Application of microcosm experiments for quantifying lateral flow and evapotranspiration on recovering bog ecotypes

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Abstract
The importance of characterizing the ecohydrological interactions in natural, damaged/dained, and restored bogs is underscored by the importance of peatlands to global climate change and the growing need for peatland restoration. An understudied aspect of peatland ecohydrology is how shallow lateral flow impacts local hydrological conditions and water balance, which are critical for peatland restoration success. A novel method is presented using microcosms installed in the field to understand the dynamics of shallow lateral flow. Analysis of the difference in water table fluctuation inside and outside the microcosm experimental areas allowed the water balance to be constrained and the calculation of lateral flow and evapotranspiration. As an initial demonstration of this method, a series of four microcosm experiments were set up in locations with differing ecological quality and land management histories, on a raised bog complex in the midlands of Ireland. The timing and magnitude of the lateral flow differed considerably between locations with differing ecological conditions, indicating that shallow lateral flow is an important determining factor in the ecohydrological trajectory of a recovering bog system. For locations where Sphagnum spp. moss layer was present, a slow continuous net lateral input of water from the upstream catchment area supported the water table during drought periods, which was not observed in locations lacking Sphagnum. Consistent with other studies, evapotranspiration was greater in locations with a Sphagnum moss layer than in locations with a surface of peat soil.

KEYWORDS
bog, ecohydrology, sphagnum moss, water budget, wetland, wetland hydrology

1 | INTRODUCTION

Peatlands make up as much as 10% of the European land surface area, but a high percentage (~46%) of the peatlands have been degraded to a degree that peat is no longer actively accumulating carbon (Tanneberger et al., 2017). During the last few decades, there has been a growing focus on peatland restoration (Holden, Chapman, & Labadz, 2004), and considerable resources have been implemented across Europe to stimulate peatland recovery (Andersen et al., 2017). Peatland restoration has been suggested as a method for climate change mitigation (Birkin, Bailey, Brewis, & Way, 2011; Wilson, Müller, & Renou-Wilson, 2013) because the greenhouse gas (GHG) dynamics and carbon cycle are often substantially different in degraded peatlands compared to pristine peatlands (Baird, Holden, &
This growing focus on restoration and management underscores the importance of understanding the ecohydrology of both intact and degraded bogs.

Intact northern ombrogenic bogs typically have a continuous ground surface layer of *Sphagnum* spp. mosses. *Sphagnum* moss is described as a "keystone genus" (Rochefort, 2000) and marker of success for bog restoration (Poulin, Rochefort, Quinty, & Lavoie, 2005), extensive *Sphagnum* moss cover has also been linked to a consistent CO₂ sink function in restored or recovering bogs (Nugent, Strachan, Strack, Roulet, & Rochefort, 2018; Swenson et al., 2019). By contrast, degraded bogs typically lack a continuous *Sphagnum* moss layer (González, Henstra, Rochefort, Bradfield, & Poulin, 2014) and instead have a ground surface of well decomposed peat soil.

The presence of a continuous *Sphagnum* moss layer alters the hydro-physical properties of the system so as to improve a stable bog environment (Price, Heathwaite, & Baird, 2003; Robroek et al., 2009; Waddington et al., 2015). A continuous *Sphagnum* moss layer is characterized by large pore spaces and resulting high saturated hydraulic conductivity (values >1 x 10⁻³ m s⁻¹ have been observed) (Baird, Milner, Blundell, Swindles, & Morris, 2016) and high specific yield (Bourgault, Larocque, Garneau, & Roux, 2018).

Understanding the interaction between micro-scale water balance and hydro-physical properties is essential for developing peatland hydrological models (Morris, Belyea, & Baird, 2011), predicting the impacts of climate change (Moore & Waddington, 2015), and on-the-ground peatland restoration and management (Holden et al., 2004; Price et al., 2003). Further, even small additional sources of water have been found to be important for maintaining *Sphagnum* physiological processes during periods of water deficit (Ketcheson & Price, 2014). Thus, recent studies have highlighted the importance and challenge of accurately characterizing hydro-physical properties (Moore, Morris, & Waddington, 2015) and the micro-scale water balance in bogs (Ketcheson & Price, 2014), which includes the lateral flux of water (Oosterwoud, van der Ploeg, van der Schaff, & van der Zee, 2017; Wilcox, Sweat, Carlson, & Kowalski, 2006).

The majority of the lateral flow of water in raised bogs typically occurs in the shallow sub-surface or as overland flow (Fraser, Roulet, & Moore, 2001; Hoag & Price, 1995; Holden & Burt, 2002) due to the rapid decrease in hydraulic conductivity with depth (e.g., Fraser et al., 2001). However, despite the importance of shallow lateral flow to raised bog hydrology (Sonnetag, Chen, Roulet, Ju, & Govind, 2008), it is difficult to quantify in the field; the saturated hydraulic conductivity in bogs has been observed to vary by several orders of magnitude over small vertical (i.e., decimetres) (Fraser et al., 2001; McCarter & Price, 2017) and horizontal (i.e., meters) (Baird et al., 2016) distances, and can also be temporally variable by orders of magnitude over a growing season due to the compressibility of highly organic soil (Schlotzhauer & Price, 1999; Waddington, Kellner, Strack, & Price, 2010). Altogether, research to date suggests that hydrological processes across a bog are strongly heterogeneous and hence, this paper presents a novel field method which can help to gain further insights into an aspect of these processes, namely the timing and magnitude of shallow lateral flow in bogs.

Further, topography (i.e., slope and catchment area) can be an important factor in bog restoration success and sustaining active raised bogs (Girard, Lavoie, & Thériault, 2002; Oosterwoud et al., 2017; Poulin et al., 2005) suggesting the importance of lateral flow to *Sphagnum* moss regeneration (Girard et al., 2002) and determining where active bogs can be found under given climate conditions (Van der Schaaf & Streefkerk, 2002). We hypothesized that *Sphagnum* development at our study site occurred in locations where the slope was sufficiently low to reduce runoff or the contributing catchment area was sufficiently large to maintain soil water during dry periods.

In this study, a set of microcosms were installed in the field, which were isolated from shallow lateral flow; thus, these microcosms were essentially one-dimensional systems. The hydrology inside these microcosms was directly compared to adjacent open areas to understand the importance of shallow lateral flow on micro-scale hydrology. This study is an initial proof of concept that the microcosm method can be used to quantify shallow lateral flow contributions to the water budget at specific locations within the peatland.

To demonstrate this method, a series of four microcosm experiments were set up in locations with differing ecological quality and land management histories, on a raised bog complex in midlands Ireland. The aim of this study was to consider the volumetric fluctuations in water storage on a short (i.e., hourly) time step in order to understand the relative importance of various components of the water balance to micro-scale hydrology.

## METHODS

### 2.1 Study site description and description of microcosm locations

Abbeyleix Bog (N 52.89714, W 7.35022, elevation approximately 90 m) is a peatland in Co. Laois, Ireland (Figure 1), which formerly consisted primarily of ombrogenic (raised) bog. The climate is a temperate, oceanic climate with a mean annual rainfall of 923 mm and a mean annual temperature of 9.4°C, average July temperature of 15.8°C and January temperature of 4.9°C (1981-2010) (Walsh, 2012).

Domestic peat extraction or “turf cutting” occurred on some, but not all, areas of Abbeyleix Bog until approximately the mid-1960s. Since then, the peat extraction or “cutover” areas have been abandoned and have naturally re-vegetated.

In the central portions of Abbeyleix Bog, peat extraction never occurred, leaving nominally intact raised bog (Figure 1). However, during the 1980s, a shallow drainage network was installed every 15 m across the bog surface. In 2009 (7 years prior to the start of this study), Bord na Móna in conjunction with Irish National Parks and Wildlife Service (NPWS) blocked over 30 km of drains on the raised bog in a restoration effort (Ryle, 2013).

Throughout the study site, the soils are acidic, low nutrient peat (histosols). The depths of peat soils are 5.0–8.5 m on the remaining raised bog and 1–3 m depth on the abandoned peat extraction areas.
The peat soil is underlain by 3–11 m of poorly sorted glacial till and in places a thin (20–500 mm) layer of shelly lake marl sediment.

2.2 Measurements of rainfall and ET

A weather station operated on site from 16th January 2016 to 22nd May 2018. The station recorded hourly measurements of air temperature and humidity (CS215 probe, Campbell Scientific, Loughborough, UK), rainfall (ARG100 Tipping Bucket Rain Gauge, Campbell Scientific), barometric pressure (PTB110 Barometer, Vaisala, Oyj, Finland), average wind speed at 3 m height (Model 05103 Wind Monitor, R. M. Young and Company, Traverse City, USA), net radiation (NR Lite 2 detector, Kipp and Zonen, Delft, The Netherlands), and soil temperature, which were recorded by a CR1000 Data logger (Campbell Scientific). The weather station was within 1 km of all microcosm locations. The rain gauge located on site stopped working on February 15, 2018. After this date, hourly rainfall data were taken from Carlow Oak-Park approx. 30 km SE, operated by Met Éireann, the Irish National Meteorological Service. The comparisons of cumulative daily rainfall for 2016 and 2017 showed a good correlation with this offsite weather station ($r^2 > 0.995$), although the total amount of rainfall over the 2 year period was 25% lower at the Carlow station. Daily rainfall data were also available from the Ballyroan (Oatlands) station from 2001 to 2017 (5 km NE of the site), which was used to compare monthly precipitation during the study period to recent averages.

The daily potential evapotranspiration for a short reference grass crop ($ET_{0}$) was calculated on site using the Penman-Monteith combination approach following the guidelines in the FAO Irrigation and drainage paper 56 (Allen, Pereira, Raes, & Smith, 1998) based on weather station measurements. The measured wind speed (at 3 m height) was adjusted, following recommendations in the FAO document, to estimate the wind speed at 2 m for the ET calculation. There were no other deviations from the standard FAO recommendations. Soil heat flux was included in this calculation but had a negligible effect on the results. This was done from 16th January 2016 to 21st May 2018 (the period that the weather station operated onsite).

Additionally, for comparison with other studies, the ET was also calculated from the weather station meteorological field data based on the Priestly–Taylor method as in McCarter and Price (2013). The microcosms in this study were used to calibrate the coefficient of evaporability ($\alpha$) similar to the soil lysimeters used in McCarter and Price (2013).

2.3 Microcosms

Microcosms (Figure 2) were each 0.5 m² and were enclosed by a collar constructed from 2.5 m × 1 m sheets of 1 mm thick aluminium. The microcosms were similar in design to the "bottomless lysimeters" in Ingram, Coupar, and Bragg, (2001) and Kelemen and Ingram (1999), but lacking a hydraulically connected bag at outside ambient hydrostatic pressure. The microcosms were inserted into the bog surface to
a depth of 0.6–0.8 m carefully to ensure that the vegetation inside the microcosm was undisturbed. The thin collar width and the relatively large enclosure meant that inserting the collar had a minimal effect on peat compression, and no obvious changes to the ground surface elevation were observed. After installation, the aluminium collar was trimmed to 0.5 mm above the surrounding ground surface. Phreatic water level was recorded hourly inside each microcosm to the nearest mm with an OTT Orpheus Mini Water Level Logger (vented transducer, ±0.05% FS accuracy, OTT Hydromet, Kempten, Germany) in a 25 mm diameter stilling well perforated and screened down to 0.5 m depth.

A shallow piezometer (also 25 mm diameter) with a 100 mm long screen opening located at the base of the microcosm (~0.60–0.80 m) was also installed inside the microcosm to measure the vertical hydraulic gradient inside the microcosm. The water level in the piezometer was initially measured manually on a weekly basis and later (after August 2017) hourly using a Micro-Diver (±10 mm accuracy, van Essen Instruments, Delft, the Netherlands).

During winter months when precipitation exceeded ET, water was pumped from the microcosms to prevent the microcosm from overflowing, and the volume was recorded. This was done approximately bi-weekly to monthly. When the microcosm did overflow, the water table data inside the microcosm was discarded until the next time that the microcosm could be pumped.

A total of four microcosms were installed between October and November 2016. One each was installed on the raised bog and cutover bog in locations with and without a continuous Sphagnum moss layer (Figure 2). The locations of the microcosms are designated by two letter codes for the cutover locations: Sphagnum Cutover (SC) and Eriophorum Cutover (EC) and by three letter codes for the restored raised bog locations: Sub-Central (SBC) and Sub-Marginal (SBM). These locations correspond to four of the five ecotypes examined in a related carbon balance study where the ecological characteristics are described further (Swenson et al., 2019).

Briefly, the SC and EC location were located on the abandoned peat extraction area. The SC location consisted of 40–60 cm tall hummocks of primarily Sphagnum capillifolium and a mixture of other bog species. The SC location was located along a linear network of Sphagnum development, which followed abandoned drainage channels and natural depressions of the historic peat extraction area. The EC location had well-decomposed peat soil and had a flat microtopography, with a moderate cover of Eriophorum angustifolium. The SBM and SBC locations were located on the recovering raised bog. The SBC location was located in an area with continuous Sphagnum lawns and limited microtopography. The SBM location contained primarily Calluna vulgaris and Eriophorum spp. with well-decomposed peat soil.

Slope and estimated catchment area (Table 1) at each of the locations was determined with ArcMap v.10.4 from high resolution Digital Terrain Model (DTM) with a horizontal point spacing of 1 m, which was based on Airborne Light Detection and Ranging (LiDAR) surveys carried out in 2014 by Bluesky Limited. Surface slope was calculated by smoothing the average elevation value in a circular neighbourhood of radius 10 m around each cell. Upstream catchment area was approximately estimated based on flow path length and topographic catchment divides.

The water table level was also measured outside each microcosm in a 50 mm diameter stilling well to the nearest mm with an OTT Orpheus Mini Water Level Logger. The location of the outside stilling well was chosen to match the physical and ecological characteristics of the microcosm, with consideration to the landscape position, microtopography, and the plant ecology. The outside stilling wells were located within 5 m of the microcosm, except for the Sphagnum Cutover microcosm where it was located ~25 m away to avoid disturbance of other experimental plots.

The stilling well and the piezometer tubes, both inside and outside of the microcosms, were installed to a total depth of 2 m to
minimize the risk of ground surface fluctuations moving the tubes and affecting the absolute pipe level. The absolute levels of the stilling wells were assumed to be constant because the greatest strain in bog surface fluctuations occurs in the top 0.50 m (Price, 2003). Thus, it should be noted that the water table data reported throughout this paper is the water table with respect to a constant elevation (i.e., spring ground level) although the bog surface level is subject to small seasonal fluctuations.

### 2.4 Water balance determination using the microcosms

The various components of the water balance for a hypothetical small section at the surface of a bog is shown in Equation (1).

\[
P - \text{ET} + \text{Lateral Inflow} - \text{Lateral Outflow} \pm \text{vertical flow} = \Delta S \quad (1)
\]

where \(P\) is precipitation, \(\text{ET}\) is evapotranspiration, and \(\Delta S\) is the change in storage. The terms lateral inflow and lateral outflow will refer to gains or losses, respectively, from the combined shallow sub-surface and overland flow. The term net lateral flow will be used to refer the sum of these two components, with an opposite sign convention.

The microcosms used in this experiment are isolated from lateral flow. This means that the water balance inside the microcosms is simplified and is essentially one-dimensional. To characterize how timing and magnitude of the various components of the water balance (including lateral flow) contribute to the micro-scale hydrology, the volumetric fluctuations in storage were calculated inside and outside of each microcosm.

The storativity (although previous studies have referred to this as the specific yield) was calculated during particular rainfall events from the volume of rainfall and the corresponding change in water table according to Equation (2), using the so called "water table fluctuation" (WTF) method as in previous studies (Bourgault, Larocque, & Garneau, 2017; Dettmann & Bechtold, 2016).

\[
S(\text{wt}) = \frac{\Delta V}{\Delta z} \quad (2)
\]

where \(S(\text{wt})\) is the storativity (dimensionless) as a function of water table level, \(\Delta z\) is the change in water table level over a rain event (mm), and \(\Delta V\) is the volumetric change per unit area (mm) \((\Delta V = \text{precipitation depth} [P]\) over a rainfall event). As in previous studies, the calculation of storativity assumes that the ET, vertical flux of water, and interception by standing vegetation are negligible during a rainfall event. Unlike previous studies, which have assumed negligible lateral flow for open systems over a rainfall event (Bourgault et al., 2017; Dettmann & Bechtold, 2016), in this study, net lateral flow can be controlled inside the microcosms.

The volumetric fluctuations in water storage were calculated from the values of storativity and the time series of water table fluctuations (on an hourly time step) by re-arranging Equation (2). This was done for all four locations inside the microcosms, and for comparison, outside the microcosms at the SBC and EC locations. The change in water table between hourly time step \(t\) and time step \(t - 1\) was multiplied by the location-specific storativity for the average water table over the time step. Volumetric inputs (positive sign convention) were calculated during any time step where water table was rising, and volumetric losses were calculated for any time step where water table was decreasing. Volumetric fluctuations per unit area were in units of mm (i.e., one-dimensional) to be directly relatable to the other aspects of the water balance. Using storativity does not give the absolute volume of water in storage, but rather the volumetric changes over time.

The minimum and maximum water table level was determined for specific isolated rain events exceeding 1.0 mm. This minimum level of rainfall is smaller than was used in Bourgault et al. (2017), a threshold which resulted in a larger total dataset of rainfall events but at the expense of higher signal to noise ratio in the calculated storativity due to measurement limitations of the rainfall and water table loggers as well as greater proportionality of water intercepted by plants and the unsaturated zone. These smaller rainfall events were included to ensure that the measured storage properties were consistent for both large and small fluctuations in water table. The largest rainfall event included in this analysis was 29 mm. Rainfall events had to be relatively discrete events, and were excluded if there was not at least a 3 hour gap between them (as in Bourgault et al., 2017). Also, when considering the locations outside the microcosms, the rainfall events were restricted to those which were less than 7 hours in total duration so as to reduce the effect of lateral losses during the rainfall event.

These measurements were undertaken between first April 2017 and fourth January 2018 for the SC and SBM microcosms and between first April 2017 and 31st August 2018 for the EC and SBC microcosms. After 15th February 2018, offsite rainfall data had to be used, and was included (with caution) to extend the storativity curves to greater depths during the drought period of summer 2018. Outside the microcosms, at the SBC and EC locations, the storativity was determined for rainfall events during the period from fourth August 2016 to 15th February 2018.

Inside the microcosms, the volumetric fluctuations were resolved to quantify \(P\), \(\text{ET}\), and vertical flux. During time steps with volumetric gains, the non-rainfall components of the water balance were assumed to be negligible. This assumption is necessary for consistency because it was used in developing the storativity curves. Similarly, all of the
volumetric losses were assumed to be due to ET and downward seep-
age, and during time steps with volumetric losses, the rainfall was assumed to be negligible.

The ET inside of the microcosm was calculated by difference of the total cumulative volumetric losses inside the microcosm and the vertical losses. The vertical hydraulic gradient was measured inside the microcosm based on the difference in head between the phreatic water level and the shallow piezometer located inside the microcosm. Hydraulic head in the piezometer was measured hourly after August 2017 when Micro-Divers were installed. Before this time, the vertical surface hydraulic gradient was estimated from a linear regression with the water table. The effective vertical hydraulic conductivity \( K_v \) inside each microcosm could be determined inside the microcosms because both the hydraulic gradient and the volumetric losses were known. Assuming that \( K_v \) was constant over time and Darcian flow, then \( K_v \) could be adjusted such that calculated vertical losses of water did not frequently exceed the total losses of water. The value of \( K_{sat} \) was also estimated from rising head slug tests in the piezometers at the base of the microcosms, using the Hvorslev rising-head slug test method (Baird, Eades, & Surridge, 2008). For three of the microcosms, the slug test gave a low \( K_{sat} \) ranging from 1.9E-7 to 5.3E-9 m s\(^{-1}\). For the SBM location, the hydraulic conductivity was found to be somewhat higher (1.5E-6 m s\(^{-1}\)), suggesting that the depth of the microcosms was sufficient that they were relatively well sealed from shallow lateral flow.

At two of the microcosms (SC and SBM), there seems to be evidence of preferential flow paths or cracks in the peat soil matrix as a result of inserting the microcosm collar. At these two collars, large additional water losses were observed up to 48 hours after large storm events, which could not be explained by a constant \( K_v \). To account for this in the microcosm water balance, additional losses as downward seepage were included when the daily water losses exceeded daily ET\( _0 \) by more than 2 mm and when a storm event of greater than 2 mm occurred within the previous 48 hours. This accounted for 2.6% and 7.3% of the of total time steps at the SBM and SC microcosms, respectively.

Due to the measurement limitations of the water table loggers (1 mm resolution), when the water table was near the transition between these increments, millimetre fluctuations occurred over subsequent hours. The effect of this type of noise was greatly reduced by applying a 3 hour moving average to the water table time series.

Although the water level loggers used in this study are generally stable, there were occasional noisy fluctuations (>1 mm) in the water table measurement, which typically occurred during periods of rapid changes in barometric pressure. These would result in additional apparent volumetric water gains and losses from the system. Inside the microcosms, noise was identified when the magnitude of both the daily inputs and daily losses exceeded the daily rainfall and ET\( _0 \), respectively, by more than 2 mm. In these cases, both the losses and inputs were reduced such that the 24 hour water balance remained unchanged. These adjustments were required for between 0.5 and 3.0% of the total number of time steps for the different microcosms.

Outside the microcosms, the volumetric fluctuations in storage were determined similarly after first taking a 3 hour moving average of the water table time series. The storage properties were assumed to be the same inside and outside the microcosms. (i.e., the storativity measured inside the microcosm was used both inside and outside the microcosms to calculate the volumetric fluctuations.) This was to eliminate potential errors in the storativity measurement due to the lateral losses or gains of water.

There are five main assumptions behind this method: (i) during rain events, the ET and vertical flux are negligible; (ii) the volume of water storage is a unique function of water table level; (iii) the storage properties are identical inside and outside the microcosm at adjacent locations; (iv) the water content profile within the unsaturated zone quickly attained static equilibrium following a rain event and (v) the difference between the water balance inside and outside a microcosm is entirely due to lateral flow, or can be quantified.

### 3 | RESULTS

#### 3.1 | Meteorological data

The mean monthly temperature over the study period ranged from 3.6°C in February 2018 to 17.8°C in July 2018 (Figure S1a). The expected seasonal pattern in ET follows the mean monthly temperature with a maximum daily ET\( _0 \) of 5.5 mm occurring in July 2017. Daily ET\( _0 \) was summed to calculate monthly ET\( _0 \), which showed good agreement with the reported potential evapotranspiration at the near-by Carlow (Oak Park) meteorological station \( (r^2 = 0.989, \text{ slope } = 1.005) \).

The monthly rainfall was higher than the average (2001–2017, the period of record) at the near-by Ballyroan rain gauging station during March, June and September 2017 and January–April 2018 (Figure S1b) while April 2017 and May–August 2018 were exceptionally dry. The annual precipitation in 2017 (966 mm) was somewhat higher than the 2001–2017 average of (847 mm) reported at the Ballyroan rain gauging station.

#### 3.2 | Water table data

The hourly water table outside the microcosms is shown in Figure S2 for 2017 and 2018. The water table at the SC location was lower relative to the Sphagnum/ground surface than the others because this stilling well is located in a tall Sphagnum hummock with >0.50 m of poorly decomposed Sphagnum over cutover peat soil. The minimum water table in 2017 at the SC location was 0.35 m below the ground surface. At the other locations, the water table remained within 0.15 m of the ground surface for almost all of 2017, dropping below this level only 15 days at the EC location and 2 days at the SBM location. During the drought of summer 2018, the water table fell to 0.34, 0.61, and 0.368 m below the ground surface at the EC, SC, and SBC locations, respectively.
The water table at the EC location exceeded the ground surface for 32% of the total study period, but rarely exceeded 10 mm above the ground surface. By contrast, the water table only exceeded the ground surface 1.7 and 2.4% of the total study period at the SBC and SBM locations, respectively.

3.3 | Storativity curves

The trend of measured storativity plotted against water table level is shown for all microcosms in Figure 3. When the water level is more than a few centimetres below the soil surface, the storativity is approximately constant with depth. This below-ground storativity is higher (0.28 and 0.41) at the sites with a continuous Sphagnum moss layer present than at the sites with a peat soil (0.12 and 0.15). Although the error in the storativity measurement increases near the ground surface due to the measurement limitations of the water level loggers, results are constrained by the assumption that the maximum value of storativity is 1 in the absence of lateral flow. The storativity curves are approximated by a set of linear regressions described in Equations (S1)–(S4) for each microcosm, respectively. The residuals around the lines in Figure 3 were further explored by normal probability plots, and the residuals appear to be normally distributed, except for some skew on the upper tail. The variance of the residuals was propagated through the season to estimate the confidence interval of seasonal water balance components, as in Table 2.

At the SBC and EC locations, the storativity (rainfall depth/water table rise) determined outside the microcosms was compared to the storativity measured inside the microcosms (Figure 4). The data from individual storm events was binned by the mean water table over the storm event into depth classes with respect to ground surface. When the mean water table was more than 40 mm below the ground surface, there was no significant difference in storativity inside vs. outside of the microcosms; this supports the assumption that the storage properties inside and outside of the microcosms were similar at these locations. When the mean water table was higher than 40 mm below the ground surface, the rainfall depth/water table rise ratio was significantly greater outside of the microcosms (Table S1); this indicates that when the water table is high, rapid lateral losses of water occur during storm events, as expected. 

![Storativity curves](image-url)
| Microcosm locations | Volumetric gains to microcosm | ET losses from microcosms | Downward flow | Net lateral flow | Change in storage | Volumetric gains to microcosm | ET losses from microcosms | Downward flow | Net lateral flow | Change in storage |
|--------------------|--------------------------------|---------------------------|----------------|-----------------|------------------|--------------------------------|---------------------------|----------------|-----------------|------------------|
| SC                 | 352                            | –97a                      | –              | –               | –                | 149b                           | –419b                     | –              | –               | –                |
| EC                 | 353d                           | –305d ± 17                | –16            | –56d ± 30       | –27              | 194                            | –197c ± 16               | –7             | –42c ± 28        | –53              |
| SBC                | 390                            | –20 ± 22                  | –7             | –13c           | –8               | 236                            | –277 ± 12                | –10            | 6 ± 22          | –44              |
| SBM                | 330                            | –49df ± 15                | –13f          | –              | –5               | –                              | –                         | –              | –               | –                |

Note: All units are to the nearest mm, with a negative sign convention indicating losses from the system. Also shown for comparison is the measured P, ET0, and the catchment scale discharge. More details on the extent of the catchment area can be found in Swenson et al. (2019). For the ET and net lateral flow, the “±” indicates the 95% confidence interval based on the propagation of error of the residuals in storativity. For each microcosm, the change in storage may be different from the sum of the water balance components due to rounding error.

aThe catchment area discharge was measured hourly at a weir gauging location. For 2018, –17.3 of the –33 mm of discharge occurred in the first 2 weeks of this period (April 10–24, 2018).
bRainfall data from the Carlow (Oak Park) weather station and is likely to be different from the actual rainfall at Abbeyleix due to spatial variation in rainfall. Also, ET0 is from potential evapotranspiration reported at Carlow (Oak Park) weather station.
cEstimated downward flow outside of the microcosms. Inside of the microcosms the downward losses of water were –33.7 and –87.1 mm for the SC and SMB location, respectively.
dSome data missing during this time period, for EC 3.1% of data missing due to the microcosm overflowing. For SMB location, 1.9% of data is missing because the outside WT logger ran out of batteries.
eAdjusted to account for reduced ET losses outside of the microcosm relative to inside of microcosms, estimated to be –18 mm.
fSome degree of uncertainty in this value due to vandalism to the stilling well. Resulting in a discrepancy between the water balance and change in storage.
The ground surface elevations inside and outside of the microcosms were not measured throughout this study as in (Schlotzhauer and Price (1999), which is a limitation of the data collected. Reviewing photographs of the microcosms, the ground surface fluctuations over the course of the study appear to remain within a centimetres approximately and the ground surface fluctuations appear similar inside and outside of the microcosms. Also, the ground surface fluctuations measured elsewhere in at the study site were quite small in comparison to many previous studies (i.e., from an usually wet period in January 2018 to an exceptional drought in July 2018, the ground surface changes measured on the bog at two locations were <50 mm).

3.4 Components of the water balance inside the microcosms

The experimental design of the microcosm experiments allowed all components of the water balance including shallow lateral flow to be determined at each of the sampling locations. The cumulative hourly aspects of the water balance are plotted together in Figure 5 and Figure S3 for summer 2017 and 2018, respectively. The seasonal components of the water balance over the summer period of 2017 and 2018 are summarized in Table 2.

The method for calculating the volumetric changes over time inside the microcosms can be checked by comparing the volumetric gains (calculated from storativity) with the measured rainfall in a cumulative mass balance. There was found to be good agreement ($r^2 = 0.9996$ for all microcosms) between the cumulative gains inside the microcosm and the cumulative rainfall (Figure 6a), with the gains in storage inside the microcosms closely matching the timing and magnitude of rainfall events (Figure 6b). The good agreement with the rainfall data suggests that this method (using storativity and water table changes to calculate volumetric fluctuations in storage) does accurately represent aspects of the water balance over time at this site. Over the period from April 1, 2017 to September 20, 2017, the total measured rainfall was 421.8 mm, and the total calculated inputs to the microcosms ranged from 395 mm at SBM to 440 mm at SBC, giving a relative error from −6.3 to +4.2%.

Based on the comparisons with the microcosm field data, the Penman-Montieth $\text{ET}_0$ for short reference grass crop gave a reasonable estimate of $\text{ET}$ during summer months (April–September) (a scaling factor of 1.0 on average) but greatly underestimated $\text{ET}$ during the winter months (October–March) (a scaling factor of 2.5 on average was required for $\text{ET}_0$). The $\text{ET}$ determined with the microcosm data were also used to calibrate the coefficient of evaporability ($\alpha$) for the Priestly-Taylor method. Again, the summer prediction of $\text{ET}$ is reasonable with an average summer $\alpha$ value of 1.3 and 1.0 for the locations with and without Sphagnum cover, respectively (Table S2). The $\alpha$ value for the winter months was on average 9.5, indicating that the Priestly-Taylor method grossly underestimated winter $\text{ET}$. It should be noted that the estimates of $\text{ET}$ during the winter months should be interpreted cautiously because there were numerous gaps in the data during the winter months when the microcosms overflowed.

During the drought period of 2018, a decrease in $\text{ET}$ was also observed at the EC and SBC locations. This decrease in $\text{ET}$ was more pronounced and occurred earlier at the EC location than at the SBC location. For example, the ratio of the measured monthly $\text{ET}$ in June 2018 compared to June 2017 was 0.67 and 0.89 for the EC and SBC locations, respectively. And, for July 2018 compared to July 2017, this ratio was 0.39 and 0.61 for the EC and SBC locations, respectively. The $\text{ET}$ rate was reduced at the EC location when the water table was approximately 100 mm below the ground surface, while at the SBC location, the $\text{ET}$ rate was not reduced until the water table fell to approximately 200 mm.

The vertical fluxes of water were also determined inside of each microcosm. The vertical hydraulic gradient was found to be linearly correlated ($r^2 = 0.60–0.90$) with the water table level for the four microcosms. The EC and SBC microcosms were found to be well sealed with low effective vertical hydraulic conductivity (0.1 mm h$^{-1}$). However, the SC and SBM microcosms were found to have much higher vertical hydraulic conductivities of 0.6 and 0.7 mm h$^{-1}$. This seems to be due to edge effects from peat compression or cracks in the peat soil matrix that were formed as a result of inserting the microcosm collar, because such large losses of water were not observed outside these microcosms. Thus, for the EC and SBC microcosms, the vertical downward seepage losses were a minor aspect of the water balance, at <5% of the total rainfall; for the SBM and SC microcosms the vertical downward seepage was a much larger aspect of the water balance accounting for 35 and 22% of the total rainfall, respectively.

3.5 Water table fluctuations and shallow lateral flow

Finally, the impact of shallow lateral flow on the microscale hydrology can be directly determined by subtracting the cumulative change in storage inside and outside of the microcosm. Cumulative net
lateral flow for the four sampling locations is shown in Figure 5c and Figure S3c for the April–August of 2017 and 2018, respectively. These four sampling locations have noticeable differences in the timing and magnitude of shallow net lateral flow, over both an unusually wet summer (2017) and an exceptionally dry summer (2018).

Over the summer months (April–August), the SBM and EC location consistently had net losses as lateral flow, with seasonal losses ranging from $-56$ to $-42$ mm, while the SC and SBC locations had net lateral flow near neutral ($-20$ to $+6$ mm). Based on the standard deviation of the residuals in Figure 3, the error of the calculated net lateral flow was propagated to compare the seasonal net lateral flow between these four sites. The differences in seasonal net lateral flow between the EC and SC location were significant ($p < .05$) in 2017, and marginally significant ($p < .1$) between the EC and SBC location in 2018.

During wet (winter) periods, the water table dropped more rapidly outside of the microcosms than inside of the microcosms after rainfall events because lateral flow resulted in net runoff losses when $P >> ET$. This was not necessarily the case during dry periods. In particular, during dry periods in spring and early summer, the water table decreased more rapidly inside than outside of the microcosms at the locations with a continuous Sphagnum moss layer (SC and SBC) (e.g., Figure S4a). Assuming that the other components of the water balance are equal inside and outside of the microcosms and similarity in storage properties, this observation indicates a net gain from lateral flow outside of the microcosm, mitigating evaporative losses. This trend was not observed at the two locations lacking Sphagnum moss (SBM and EC) (e.g., Figure S4b).

A few caveats for the net lateral flow presented in Figure 5c and Figure S3c should also be pointed out: Due to an act of vandalism in April 2017, the stilling well at the outside SBM location was pushed into the peat so that the top of the well screen was 20–30 mm below the surface of the peat. This was not noticed until November 2017 at which point it was re-levelled. However, this resulted in a delay in the water table rise relative to rainfall when the water table was at or near the ground surface. The overall hydrograph is reasonable, but the delay in timing becomes noticeable in the plot of the net lateral flow, resulting in an apparent dip following large rain events. Still, the general pattern of the net lateral flow at this location is quite similar to the EC location. Also, during the drought period of late May and early June 2018, the water table is initially higher inside the EC microcosm than outside. The soil moisture becomes low enough to limit ET

![Figure 5](image-url)
Menberu et al., 2016; Price et al., 2003) for humidified peat.

Equations S1

The values of sub-surface storativity found in this study (defined by linear regression for the period shown in Figure S3c. The locations with a Sphagnum moss layer (SBC and SC) had a higher ET than the locations with a peat soil (EC and SBM) by an average factor of 1.3, which is similar to the observations of Van Seters and Price (2001). The higher evapotranspiration from the Sphagnum surface compared to the peat may be attributed to the higher suction potential in the peat soil (Price, 1997). A substantial decrease in ET was observed at the EC and SBC location during the drought period of 2018, as expected from other studies (e.g., Kettridge & Waddington, 2014), although the ET rate at the SBC location was less affected by drought conditions than at the EC location. This shows that the EC location (with peat soil) more strongly regulates evaporative water losses during drought conditions than the SBC location (with a Sphagnum moss layer). Importantly, these observations may indicate that Sphagnum development increases ET, which would be a potential negative feedback loop inhibiting Sphagnum development on bare peat soil.

When compared with the microcosm data, the Penman-Monteith ET calculated for a short reference grass crop gave very similar ET to that measured with the microcosm during the summer but greatly underestimated ET during the winter months. Similarly, the Priestley-Taylor α values determined from the microcosms were comparable to previous studies in the summer (e.g., McCarter & Price, 2013), but during the winter months, were much higher than has previously been reported for peatlands.

4 | DISCUSSION

4.1 | Storativity and the WTF method

The values of sub-surface storativity found in this study (defined by Equations S1–S4) is similar to the values reported in previous studies (Menberu et al., 2016; Price et al., 2003) for Sphagnum moss and humidified peat.

The WTF method has been presented by recent studies (Bourgault et al., 2017; Dettmann & Bechtold, 2016) as a method to determine storage properties at field locations in peatlands. A major assumption of the WTF method is that volumetric changes at a particular location are equivalent to rainfall, and that lateral gains/losses are negligible during a storm event. During storm events when the water table was near the ground surface (within 40 mm), the lateral losses outside of microcosm significantly increased the ratio of rainfall depth to water table rise. This was true even for SBC location with quite a low surface gradient (0.18 ± 0.03%).

Hence, the data presented here would suggest that the assumption of negligible lateral flow during storm events (i.e., Dettmann & Bechtold, 2016) is not always true. The WTF method should thus be used with this limitation in mind. For example, Bourgault et al. (2017) note that storativity measured by the WTF method could be affected by “input from uphill or from the redistribution of precipitation within the peatland.” If there are lateral losses or gains of water, the apparent property determined by the ratio of rainfall depth to water table rise is a fundamentally different quantity than storage. It is thus valuable to quantify both the storativity and the net lateral flow separately, as done here.

4.2 | Evapotranspiration

The locations with a Sphagnum moss layer (SBC and SC) had a higher ET than the locations with a peat soil (EC and SBM) by an average factor of 1.3, which is similar to the observations of Van Seters and Price (2001). The higher evapotranspiration from the Sphagnum surface compared to the peat may be attributed to the higher suction potential in the peat soil (Price, 1997). A substantial decrease in ET was observed at the EC and SBC location during the drought period of 2018, as expected from other studies (e.g., Kettridge & Waddington, 2014), although the ET rate at the SBC location was less affected by drought conditions than at the EC location. This shows that the EC location (with peat soil) more strongly regulates evaporative water losses during drought conditions than the SBC location (with a Sphagnum moss layer). Importantly, these observations may indicate that Sphagnum development increases ET, which would be a potential negative feedback loop inhibiting Sphagnum development on bare peat soil.

When compared with the microcosm data, the Penman-Monteith ET calculated for a short reference grass crop gave very similar ET to that measured with the microcosm during the summer but greatly underestimated ET during the winter months. Similarly, the Priestley-Taylor α values determined from the microcosms were comparable to previous studies in the summer (e.g., McCarter & Price, 2013), but during the winter months, were much higher than has previously been reported for peatlands.

4.3 | Shallow lateral flow with the microcosm design

Few studies (if any) have successfully measured the timing and magnitude of net lateral flow at particular locations in a peatland on a short
time step, although two studies (Ingram, Coupar, & Bragg, 2001; Kelemen & Ingram, 1999) quantified the net lateral flow on a longer (10 or 15 day) time interval using "bottomless lysimeters" (Kelemen & Ingram, 1999), somewhat similar to the microcosms used here.

A few limitations of this study should be pointed out. The results are from a single replicate of each of four quite different locations throughout the study site. A more systematic test of this method would be a valuable addition for future research, with multiple microcosm replicates closely spaced together to account for the spatial heterogeneity of peatlands. Also, measuring hydro-physical properties inside and outside of the microcosms as well as prior to installation could help validate the inside-outside comparison. Still, the comparison of rainfall depth to water table rise does give some evidence that the storage properties were the same inside and outside of the microcosms. Also, the close physical proximity of measurements inside and outside of the microcosms and the intentional matching of the outside locations to the microtopography and ecology supports the assumption that physical characteristics inside and outside of the microcosms are similar.

One of the advantages of this method is its simplicity, in which water storage is uniquely related to the fluctuations in water table. The comparison of the microcosm data to measured rainfall and (in the summer months) calculated ET show that this method does capture these components of the water balance with reasonable accuracy and supports the use of water table as simple proxy of storage changes at this site. All microcosm locations in this study had a shallow water table, which responded rapidly to rainfall; the method presented here would break down if this were not the case. Although the comparison of the microcosm data to measured rainfall is reasonably close, the error in the soil water storage could probably be reduced by including other variables such as soil moisture in the unsaturated zone or peat compressibility.

In this study, the standing vegetation was low and sparse, and the interception losses were assumed negligible. This assumption may result in a slight over estimate in the storativity values and a corresponding overestimate in the calculated water balance components. By contrast, the peat compression and expansion may cause an underestimate of the storativity. These errors apply equally inside and outside of the microcosm, so the overall conclusions would remain unchanged, even if they affect magnitude of the water balance components.

With these limitations in mind, a few examples are given below demonstrating the utility of this method and the spatial variability of lateral flow in a recovering raised bog.

### 4.4 Examples of the application of the microcosm method and spatial variability of shallow lateral flow

As an example of the spatial variability of net lateral flow, two storm events during June and July of 2017 are considered at the SC and EC location (Figure 7a,b). Inside the microcosms at both locations, the cumulative change in storage closely matches the cumulative rainfall over the rainfall events. By contrast, outside of the microcosms the cumulative change in storage is much larger than the cumulative rainfall over the rainfall event, indicating additional inputs as lateral flow. At the EC location, this additional input is quickly lost again such that the cumulative change in storage drops below that inside of the microcosm within 24 hours. At the SBC location, the additional lateral flow

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**FIGURE 7** Cumulative changes in storage (mm) inside and outside the microcosms plotted together with the cumulative rainfall for rainfall events occurring on (a) June 26, 2017, and (b) July 19–21, 2017 and (c) for January 2018. For (c), the cumulative change in storage outside the microcosms is shown for the EC, SBC, and SC locations and for comparison, inside the EC microcosm. The gap in the data inside the EC microcosm is due to overflowing of the microcosm collar.
inputs are initially delayed with respect to rainfall followed by a change in storage much larger than the total rainfall. This pattern of lateral inputs at the SC location is not surprising given its topographic location. As the site history of peat extraction are identical at the EC and SC locations, these differences in lateral flow can help explain the successful development of Sphagnum moss at the SC location but not at the EC location. Thus, the heterogeneous Sphagnum development on the cutover bog seems to be supported by lateral flow intercepted from a larger catchment area, which counter-balances the losses due to a somewhat steeper slope (0.5–0.6%) than areas where successful Sphagnum development occurred on the raised bog.

Additionally, the short term volumetric fluctuations in water storage outside the microcosms are useful for understanding the hydrological response to storm events during wet (winter) periods at different locations in the bog. For example, this comparison is shown for the exceptionally wet period of January 2018 for the EC, SC, and SBC locations (Figure 7c). Again, the cumulative change in storage inside of the EC microcosm matches closely with the cumulative rainfall (except for when it overflowed). Outside of the microcosms, the cumulative change in storage was much smaller than rainfall. For example, during the storm event on January 21, 2018, 37.1 mm of rainfall fell and the changes in storage outside of the microcosm were 10.1, 16.6, and 31.3 mm at the EC, SC, and SBC locations, respectively. This demonstrates that rapid losses of water occurred outside of the microcosm over the course of the rainfall event. The differences between these locations is interesting. The SBC location initially retains much more of the storm water than the EC location, despite the fact that the EC location has a steeper surface slope (0.67%) than the SBC location (0.18%).

A Sphagnum moss layer has much higher hydraulic conductivity and sub-surface transmissivity compared to a well-decomposed peat soil (Boelter, 1968; McCarter & Price, 2015). Interestingly, this seems to result in more initial retention of storm water during wet periods in locations with a Sphagnum layer because shallow sub-surface flow is the predominant flow path while locations with peat soil have overland flow as the predominant flow path. The increased storm water retention is also due to the higher near surface storage in Sphagnum moss. At the locations with a continuous Sphagnum moss layer, the higher sub-surface hydraulic conductivity means that more water is lost between rainfall events than at the EC location, resulting in more available storage for the subsequent rainfall. By contrast, at the EC location, water appears to be rapidly lost via overland flow when a surface ponding threshold is exceeded (approx. 10 mm above the ground surface), while very little water is lost as lateral flow when the water table drops below this level. These results demonstrate that, even during very wet periods, the presence of a continuous Sphagnum moss layer can delay the rainfall-runoff response, which has important implications for understanding flood attenuation for intact and degraded bogs. These findings generally agree with previous observations; for example, catchment runoff from intact or restored bogs with an interconnected Sphagnum layer has been observed to be lower than from degraded bogs with a peat surface soil (McCarter & Price, 2013; Shantz & Price, 2006).

In this study, there are noticeable differences in the timing and magnitude of the net lateral flows at these four locations (Figures 5c and S3c), which have differences in recovering plant ecology. At times, particularly during spring and early summer, locations with a continuous Sphagnum layer (SC and SBC) were observed to receive a small net input from lateral flow during dry periods, which helped sustain surface soil moisture. These findings suggest that internal redistribution of water within a peatland due to shallow lateral flow improves drought resilience where an interconnected Sphagnum moss layer is present. This seems to be the case even for the SBC location, with a relatively small upstream catchment area. Presumably, systems with a larger upstream contributing area would have more drought resilience provided by lateral flow, as hypothesized by Kopf et al. (2013).

This type of slow lateral flow through the shallow Sphagnum surface agrees with previous observations (e.g., Hoag & Price, 1995), and the results here are similar to Ingram et al. (2001) who also report net gains from shallow lateral flow during dry summer periods, at 3 of 4 locations in a bog in Scotland. This is an important point because a number of previous studies (e.g., Waddington et al., 2015) have implied that lateral flow results only in losses of water from bog systems. Except for at the crest of a raised bog, the shallow lateral flow can account for both net gains and net losses of water at various time periods. Indeed, if there is any flow, and there are net evaporative water losses along a flow path, then conceptually for a given section of the flow path, the lateral inflows must exceed the lateral outflows, resulting in a net gain from lateral flow.

Previous studies (McCarter & Price, 2013; McCarter & Price, 2015; Sherwood et al., 2013) have demonstrated how the development of a Sphagnum layer over an older peat soil results in changes to the hydro-physical properties, which increases the storage properties and impacts the vertical flux of water.

The results from this study suggest that the development of a Sphagnum layer can also impact the timing and magnitude of lateral flow as part of a positive feedback loop of Sphagnum development. As a Sphagnum moss layer develops, the higher storativity and hydraulic conductivity compared to peat soil allows for more water to be retained initially, and then, subsequently distributed throughout the system.

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**DATA AVAILABILITY STATEMENT**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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