Journal of Hydrology 381 (2010) 333–340

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Water flow in *Sphagnum* hummocks: Mesocosm measurements and modelling

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ARTICLE INFO

Article history:
Received 25 March 2009
Received in revised form 30 November 2009
Accepted 3 December 2009

This manuscript was handled by P. Baveye Editor-in-Chief, with the assistance of Hans-Jörg Vogel, Associate Editor

Keywords:
Unsaturated hydraulic conductivity
Water retention
Mosses
Evaporation
RETC
Hydrus 1D

SUMMARY

The internal water fluxes within *Sphagnum* mosses critically affect the rate of evaporation and the wetness of the living upper few centimetres of moss (capitula) and the physiological processes (e.g. photosynthesis) that support them. To quantify water fluxes and stores in *Sphagnum rubellum* hummocks we used a 30 cm high column (mesocosm) of undisturbed hummock moss including the capitula, and applied a number of experiments to investigate (1) staged lowering (and raising) of the water table (*wt*) with a manometer tube; (2) pumped seepage of about 0.7 cm d^{-1} to produce a *wt* drop of 1.5 cm day^{-1}; and (3) evaporation averaging 3.2 mm d^{-1}. Water content (θ) at saturation (θ_s) was $\sim$0.9 $cm^3\ cm^{-3}$ for all depths. Residual water content (θ_r) was 0.2 $cm^3\ cm^{-3}$ at 5 cm depth, increasing to 0.47 $cm^3\ cm^{-3}$ at 25 cm depth. Hydraulic conductivity (K) of the same top 5 cm layer ranged from 1.8×10^{-3} m s^{-1} at θ_s to 4×10^{-8} m s^{-1} at θ_r. By comparison K at 25 cm depth had a much more limited range from 2.3×10^{-4} m s^{-1} at θ_s to 1.1×10^{-5} m s^{-1} at θ_r. Staged *wt* lowering from -10 cm to -30 cm (no evaporation allowed) resulted in an abrupt change in θ that reached a stable value generally within an hour, indicating the responsiveness of moss to drainage. Staged increases also resulted in an abrupt rise in θ, but in some cases several days were required for θ to equilibrate. Pumped seepage resulted in a sequential decline of θ, requiring about 10 days for each layer to reach θ_r after the water table dropped below the sensor at the respective depths. Evaporation resulted in a similar pattern of decline but took almost three times as long. The computer simulation Hydrus 1D was used to model the fluxes and provided a good fit for the staged lowering and pumped seepage experiments, but overestimated the water loss by evaporation. We believe the reason for this is that over the longer evaporation experiment, the monolith underwent consolidation and shrinkage which reduced saturated hydraulic conductivity, thus reducing the rate of upward water flux – not accounted for in the simulation. Declining θ_s in lower layers (i.e., before pore drainage) was evidence of consolidation. The study confirms that the hydraulic structure results in a rapid transition to a low but stable water content in upper mosses when the water table falls, a low unsaturated hydraulic conductivity in such circumstances that constrains upward water flux caused by evaporation when θ_r is reached, but sustains it for a wide range of water tables. Moreover, the hydraulic parameters can be represented with the Mualem–van Genuchten approach, enabling the fluxes to be modelled in one dimension with reasonable accuracy.

Introduction

Sphagnum mosses are the primary peat-forming plant in northern peatlands (Kuhry and Vitt, 1996). There is a critical water requirement at the growing moss surface (capitula) to support plant metabolic processes including photosynthesis and plant matter decomposition (Clymo and Hayward, 1982; McNeil and Waddington, 2003), and evaporation (Lafleur et al., 2005) yet water transport processes in mosses, particularly in the unsaturated condition, remain an enigma because of the difficulty of measuring hydraulic properties and flows in the delicate moss matrix (Price et al., 2008). In natural systems moss grows upon its own remains, resulting in a transition from living growing moss near the surface, to progressively more decomposed mosses with depth (Clymo, 1970, 1983, 1984; Clymo and Hayward, 1982; Hayward and Clymo, 1982; Rochefort et al., 1990), thus a concomitant range of hydraulic properties that affect water flows and stores. The peat below the lowest annual average water table is referred to as the "catotelm" (Ingram, 1978), and is characterized by relatively small average pore-diameter and low hydraulic conductivity (Hayward and Clymo, 1982). Above this, the "acrotelm" comprises plant structures ranging from relatively poorly to moderately decomposed mosses at depth, to undecomposed and living mosses near the surface (Ingram, 1978). The upper layer has a larger average pore-diameter (Rezanezhad et al., 2009) and higher saturated hydraulic

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doi:10.1016/j.jhydrol.2009.12.006

conductivity, but when drained its poor water retention results in low unsaturated hydraulic conductivity (Price et al., 2008), thus limited ability to sustain upward water movement.

Mosses are non-vascular, thus water transport occurs primarily as capillary flow in the spaces between individual leaves and pendant branches (Hayward and Clymo, 1982), while vapour constitutes only 1% of the total flux (Price et al., 2009). Water is also held in intercellular spaces called hyaline cells, that can hold 10–20% of the sample volume's water at pressures greater than −100 cm of water (Hayward and Clymo, 1982) so that during all but the driest periods the top, growing part of the *Sphagnum* remains moist. Consequently, community architecture, which is a function of species type and water availability (Schipperges and Rydin, 1998) affects water conductance potential. For example, *Sphagnum* species in hummocks (e.g. *S. fuscum*) are smaller than hollow species (e.g. *S. magellanicum*) (Schipperges and Rydin, 1998) and have higher spatial density of capitula (Gunnarsson and Rydin, 2000) which imparts a higher water retention capacity (Luken, 1985) (see also Clymo, 1970). While the water flux dynamics of hummocks and hollows have been measured using mass balance (Yazaki et al., 2006), no rigorous attempts to numerically simulate flow phenomena has been done because reliable estimates of hydraulic parameters, especially unsaturated hydraulic conductivity, have not been available until recently (Price et al., 2008). Schouwenaars and Gosen (2007) modelled water flow in mosses re-established on cutover peat and showed that it becomes increasingly difficult to sustain a water flux to the surface (capitula) once the layer grew 5–15 cm thick. However, they also suggested that as the moss layer developed even further, water storage in the lower mosses became a source that could sustain the upward flow. While this modeling contributed to the understanding of the functioning of a regenerating layer of mosses, the absence of direct measurements of hydraulic conductivity and comparative field measurements limits its applicability and reliability.

Disturbances such as drainage (Whittington and Price, 2006) or climate shifts (Tolonen and Turunen, 1996) can profoundly alter the hydrological regime, and the ecosystem response can range from desiccation and death (Sagot and Rochefort, 1996) in the short-term, to changes in moss community composition (Strack et al., 2006) over time. Improved knowledge of the linkage between groundwater and moisture at the moss surface will allow us to better predict the response. Therefore, the overall goal of this paper is to seek a better understanding of liquid water flux in a *Sphagnum* hummock profile, through measurement and modeling. The specific objectives are to (1) characterize the hydraulic structure (water retention capacity and unsaturated hydraulic conductivity relation) of a moss profile; (2) evaluate the detailed moisture response in a moss profile under changing boundary conditions (drainage, evaporation); and (3) effectively simulate the water fluxes and stores.

Methods

Our approach was to manipulate the water table in, or water flux through, intact ∼35 cm diameter monoliths of *Sphagnum rubellum* hummocks in a laboratory setting; section the profile and determine the vertical hydraulic properties; and use these measurements to specify and test a 1-dimensional mathematical model.

Sample extraction and preparation

The sample was obtained from a Southern Ontario bog (49.94°N, 80.45°W) in December (when the ground was frozen), by cutting (with a saw) a cylindrical monolith of peat with a diameter and height of ∼35 cm. The moss monolith was then placed on top of a large bucket (20 l, 30 cm diameter) and the edges of the sample trimmed so that the sample slid into the bucket, ensuring a snug fit. The sample was then returned to the laboratory, flooded with deionised water, and frozen. It was then removed from the bucket so that it could be inserted intact into a second bucket that contained a 3 cm deep layer of fine gravel base (average stone diameter ∼3 mm), which distributed the hydraulic connection to a flexible manometer tube fixed to the bottom of the bucket which allowed for water table manipulation and/or drainage and rewetting. The sample was allowed to thaw and then flushed with deionized water several times. To limit all vertical moisture flow to that in the *Sphagnum* matrix, the ericaceous vegetation was clipped, with roots left in place.

Moisture content was measured with a Campbell Scientific TDR100 system with 30 cm CS-605 probes connected to a CR10x data logger. Six probes were installed horizontally into the sample at −5, −10, −15, −20 and −25 cm depths, with the sixth probe inserted on an angle from 0 to −5 cm. (the angle allowed the 30 cm long probe to obtain an average of the moisture content over the top 5 cm of the sample, arguably the most important layer for water loss. As the sample surface was not perfectly flat, obtaining reliable moisture contents in this range would be impossible as part of the probe could be exposed to the air in the middle of the sample.) Small holes were drilled into the side of bucket, and the TDR probes inserted and sealed in with General Electric Silicone II to eliminate leaks. The silicone was applied to the outside of the bucket and thus there was minimal contact with the sample. Moisture content was recorded hourly unless otherwise noted. Deionized water was used for all of the following experiments.

Bucket experiments

Experiment 1: The water table (*wt*) in the sample was adjusted to −10 cm by allowing the fully saturated sample to drain though the manometer tube until the water level in the manometer was 10 cm below the moss surface. The sample was then covered loosely to prohibit evaporation. When a stable moisture content (no discernable change over at least 12 h) was achieved in the sensors above the water table, *wt* was "instantaneously" lowered 5 cm by basal drainage using the manometer tube, to five subsequent *wt* depths (−10, −15, −20, −25 and −30 cm). The process was then reversed, and the *wt* increased to the same series of depths by connecting the flexible manometer tube to a water-filled bucket that was raised above the sample.

Experiment 2: With the *wt* at −10 cm (end of experiment 1, sample still covered), the manometer tube was connected to a VWR peristaltic variable flow mini-pump (pump I, model 3384, ultra low flow; see www.vwr.com) that generated a controlled continuous basal seepage of ∼0.7 cm day^{-1} to produce a *wt* drop of 1.5 cm day^{-1}. The *wt* was measured daily in the manometer tube.

Experiment 3: The *wt* was returned to −10 cm and the cover removed. Water loss via evaporation was monitored by periodic (∼daily) weighing of the monolith. The sample was placed under grow lights (0600–1900 h) with a fan ∼2 m away to increase evaporation. The experiment ended when a *wt* of −30 cm was achieved.

Hydraulic conductivity and retention

Upon completion of the experiments, the core was drained of water and frozen. The frozen core was cut into five horizontal layers ∼5 cm thick centered at −5, −10, −15, −20 and −25 cm below the surface (e.g., the first was −2.5 to −7.5 cm). The 0 to −2.5 cm layer was discarded as the core did not have a perfectly flat surface and a viable sample was infeasible. The lowest layer (−27.5 to