateral and downward hydraulic gradients. Beneath the peat deposit, hydraulic conductivity was low (10^{-8} to 10^{-9} m s^{-1} or 3 to 30 cm per year). While these and other deeper peat hydraulic conductivity estimates suffered from too-short recovery times and thus may overestimate the true value, they are consistent with reported values for like materials (e.g., Boelter 1964, Freeze and Cherry 1979). Thus, vertical downward seepage losses are relatively small (one to two orders of magnitude less than evaporation). However, the clay exists only directly below the deep peat in the basin, and sandy sediment is present up to the surface at the boundaries of the peat deposit. During periods of relatively high water, water flows horizontally from the lake or flows through the moderately permeable upper layer of the buoyant vegetation mat (10^{-4} to 10^{-5} m s^{-1}) and leaks laterally through the ''shoulders'' of the sandy mineral sediment that abuts the peat (see Figure 4). During periods of lower water table, lateral flow losses are severely restricted by the low permeability of the deeper peat (10^{-7} to 10^{-8} m s^{-1}), in spite of the high hydraulic gradient. It is evident that water losses have been and are presently restricted at lower water levels because the accumulation of peat requires prolonged inundation. This system could not have developed with a direct and substantial seepage loss.

The substantial peat accumulation in Spongy Lake holds the water table much higher than it would otherwise be and thus maintains a relatively high hydraulic gradient between the local (perched) and regional water table. The local water table itself is sustained at a high position relative to the peatland surface because peat swelling and subsidence (Price 2003) impart stabilizing conditions with respect to water-table depth below the surface (Kennedy and Price 2005). Consequently, water-storage changes result in an adjustment of the surface level so that the water-table remains always close to the surface. These are the conditions that favor peat accumulation (Clymo 1984).

Spongy Lake's hydrology does not neatly fit into Winter's (1999) conceptual framework of ground-water interaction in wetlands. Here, the influence of upland areas seems to play little direct role in the wetland's ground-water system, since Spongy Lake is perched well above the regional ground-water system. In other kettle wetlands, spatial and temporal variability of recharge and discharge occur at small scales (e.g. a few meters) (Drexler et al. 1999) and at larger scales (e.g., 100s of meters) (McNamara et al. 1992). Under the recharge conditions noted here, ombrotrophy could develop (e.g., McNamara et al. 1992), although the fen-like vegetation clearly indicates a source of mineralized ground water (Bunting and Warner 1998). Significant quantities of mineralized surface water enter this system during the snowmelt period, which have clearly boosted the trophic state, help sustain water levels sufficient to maintain the wetland, and which are eventually recharged to the regional aquifer.

In conclusion, Spongy Lake has developed independently of regional ground-water inflows. Its current surface elevation is approximately 6 m above the regional water table, and hydraulic gradients are strongly away (laterally and downwards) from the wetland. Annual precipitation excess (over evapotranspiration losses) and the considerable volume of snowmelt draining from adjacent farm land are recharged through Spongy Lake wetland. Spongy Lake is an important recharge zone for the regional aquifer and the hydrologic and ecological integrity of the system should be protected, particularly from agricultural fertilizers, which could contribute to contamination of the regional aquifer.

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