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A field-scale, natural gradient solute transport experiment in peat at a Newfoundland blanket bog

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Abstract

A field-scale, natural gradient solute transport experiment conducted at a Newfoundland blanket bog resulted in an asymmetrical plume owing to solute retardation in the dual-porosity matrix. An order of magnitude decrease in hydraulic conductivity 10–20 m downslope of the spill caused the transport rate to decrease and lateral dispersion to increase. Most transport occurred near the watertable and the transport rate increased as the watertable rose. Hydraulic conductivity between a depth of 0 and 0.2 m was 1.6×10^{-2} m s^{-1}, whereas at a depth of 0.5 m it was 5–6 orders of magnitude lower owing to greater compaction and humification of the peat with depth. At a depth of 0.4–0.45 m diffusion may have become the dominant transport mechanism. In spite of the retardation process, the solute front's rate of movement was relatively high, about 2.3 m day^{-1}, owing to a combination of the high watertable during the study and a relatively steep hydraulic gradient of 0.055. Rain caused dilution and mixing of solute near the watertable. Evaporation did not have an appreciable effect on solute concentration, which is attributable to the high transport rate.

1. Introduction

In recent years, there has been increasing interest in using wetlands for wastewater treatment and as repositories for low-level radioactive and toxic contaminants (Schell et al., 1985; Viraraghavan and Ayyaswami, 1987). However, the processes governing contaminant transport in wetlands are poorly understood, and most work has been conducted at the theoretical level (Loxham, 1980) or at the laboratory scale in

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columns (Loxham and Burghardt, 1983; Price and Woo, 1988a; Viraraghavan and Ayyaswami, 1989). These studies show that peat can attenuate contaminants through diffusion into closed pores, or through adsorption onto the peat surface. Although studies at the laboratory scale are useful for estimating parameters such as retardation, they provide only one-dimensional data and fail to account for large-scale variability in hydraulic conductivity and dispersivity. Furthermore, the effects of precipitation and evaporation are not taken into account in column experiments, so the transferability of the results to the field scale in a shallow watertable environment is essentially unknown. The purpose of this experiment is to examine the processes which govern the transport of a non-reactive solute in a peatland. Specifically, the objectives are to examine the spatial and temporal development of a non-sorbing solute plume following a simulated spill by evaluating (1) the effect of field-scale heterogeneity in peat, (2) the effect of the dual-porosity matrix on solute retardation, and (3) the effects of other hydrological processes, such as evaporation and precipitation, on solute transport.

2. Solute transport mechanisms in peat

The processes of advection, dispersion and retardation are applicable to peat soils, although the structure of the peat matrix elicits a response different from that in granular geologic porous media. Pores within peat may be connected and open, dead-end, completely isolated, or remains of cells with more or less intact cell walls (Loxham, 1980). Solute advection occurs only in the open and connected (active) pores. Variations in groundwater velocity within these pores are caused by the viscous drag of water against the plant cells, different pore-throat sizes, and tortuosity of the flow path, resulting in micro-scale dispersion (Freeze and Cherry, 1979). Field-scale dispersion is enhanced by large-scale heterogeneity (Sudicky, 1986). In peatlands, heterogeneity is associated primarily with microtopography such as hummocks and hollows and vertical variations in the degree of peat decomposition (Boelter, 1965).

Retardation of the solute flowing through a peat soil can be caused by the concentration gradient which develops between the water in active pores and that in inactive pores. Molecular diffusion directs solute into or out of the inactive pores, depending on the direction of the gradient. Price and Woo (1988a) determine that chloride has a retardation factor of 1.5–1.6 for poorly decomposed peat in a laboratory column. Hoag and Price (1995) found that a retardation factor as high as 7.3 could be expected for well-humified peats with high matrix porosity. As in fractured media, the dual-porosity effect serves to enhance dispersion (Hoag and Price, 1995). Retardation of other solutes may also be caused by the high sorption capacity of the organic soil in peatlands (Viraraghavan and Ayyaswami, 1987).

Two major hydrological zones exist within a natural peatland. The thin, upper, hydrologically active zone, or acrotelm (Ingram, 1978), consists of living and undecomposed dead plant material. The acrotelm commonly experiences fluctuations in watertable, and thus in water storage. The catotelm (Ingram, 1978) is the well-decomposed peat layer beneath the acrotelm, where water storage is relatively constant (Ingram, 1983). Boelter (1965) found the hydraulic conductivity of the acrotelm to be five orders of magnitude greater than that of the catotelm; this has implications for solute transport.

In peatlands, the watertable is close to the surface, so solute concentration is increased by evaporation (Damman, 1987; Price and Woo, 1988b) and diluted by precipitation (Price, 1994). In oceanic bogs, fog can have ten times the concentration of sea salts compared with rain, which enhances the background concentration in groundwater (Price, 1994).

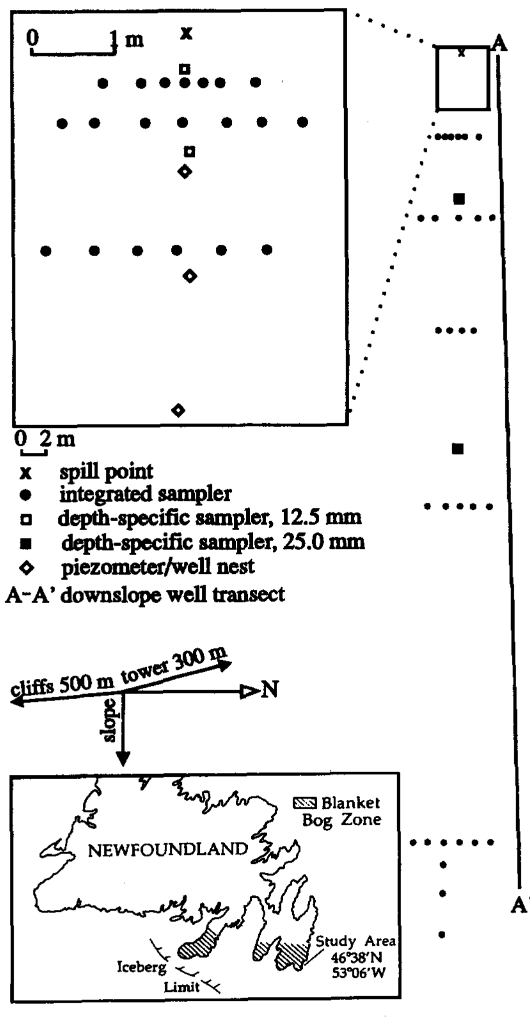

Fig. 1. Layout of the study site, showing location of spill, samplers, wells and piezometers. Inset shows the location of the study site; also shown are the annual iceberg limit and the blanket bog zone of Newfoundland.

3. Study site description

The study site is located at Cape Race, Newfoundland (46°38′N, 53°06′W), which lies at the southeast tip of the Avalon Peninsula (Fig. 1), and adjacent to the site described by Price (1992a, b). The climate is affected by the Labrador current, which brings cold water and icebergs in the spring and summer (Farmer, 1981). As a result, the summers are cool, with persistent fog produced by the southwesterly airflow over the cold ocean (Banfield, 1981). The average total annual precipitation measured at an Environment Canada weather station located 1500 m northeast of the site is 1379 mm, with 12% falling as snow (Environment Canada, 1982). Water input by occult precipitation (mist, fog, and dew; Rutter, 1975) is significant at 10–18% of rain (Price, 1992a). These climatic conditions have resulted in the development of blanket bogs, which are extensive peat-covered wetlands on level and gently to moderately sloping terrain, and are independent of regional groundwater input (Environment Canada, 1987).

Deglaciation occurred about 10 000 years ago (MacPherson, 1981). Based on drill logs in the area, about 1.5 m of stony, largely unsorted till overlies sandstone bedrock (D. Lapen and J.S. Price, unpublished data, 1993). The terrain is gently rolling hills, ranging in elevation from 30 to 50 m above sea-level at the cliffs to approximately 50–60 m above sea-level at the study site located 500 m inland. Blanket bogs cover approximately 79% of the ground surface. The remainder of the ground surface comprises heath-covered hillocks (10%) and ponds and bog pools (11%) (Price, 1992a). The primary species covering the surface of the bog is *Sphagnum fuscum*, and *Empetrum* spp. and a patchy cover of *Rubus* spp. and *Cladonia* spp. are also present. Discontinuous ground ice was present throughout the site until late June to early July.

A portion of the bog about 500 m from the coast was chosen to perform the experiment. The slope is approximately 3.2°, which is significant for a bog, and the thickness of the peat layer ranges from 1.1 to 1.5 m. The surface is characterized by *Sphagnum* hummocks, which are 0.1–0.25 m higher than the hollows.

4. Methods

The experiment was conducted over a 30 day period from 12 July to 10 August 1992, after all of the ground ice had thawed. A series of wooden catwalks was placed on the ground surface to avoid damage to the peat by foot traffic. Rain was measured using a tipping bucket rain gauge located in a slight depression 500 m northwest of the site. Sensors mounted on a tower approximately 300 m north of the site were used to measure other meteorological variables. Evaporation was calculated using the Bowen ratio–energy balance method, discussed in detail by Price (1991). Net radiation was measured using a net radiometer. The ground heat flux was measured using a soil heat flux plate placed 10 mm below the surface. Psychrometers and thermocouples installed on the tower at heights of 0.5, 1.0, 1.5, and 2.0 m were used to measure dry and wet bulb temperatures.

The following instrumentation was used to measure the hydraulic variables and parameters. Three 25 mm i.d. PVC wells 1 m in length were installed along a 4.5 m transect in the expected path of the plume. Three piezometer nests of 25 mm i.d. PVC pipes, installed at the same locations, were slotted over a 0.1 m interval, bottoming at depths of 0.3, 0.4, 0.6, 0.7, 0.8, 0.95, 1.1 and 1.2 m (Fig. 1). A 70 m transect of eight equally spaced 0.75 m long, 12.5 mm i.d. PVC wells was installed parallel to the direction of plume movement to measure watertable position and hydraulic conductivity (not shown in Fig. 1). Estimates of hydraulic conductivity were obtained prior to the spill using bail tests and the method of analysis described by Hvorslev (1951).

To determine the location and concentration of solutes, water was sampled from 12.5 mm i.d. PVC pipes, prepared as follows. Integrated samplers slotted over a 0.4 m length and pushed into the ground to a depth of 0.3–0.35 m were used to determine the position of the plume in plan view. Four sets of integrated samplers were installed prior to the release of the solute, and additional transects were added when the direction of plume migration was known. Depth-specific samplers were used to assess the vertical distribution of solute. The depth-specific sampling nests 0.45 and 1.5 m from the spill location had 12.5 mm slotted intakes, and a vertical spacing of 25 mm between each intake. Further downslope, depth-specific samplers had 25 mm slotted intakes, with 50 mm vertical spacing between intakes.

A 200 l plastic drum with a valve at its base was filled with a 1.4×10^5 mg l^{-1} solution of NaCl, the electrical conductivity of which was 181.0 mS cm^{-1}. The solution was released using the valve to maintain a flow rate of approximately 1 l min^{-1}, insufficient to cause overland flow (i.e. less than the saturated hydraulic conductivity), yet fast enough to be considered an instantaneous source.

Water samples were collected from each sampler using a syringe connected to a flexible piece of tubing. One sampler volume of water was removed to ensure that the water collected was that from the formation adjacent to the screen, then 40 ml of sample was collected from the sampler and transferred to a small container. Electrical conductivity (EC) adjusted to 25°C was measured using an Orion (Boston, MA) Model 140 Conductivity/Temperature/Salinity Meter. After the conductivity measurement, the sample was poured into a waste bucket, and the EC meter cell, the sample container, and the syringe and tubing were flushed to prevent cross-contamination between samplers, and to ensure that contamination of the samples did not occur. The background electrical conductivity of groundwater was measured four times over a 2 week period prior to the spill. Four sets of samples were taken on the first day of the test to monitor the early migration of the plume. The plume developed rapidly at early time (of the order of metres per day), so that sampling was performed once daily except for 20 July and 1, 5, 6, 8 and 9 August.

5. Results

The 30 year mean precipitation for July at the Environment Canada rain gauge located 1500 m northeast of the site is 85 mm (Environment Canada, 1982). Price

(1992a) suggested that this value seriously underestimates the true value because of the exposed gauge location on cliffs overlooking the coast. Total rain for July 1992 was 245 mm (Fig. 2), compared with 125 mm in 1989 (Price, 1992a). The high total precipitation in July 1992 was biased by one extremely heavy rain event on 7 July (91 mm). Following this event, the watertable was at the surface in many hollows, a situation not previously observed in 5 years of study (J.S. Price, unpublished data, 1994). The depth to the watertable following this event varied over the duration of the test (Fig. 2), and was generally within 0.2 m of the surface. It should be noted that the experimental spill occurred 5 days after the large rain event. Total precipitation for the duration of the test was 113 mm, and evaporation was 77 mm, yielding a water surplus of 36 mm. Most of this was balanced by runoff, as the net storage change (ΔS) was small. Change in water storage was determined from the change in elevation of

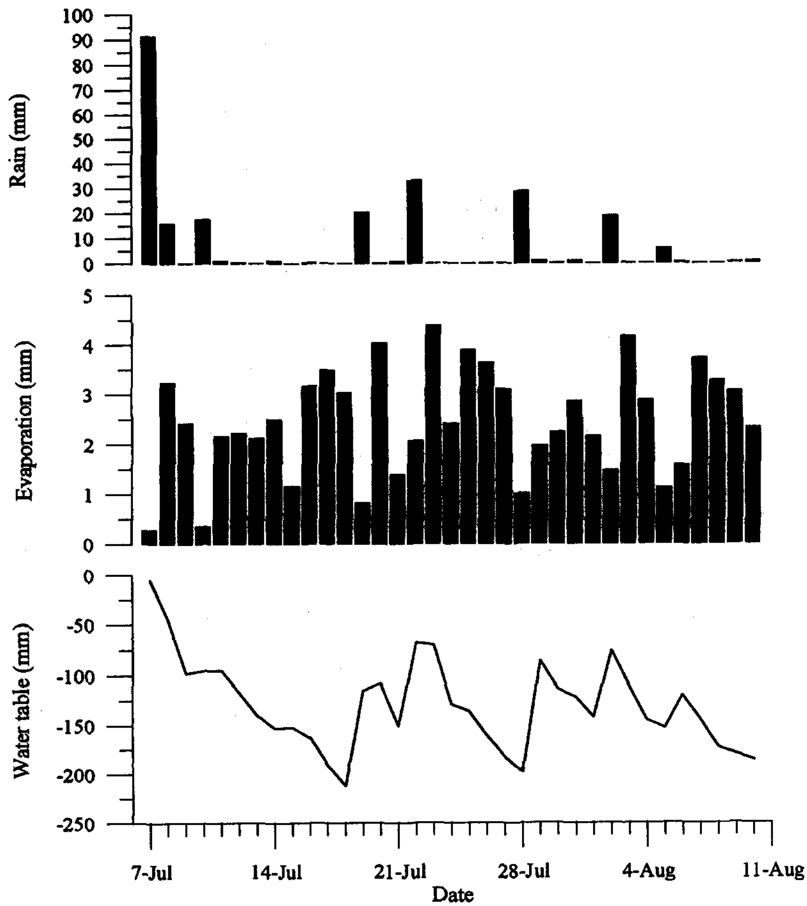

Fig. 2. From top to bottom: precipitation, evaporation and watertable depth below the surface, from 7 July to 10 August, 1992.

the watertable (Δh) and the specific yield (S_y), such that

$$\Delta S = \Delta h S_y \quad (1)$$

Over the study period (12 July to 10 August) the net change in the watertable elevation (Δh) was 6.9 mm. As the average S_y is 0.25 (Price, 1992a), net storage change was less than 2 mm.

Dead and partly decomposed *Sphagnum* spp. dominate the upper 0.4–0.45 m of the peat profile, indicating the approximate depth of the acrotelm. The catotelm contains fairly well-humified *Sphagnum* peat, with some undecomposed roots and grasses present throughout the profile. Hydraulic conductivity was highest when the watertable was high within the acrotelm. Bail tests (Hvorslev, 1951) performed on wells after a heavy rain event which nearly saturated the bog, yielded a hydraulic conductivity of 1.6×10^{-2} m s^{-1}. Hydraulic conductivity decreased markedly with depth (Fig. 3). Below the acrotelm, hydraulic conductivity was relatively constant with depth. Average linear velocity calculations at various depths in the peat profile using Darcy's law and an estimated hydraulic gradient of 0.055 (the average watertable gradient observed at the site) indicate that at a depth of 0.15–0.20 m (estimated hydraulic conductivity of 1.0×10^{-3} m s^{-1}, active porosity of 0.48 (Hoag and Price, 1995)) the average linear groundwater velocity was 2.8×10^{-4} m s^{-1}, or approximately 5 m day^{-1}. By comparison, the specific discharge at a depth of 0.5 m (hydraulic conductivity of 1.0×10^{-9} m s^{-1}, active porosity of 0.16) was 5.5×10^{-10} m s^{-1}, or 3.2×10^{-4} m day^{-1}. Spatial variation of hydraulic conductivity in plan view was also noted. There is a general trend of decreasing hydraulic conductivity downslope, particularly between 10 and 20 m, where it decreases by almost an order of magnitude (Fig. 4).

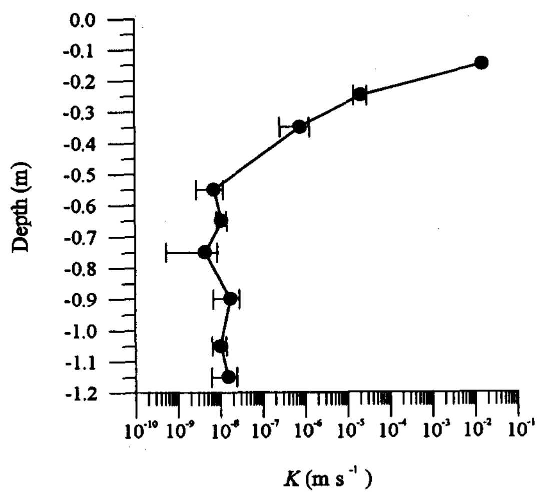

Fig. 3. Change in hydraulic conductivity with depth from three piezometer nests shown in Fig. 1. The variability at each piezometer was large enough that a spatial trend could not be noted in this short (4 m) transect, so the data were combined. Bars indicate error.

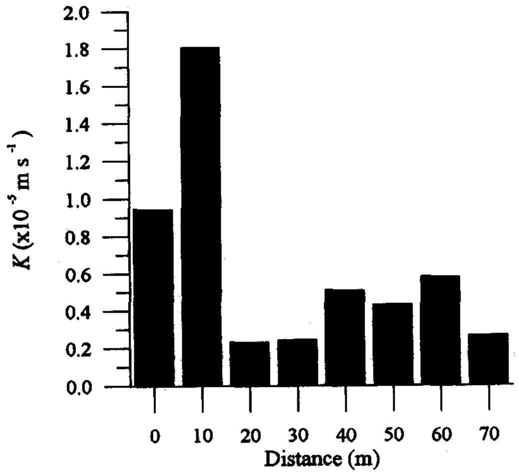

Fig. 4. Variation in hydraulic conductivity downslope at the same depth in the peat profile. The transect started about 0.5 m upslope and 3.5 m north of the spill point, running parallel to the direction of plume migration.

The background electrical conductivity of the groundwater was 50–90 μS cm^{-1}. The watertable near the drum rose about 25 mm during the spill. During the first day of the test the plume developed rapidly (Fig. 5). Most of the lateral dispersion occurred during this period and the plume began to develop asymmetrically both

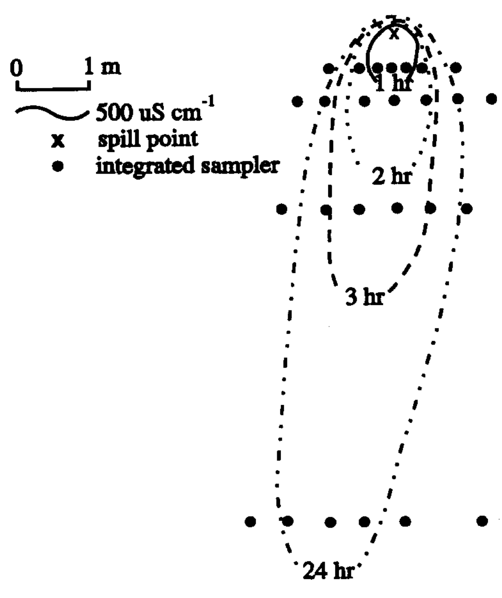

Fig. 5. Development of the plume after approximately 1, 2, 3 and 24 h. Each contour represents an EC of 500 μS cm^{-1}.

in the longitudinal and transverse directions. Four days after the solute was released (15 July), the asymmetrical development of the plume continued, particularly in the longitudinal direction (Fig. 6(a)). The solute front was advancing, whereas the bulk of the solute remained near the spill point, leading to the highly asymmetrical shape in the direction of flow. By the fourteenth day (23 July), the plume began to spread laterally, but with the front not advancing as quickly (Fig. 6(b)). Based on an electrical conductivity of 1 mS cm^{-1}, the plume front travelled 70 m in 30 days (Fig. 6(c)) (average advance of 2.3 m day^{-1}), which is slower than the average linear groundwater velocity calculated previously, indicating retardation of the front by a factor of 2.2. The peak concentration remained near the spill location for the duration of the test.

Most of the solute travelled at or near the watertable (which rose during the spill)

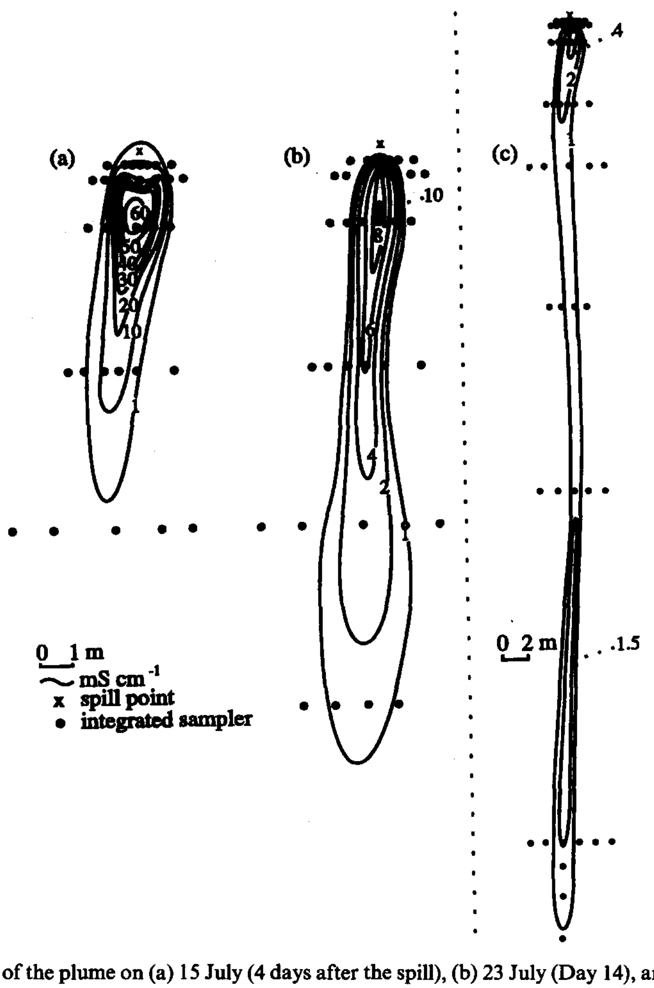

Fig. 6. Plan views of the plume on (a) 15 July (4 days after the spill), (b) 23 July (Day 14), and (c) 10 August (Day 30). (Note change in scale for (c).) The outer contour represents an EC of 1 mS cm^{-1}.

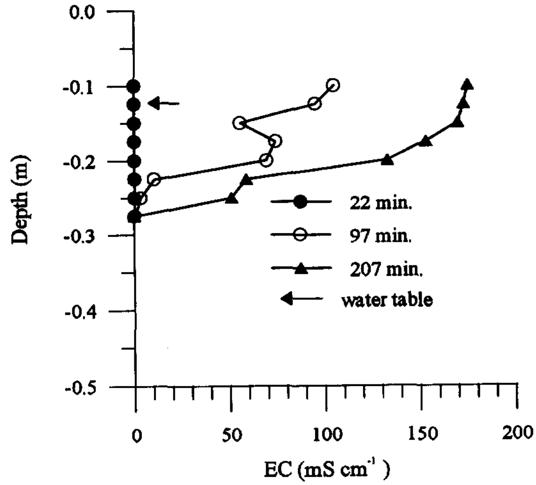

Fig. 7. Vertical distribution of EC 22, 97 and 207 min following the spill on 12 July, 0.45 m from the spill point. The arrow indicates the position of the watertable immediately before the spill.

immediately following the spill on 12 July, as is evident from the large and rapid change in electrical conductivity at the sampling nest 0.45 m from the spill site (Fig. 7). By 14 July, the conductivity of the water in the upper 0.20 m of the peat at the same location had returned to background levels (Fig. 8). Below 0.25 m, the electrical conductivity decreased rapidly for the first 2–3 days of the test, after which electrical conductivity became relatively constant for the remainder of the experiment. Below a depth of 0.45 m, electrical conductivity did not change significantly relative to the upper part of the peat profile over the course of the experiment. This is illustrated both near the spill point (Fig. 8) and further downslope (Fig. 9). Post-experiment

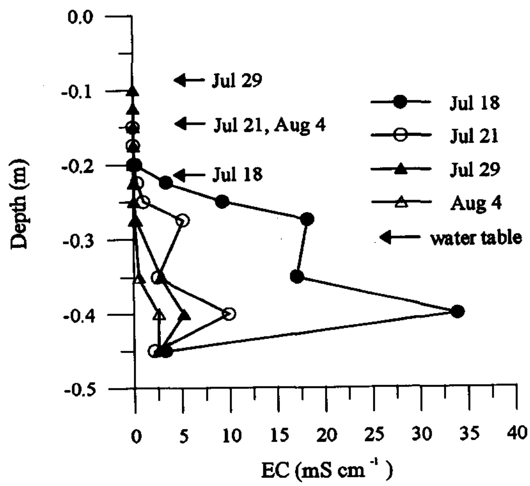

Fig. 8. Vertical distribution of EC on 18, 21, 29 July and 4 August, 0.45 m from the spill point.

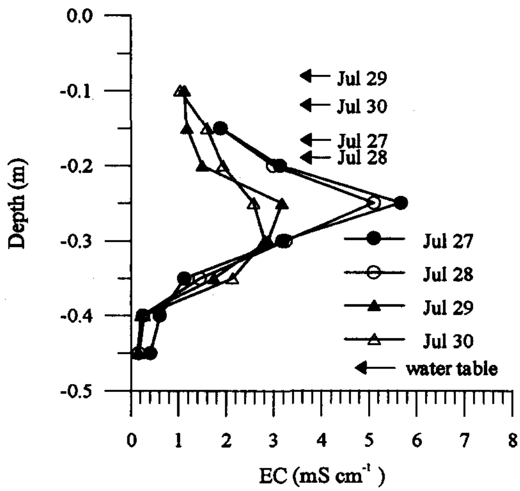

Fig. 9. Vertical distribution of EC from 27 to 30 July, 12.6 m from the spill location. Sampling on 28 July was performed prior to the rain event.

sampling performed in 1993 showed that the peak concentration of the plume had descended to 0.6 m, and migrated only 0.8 m downslope.

Rain events on 28 and 29 July decreased the solute concentration in the upper part of the peat profile (Fig. 9). By 30 July, the electrical conductivity in the upper 0.22 m had partially recovered. Below a depth of 0.22 m, electrical conductivity continued to decrease as the dilution wave was transmitted downward.

6. Discussion

Within the acrotelm the hydraulic conductivity was relatively high but decreased markedly with depth (Fig. 3) (see Boelter, 1965). Below a depth of 0.5 m, hydraulic conductivity was a relatively constant low value (see Ingram, 1983; Chason and Siegel, 1986). As a result, most of the solute transport occurred near the watertable (Fig. 7). On the first day of the test, the high watertable (within 0.1 m of the surface) was associated with a high hydraulic conductivity, resulting in rapid plume development (Fig. 5). Furthermore, the watertable 'mound' at the spill location increased the local hydraulic gradient and caused lateral dispersion during the initial development of the plume. The slow change in electrical conductivity at depths below 0.45 m (Figs. 8 and 9) is due to the low hydraulic conductivity of the catotelm. Therefore, diffusion may be an important mechanism in the transport of solute to and from the catotelm.

Although the vertical variation in peat structure was important in focusing transport in the upper layer, broad spatial trends in hydraulic conductivity also affected the rate and nature of plume development. Here, large-scale heterogeneity is evident from the downslope decrease in hydraulic conductivity. Price (1992a) noted a similar but gradual trend at a nearby slope and attributed it to the developmental stage of the peat, whereby older, more decomposed peat lies toward the valley bottom. However, as the hydraulic conductivity is dominated by the acrotelm, the sudden decrease along this transect is probably due to some localized process affecting the permeability of the more recently developed upper layer. The order of magnitude decrease in hydraulic conductivity 10–20 m downslope from the spill decreased the rate of the solute front advance, and caused lateral spreading of the plume (Fig. 6(b)).

The asymmetrical shape of the plume in the direction of flow can be partially attributed to retardation of the solute owing to the dual-porosity nature of the peat matrix. Immediately following the spill, concentrated solute entering active pores in the acrotelm established a concentration gradient between the active and closed pores (see Price and Woo, 1988a). This strong gradient operating over short distances resulted in molecular diffusion of the solute into closed pores and plant cell remains, abstracting solute from the flowing solution. The closed pores therefore acted as a sink for the solute, and retarded the advance of the plume. As the concentration of solute in the active pores decreased over time, the concentration gradients reversed, allowing solute to re-enter the active pores, with the closed pores acting as a source of solute. This matrix diffusion resulted in increased dispersion along the travel path. Further evidence of retardation is the 'tailing' of electrical conductivity over time at depths below 0.25 m, where changes in solute concentration were slow (Figs. 8 and 9) (see Lamarche, 1991). No tailing of electrical conductivity was evident at depths less than 0.25 m, as diffusion from the closed pores to the active pores was masked by the relatively high advection rate.

The micro-scale dual-porosity effect was only partly responsible for the stationary peak in electrical conductivity (Figs. 7 and 8), which remained proximal to the input location over the duration of the test. At the meso-scale, density-dependent flow (Freeze and Cherry, 1979) and molecular diffusion in the downward direction further attenuated the plume by trapping solute in the catotelm. As the solute within the acrotelm was replaced by fresher water, the concentration gradient reversed, and the catotelm peat, which previously acted as a sink, became a source of solute. Reversals of the hydraulic gradient (R.S. Hoag and J.S. Price, unpublished data, 1994) may also have remobilized the solute, particularly if macropores were present. The combined effect of matrix diffusion and vertical exchanges of solute delayed the migration of the plume front by a factor of 2.2 over the value calculated as the average linear pore water velocity. Colloid formation, caused by the high concentration of electrolytes (Faure, 1991), may have increased the transport rate, because colloids are not subject to matrix diffusion.

Rain events caused dilution of the solute in the upper 0.30 m of the peat profile (Fig. 9). At the site 12.6 m from the spill, the largest change in electrical conductivity owing to rain occurred at a depth of 0.25 m. Between 0.11 and 0.22 m, electrical conductivity decreased during the rain event but increased following the rain event. This indicates that mixing was occurring and that rain may have remobilized solute in the unsaturated zone (Price, 1994). Evaporation did not have a noticeable effect on daily changes in solute concentration, as it was a small flux largely derived from the unsaturated zone (Price, 1991).

7. Conclusions

The physical structure of peat has a strong effect on solute transport. Field-scale heterogeneity is caused by a downslope decrease in hydraulic conductivity possibly associated with more humified peat deposits. As a result, plume development in the direction of flow was slowed downslope from the spill point. Most of the solute transport occurred at or near the watertable, and the transport rate depended on watertable position. Below a depth of 0.45 m, diffusion may be an important transport mechanism because of the decrease in hydraulic conductivity with depth. Solute retardation is caused by the peat's dual-porosity matrix, whereby solute enters closed and dead-end pores by diffusion and is abstracted from the flowing solution. Owing to the high watertable during the study and a relatively steep hydraulic gradient of 0.055, the transport rate was still rather high. Rain caused dilution and mixing of solute in the upper part of the peat profile, whereas evaporation did not have an appreciable effect on solute concentration.

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References

Banfield, C.E., 1981. The climatic environment of Newfoundland. In: A.G. MacPherson and J.B. MacPherson (Editors), The Natural Environment of Newfoundland, Past and Present. Memorial University of Newfoundland, St. John's, pp. 83–153.

Boelter, D.H., 1965. Hydraulic conductivity of peats. Soil Sci., 100(4): 227–231.

Chason, D.B. and Siegel, D.I., 1986. Hydraulic conductivity and related physical properties of peat, Lost River peatland, Northern Minnesota. Soil Sci., 142(2): 91–99.

Damman, A.W.H., 1987. Variation in ombrotrophy: chemical differences among and within ombrotrophic bogs. In: C.D.A. Rubec and R.P. Overend (Editors), Symposium '87 Wetlands/Peatlands, 23–27 August 1987, Edmonton Convention Centre, Edmonton, Alta. Environment Canada, Ottawa, pp. 85–94.

Environment Canada, 1982. Canadian Climate Normals 1951–1980: Temperature and Precipitation, Atlantic Provinces. Atmospheric Environment Service, Downsview, Ont., 136 pp.

Environment Canada, 1987. The Wetland Classification System. Land Classification Series. National Wetlands Working Group, Inland Waters/Lands Directorate, Ottawa, Ont., 18 pp.

Farmer, G.H., 1981. The cold ocean environment of Newfoundland. In: A.G. MacPherson and J.B. MacPherson (Editors), The Natural Environment of Newfoundland, Past and Present. Memorial University of Newfoundland, St. John's, pp. 56–75.

Faure, G., 1991. Principles and Applications of Inorganic Geochemistry. MacMillan, New York, 626 pp.

Freeze, R.A. and Cherry, J.A., 1979. Groundwater. Prentice–Hall, Englewood Cliffs, NJ, 604 pp.

Hoag, R.S. and Price, J.S., 1995. The effects of matrix diffusion on solute retardation and transport in peat in laboratory columns. J. Contam. Hydrol., submitted.

Hvorslev, M.J., 1951. Time lag and soil permeability in groundwater observations. US Army Corps Eng. Waterways Exp. Stn. Bull., 36, 50 pp.
Ingram, H.A.P., 1978. Soil layers in mires: function and terminology. J. Soil Sci., 29: 213–218.
Ingram, H.A.P., 1983. Hydrology. In: A.J.P. Gore (Editor), Mires: Swamp, Bog, Fen and Moor. Elsevier Scientific, New York, pp. 67–158.
Lamarche, P., 1991. Dissolution of immiscible organics in porous media. Ph.D. Thesis, Department of Civil Engineering, University of Waterloo, Waterloo, Ont., 342 pp.
Loxham, M., 1980. Theoretical considerations of transport of pollutants in peats. Proc. 6th Int. Peat Congress, Duluth. Int. Peat Soc., Helsinki, pp. 600–606.
Loxham, M. and Burghardt, M., 1983. Peat as a barrier to the spread of micro-contaminants to the groundwater. In: C.H. Fuschman and S.A. Spigarelli (Editors), Proc. Int. Symp. on Peat Utilization, Bemidji State University, Bemidji, MN. Bermidji State University, Bermidji, pp. 337–349.
MacPherson, J.B., 1981. The development of the vegetation of Newfoundland and climate change in the Holocene. In: A.G. MacPherson and J.B. MacPherson (Editors), The Natural Environment of Newfoundland, Past and Present. Memorial University of Newfoundland, St. John's, pp. 184–217.
Price, J.S., 1991. Evaporation from a blanket bog in a foggy coastal environment. Boundary-Layer Meteorol., 57: 391–406.
Price, J.S., 1992a. Blanket bog in Newfoundland. Part 2. Hydrological processes. J. Hydrol., 135: 103–119.
Price, J.S., 1992b. Blanket bog in Newfoundland. Part 1. The occurrence and accumulation of fog-water deposits. J. Hydrol., 135: 87–101.
Price, J.S., 1994. Sources and sinks of sea salt in a Newfoundland blanket bog. Hydrol. Proc., 8: 167–177.
Price, J.S. and Woo, M.K., 1988a. Wetlands as waste repositories? Solute transport in peat. Proc. Nat. Student Conference on Northern Studies, 18–19 November 1986, Assoc. of Canadian Universities for Northern Studies, Ottawa, Ont., pp. 392–395.
Price, J.S. and Woo, M.K., 1988b. Studies of a subarctic coastal marsh. II. Salinity. J. Hydrol., 103: 293–307.
Rutter, A.J., 1975. The hydrological cycle in vegetation. In: J.L. Monteith (Editor), Vegetation and the Atmosphere, Vol. 1, Principles. Academic Press, London, pp. 111–154.
Schell, W.R., Sanchez, A.L., Underhill, D.W. and Thomas, E., 1985. Natural geochemical repositories for wastes: field and laboratory measurements of diffusion and distribution coefficients in age dated peat bogs. In: T.H. Sibley and C. Myttenaere (Editors), Application of Distribution Coefficients to Radiological Assessment Models. Univ. Cathol. Louvain, Louvain la Neuve, Belgium, pp. 207–223.
Sudicky, E.A., 1986. A natural gradient experiment on solute transport in a sand aquifer: spatial variability of hydraulic conductivity and its role in the dispersion process. Water Resour. Res., 22(13): 2069–2082.
Viraraghavan, T. and Ayyaswami, A., 1987. Use of peat in water pollution control: a review. Can. J. Civ. Eng., 14(2): 230–233.
Viraraghavan, T. and Ayyaswami, A., 1989. Batch studies on septic tank effluent treatment using peat. Can. J. Civ. Eng., 16(2): 157–161.