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Hydrologic-based modelling of burn depth potentials in degraded peat soils

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Abstract

Peatland drainage may degrade system resilience to high intensity, soil-consuming fires. Peat soil fires are unique in that they can smoulder vertically through the soil column, with a multitude of consequences including large carbon emissions, altered hydrology, and dramatic shifts in vegetation communities. In this work we developed and verified a new method to model peat burn depths with readily available water level and peat hydraulic property data at the Great Dismal Swamp National Wildlife Refuge (VA and NC, USA). To model peat burn depths across 11 sites in the Great Dismal Swamp National Wildlife Refuge we combined water table time series data and soil moisture release curves, developed at multiple depths, with moisture-to-ignition thresholds. A subset of the results from this empirical modelling approach of peat burn depth severity were compared against those made using a mechanistic model of soil moisture, HYDRUS 1-D. By comparing modelled burn depth potentials between these two approaches for a range of peats, we confirmed that our simpler, water table-based approach had similar performance to HYDRUS 1-D in drained and degraded peats, like those found in the Great Dismal Swamp National Wildlife Refuge. A comparative analysis of modelled burn depths across our study site found that water table position and peat water holding capacity were the key governing controls on burn depth potential. Our findings suggest that drainage weakens both short- and long-term controls on peat burn depths by reducing soil moisture and by decreasing peat water holding capacity. This new approach offers land managers with an additional tool for assessing risk while offering insight into the drivers of peatland wildfire severity.

KEYWORDS
fire, great dismal swamp, hydrology, HYDRUS-1D, modelling, peat

1 | INTRODUCTION

Peatlands are a diverse set of wetland ecosystems characterized by saturated soils and high levels of soil organic matter. Supplying a wide variety of important ecosystem services, peatlands improve water quality, provide water storage, and support a diverse array of flora and fauna (Zedler & Kercher, 2005). The deep organic soils that characterize peatlands develop as net primary productivity outpaces decomposition, which is limited due to anaerobic conditions and enzymatic constraints (Freeman et al., 2001; Limpens et al., 2008). Consequently, peatlands are major carbon (C) sinks, with northern circumpolar zones alone storing 1460 to 1600 Pg C, or approximately twice the amount of C in the atmosphere (USGCRP, 2018). In North America, many peatlands were drained for expanding development and agriculture, with an estimated 14.1% of peatlands in the contiguous United States degraded by the mid-1990s (Joosten, 2010). Decades of drainage have resulted in increased soil oxidation, altered vegetation communities, and, importantly, greater fire risk (Holden et al., 2004; Paal et al., 2016; Page & Baird, 2016; Poulter et al., 2006).

While periodic surface fires are normal in peatlands, threats to peatland resilience arise as fire severity increases. Compared to other ecosystems, fires in peatlands are unique in that they can smoulder vertically down within the soil column, burning considerable quantities of organic matter (Hawbaker et al., 2016; Reardon et al., 2007). Particularly severe smouldering fires can consume up to 2 m of peat vertically and can burn for months (Drexler et al., 2017; Sleeter et al., 2017; Turetsky et al., 2015). The deeper a peat-consuming fire burns, the larger the C emissions (Poulter et al., 2006). High severity fires can reduce a system's long-term potential for C sequestration (Pindilli et al., 2018; Rein, 2015) as they release centuries worth of C (Kuhry, 1994; Sleeter et al., 2017; Turetsky et al., 2015). Beyond these global C implications, high severity burns also have dramatic local impacts, as they can vastly alter local topography and therefore hydrology (Watts et al., 2015). Deep burns also remove vegetation, seeds, and buds both above and below ground thereby influencing the plant community that returns (Matlaga et al., 2010). As such, land managers are increasingly interested in peatland fire prevention via hydrologic restoration (Fire Environment Working Group, 2009). Land managers have also expressed interest about peatland fire prediction tools that would help identify high risk areas. Both prediction and prevention efforts would benefit from an improved understanding of the drivers of peat fire severity and potential predictions thereof.

High peat moisture content reduces flammability and diminishes fire spread (Prat-Guitart et al., 2016; Reardon et al., 2007). Therefore, both potential for ignition and depth of peat consumption are directly dependent on dynamic soil moisture regimes. Soil moisture profiles in peatlands are controlled by both hydrologic inputs and outputs as well as soil hydraulic properties. Draining a peatland has clear short-term implications for flammability as it increases the amount of peat exposed to aerobic conditions, thus reducing soil moisture, and increasing potential for ignition (Reardon et al., 2007; Schulte et al., 2019). Sustained drainage can also impact a variety of soil hydraulic properties (e.g., water retention properties, capillary lengths, pore size distributions, and hydraulic conductivities) (Schwärzel et al., 2002; Word et al., 2022) and may therefore act as a persistent influence on soil moisture regimes and flammability. Beyond the influence of drainage, these soil hydraulic properties differ both between peatlands and also within peatlands both laterally and vertically (Benscoter et al., 2011) and may be impacted by hydrologic restoration efforts. The variation in soil hydraulic properties indicates that there may be similar variability in soil moisture regimes and associated smouldering fire risk among and within sites.

Predicting peat fire risk spatially and temporally then requires site-specific knowledge of soil moisture thresholds for ignition along with soil moisture observations, or predictions based on soil hydraulic properties and hydroclimatic forcing. Schulte et al. (2019) quantified site-specific soil-moisture thresholds for peat ignition and developed soil moisture release curves (MRCs), which relate tension (i.e., soil water pressure potential) to moisture content. By combining these two properties, they made temporal predictions of smouldering ignition probability from water table time series at four sites. Those predictions, however, were limited to surface ignitions as they relied upon MRCs developed using surface samples. Characterizing the heterogeneity of peat properties at multiple depths would enable predictions of the moisture profile throughout the vadose zone, thereby allowing for depth of burn predictions.

The water table-based models of soil moisture made by Schulte et al. (2019) also operated under the unverified assumption that soil water in the peat profile rapidly returned to a resting state (i.e., hydrostatic equilibrium). If a peat profile is in hydrostatic equilibrium, then the negative tension driven by the relative position of the water table is the only dynamic factor influencing the overlying soil moisture profile. That assumption may be inappropriate in systems where soil water redistribution is slow, as is the case in soils with low hydraulic conductivities (Dingman, 2015). To evaluate the limits of this assumption, simultaneous predictions of burn depth potentials made by the method employed in Schulte et al. (2019) and by process-based models soil moisture models, such as HYDRUS-1D (Šimůnek et al., 2006), could be compared. Previous studies in northern peatlands have used HYDRUS to model hydrology in peat with notable successes (see Kettridge et al., 2015; Mccarter & Price, 2014; Price & Whittington, 2010).

An assessment in this way would allow for a robust appraisement of situations where the assumption of rapid hydrostatic equilibration is, or is not, met.

Our first objective in this study was to predict smouldering depth potential, both spatially and temporally, in a drained, temperate peatland: The Great Dismal Swamp National Wildlife Refuge, located in Virginia and North Carolina, USA (Figure 1). Our approach to meet this objective was to: (i) compare burn depth potentials of a water table-based approach that assumes rapid hydrostatic equilibration against those generated using HYDRUS and (ii) employ the water table-based approach, if appropriate, to predict smouldering depth potentials over time (April 2017–September 2019) at 11 sites across the Great Dismal Swamp National Wildlife Refuge. The second objective of our study was to explore how historical drainage affects contemporary peat fire risk via changes in hydrology and soil hydraulic properties.

2 | MATERIALS AND METHODS

2.1 | Study area

The Great Dismal Swamp (hereafter GDS) is a 75 000 ha palustrine, forested peatland in the coastal plain ecoregion of southeastern Virginia and northeastern North Carolina, USA (36°35′49″N, 76°29′26″W). GDS is managed cooperatively between the U.S. Fish and Wildlife Service's Great Dismal Swamp National Wildlife Refuge

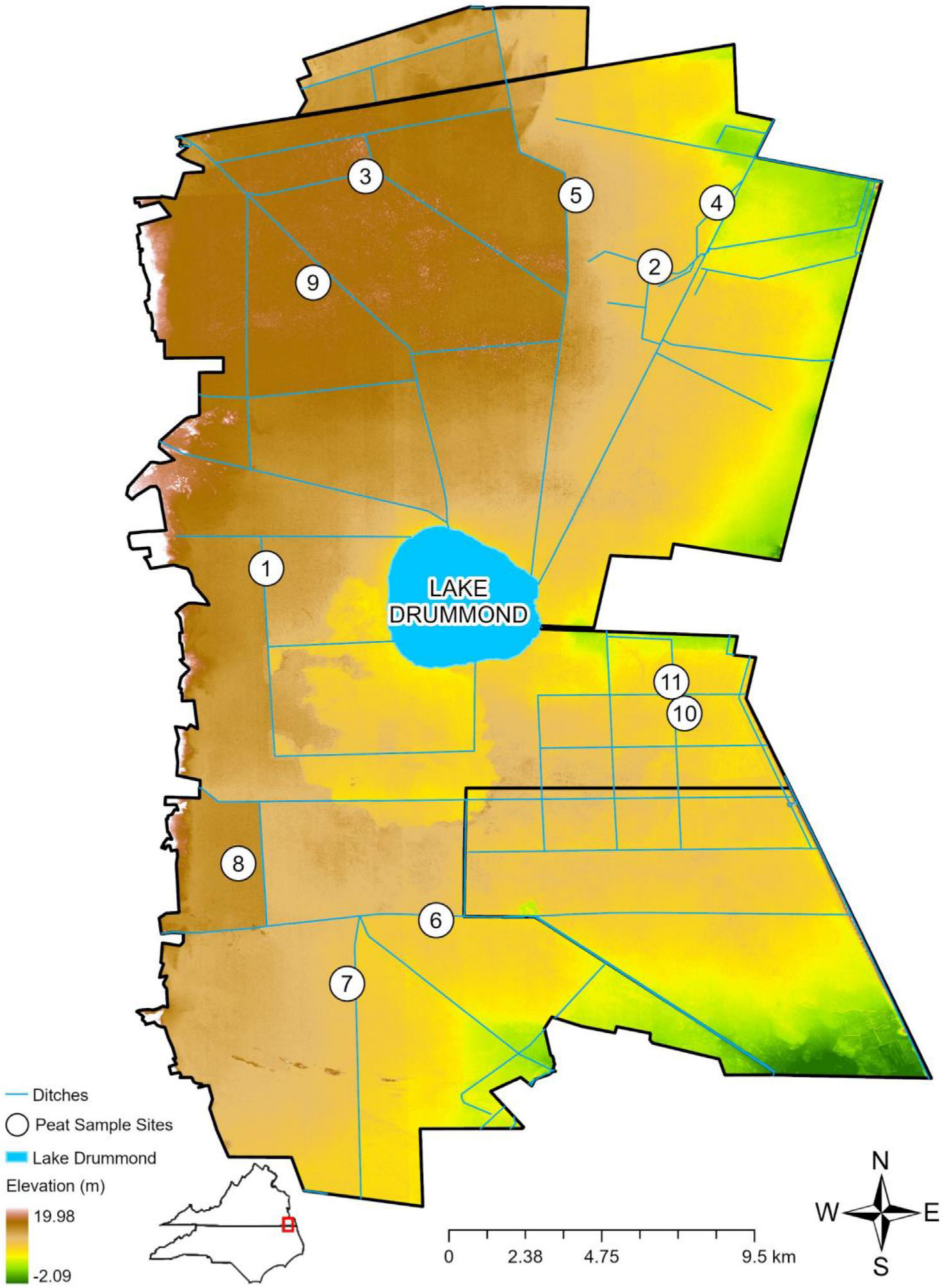

FIGURE 1 Location of the Great Dismal Swamp in Virginia and North Carolina, USA. Peat sample locations and drainage ditches noted

and the Great Dismal Swamp State Park of North Carolina (National Wildlife Refuge boundaries shown in Figure 1). Characterized by a temperate climate, the summers are hot and humid, and the winters are mild. GDS is largely rain-fed, with a mean annual precipitation of 116.2 cm (USFWS, 2006), which accounts for 92% of all hydrologic inputs (Eggleston et al., 2018). The main output is evapotranspiration, at an annual rate of 81.3 cm (USFWS, 2006) which accounts for more than half of all hydrologic outputs (Eggleston et al., 2018). The water table in the Dismal Swamp fluctuates seasonally with changing precipitation patterns and evapotranspiration rates. Annually, the water table fluctuates approximately 60 cm between the seasonal high and low water level. Highest water levels are typically in February and March before tree leaf-out at the beginning of the growing season. Lowest annual water levels are typically in August and September, prior to leaf-off (Speiran & Wurster, 2020). Early sections of the 144-mile drainage ditch network that bisects GDS were famously surveyed by George Washington prior to the Revolutionary War in the late 18th century (Hansen, 2010). However, the majority of the existing ditch network was constructed in the 1950s and 1960s to lower water tables and facilitate logging operations (Eggleston et al., 2018; Speiran & Wurster, 2020). Formerly a species-rich mosaic of forested wetland community types, GDS is now dominated by maple-gum forests (*Acer rubrum*—*Nyssa spp*.) with a less significant contribution from wetland obligates such as bald-cypress (*Taxodium distichum*) and Atlantic white-cedar (*Chamaecyparis thyoides*) (Ludwig et al., 2021). Drainage has lowered the water tables, which has likely contributed to increased smouldering fire vulnerability, as evidenced by two recent major wildfires. The 2008 South One and 2011 Lateral West Fires, burned 1800 ha and 2500 ha respectively and released a combined 1.83 Tg C (Hawbaker et al., 2016). The 2011 fire burned down 47 cm into the peat on average (Reddy et al., 2015). In response, the US Fish and Wildlife Service currently operates water control structures in the ditch network to slow drainage and stabilize the water table. Those hydrologic restoration efforts are aimed at supporting increased C sequestration, restoring historical forest communities, and reducing vulnerability to deep, smouldering fires (Balentine, 2020).

2.2 | Study sites and peat properties

GDS is commonly referred to as a peatland based on the general definition as a wetland system with a Histosol greater than 40 cm in depth (Joosten & Clarke, 2002). Hereafter, we refer to the organic rich soils found in GDS as peats. The sapric peats of GDS often have two physically distinct strata with mineral soils underlying them and occasionally occurring at the surface (Natural Resources Conservation Service, 2021). The upper layer has lower organic matter and fibre contents, higher bulk densities, and lower water retention properties than the lower layer. Differences between the two layers are attributed to a history of prolonged peat drainage, as the upper layers are more regularly exposed to aerobic conditions than the lower layers (Word et al., 2022).

We acquired previously collected water table data and peat properties for 11 sites across GDS (site locations indicated in Figure 1). Water table dynamics were monitored at each site with one vented, submersible, pressure transducer (either Campbell Scientific CS 450, Campbell Scientific, Logan, UT, USA; In-Situ Level Troll 500, In-Situ Inc., Fort Collins, CO, USA; or KPSI 500; Pressure Systems Inc., Newport News, VA, USA) that collected continuous, hourly data from 27 April 2017 through 17 September 2019. Previous work by Word et al. (2022) collected peat cores from each site and measured both total thickness and thickness of each individual stratum (hereafter Upper and Lower Peat). Samples were analysed to develop MRCs that relate soil moisture (as percent saturation) to matric potential, expressed as positive tensions. Specific details on laboratory procedures and the development of soil MRCs can be found in Word et al. (2022) and are briefly described here. For each of the 11 sites, MRCs were developed for individual samples at the 25th, 50th and 75th depth percentiles of each observed stratum, with a maximum of six depth samples per site (i.e., Upper-1, Upper-2, Upper-3, Lower-1, Lower-2, and Lower-3). In situations where a stratum was <40 cm thick, a single depth sample at the layer midpoint (50th depth percentile) was collected. For each depth sample, multiple tensions were applied using the tension table approach for low tensions (<6 kPa) and pressure plate approach for higher tensions (>33 kPa). By relating these applied tensions to their corresponding measured soil moisture values, MRCs were developed for each depth sample using the Brooks and Corey (1964) model for water retention.

We also took advantage of soil moisture content thresholds for 50% smouldering probability ($s_{smolder}$) that were previously developed for three GDS locations with organic soils (see Schulte et al., 2019 for details). The highest percent saturation that allowed for ignition was used as a threshold value in the calculations of burn depth potentials for both the water table-based and HYDRUS approaches described below. We held the threshold value constant across our sites to isolate the impact variable hydrology and soil hydraulic properties had on variation in wildland fire risk.

2.3 | Water table-based method versus HYDRUS for burn depth predictions

2.3.1 | HYDRUS

HYDRUS models a one-dimensional soil moisture profile by solving the Richards equation for unsaturated flow (Richards, 1931) given meteorological and soil property inputs (Šimůnek et al., 2006). We determined hourly burn depth potentials in the HYDRUS models as the shallowest point greater than the $s_{smolder}$ threshold. We modelled burn depth potentials with this process-based model of soil water redistribution to evaluate the accuracy of the water table-based method and the limits of the assumption of hydrostatic equilibrium. HYDRUS was used as a benchmark as it has been shown to be a good model of soil moisture in peats (Price & Whittington, 2010).

HYDRUS model parameters such as residual soil water content, saturated soil water content, pore size index, and bubbling pressure from Word et al. (2022) and saturated hydraulic conductivity (K_{sat}) values from Eggleston et al. (2018) were used to model soil profiles. The one-dimensional profiles were evenly discretized to reflect the number and depth of samples reported at each site. All HYDRUS models had a 0.25 cm depth resolution. We gathered meteorological data from a weather station located at Suffolk Executive Airport, approximately 4.5 km west of GDS. We used atmospheric boundary conditions with a surface layer up to 10 m for the upper boundary condition in HYDRUS and constant flux of 0 for the lower boundary condition.

To ensure that our models in HYDRUS were accurately representing soil moisture profiles in our system, we calibrated hourly modelled water table positions against corresponding water table observations at a single site (Site 9). The model was calibrated to data from Site 9 because it has an intermediate soil capillary length (here used as a singular value to quantify water retention capacity) within the Upper Peat samples (Figure 2a). Along with hourly precipitation amounts, meteorological data were used to calculate hourly evapotranspiration rates (ET) using the Penman-Monteith (1965) equation. Adjustments to ET were made to account for differences between potential evapotranspiration (PET) and ET via the crop coefficient method (Allen et al., 1998). Adjustments to precipitation were made to factor in losses due to canopy interception. Our calibration approach was to tune ET and interception adjustment factors in our Site 9 model in order to maximize the coefficient of determination

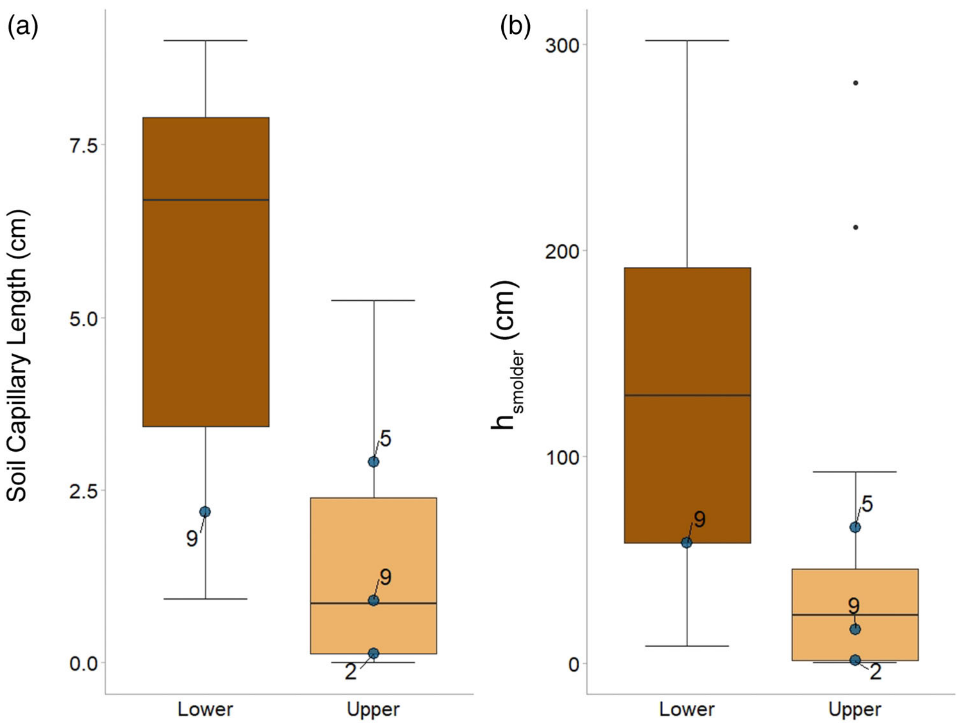

FIGURE 2 (a)) Comparison of the Upper and Lower Peat soil capillary lengths for the 11 sites. (b) Comparison of the Upper and Lower Peat tension-to-ignition ($h_{smolder}$, cm) values for the 11 sites. Specific values for Sites 2, 5 and 9 from Upper-1 and Lower-1 samples labelled where present

between hourly HYDRUS predicted water table positions and water table observations at Site 9 for a 7-week modelling period (16 June 2017–02 September 2017). We evaluated the final meteorological calibration values against regionally specific measurements for both the ET to PET ratio (Barclay Shoemaker & Sumner, 2006; Drexler et al., 2004; German, 2000) and interception (Bryant et al., 2005) to ensure their appropriateness. These meteorological calibration factors were applied uniformly to all subsequent HYDRUS models.

Following calibration of meteorological factors, we generated HYDRUS models for three sites (Sites 2, 5 and 9) for a 7-week modelling period (16 June 2017–02 September 2017). These 3 sites represented a broad range of Upper Peat soil capillary lengths and therefore water retention properties (Figure 2a). We focused on capturing the range in water retentions because hydraulic properties were expected to largely determine the limits of the assumption of hydrostatic equilibrium and thus the appropriateness of the water table-based approach (described below) or the necessity for the usage of HYDRUS. Additionally, the sensitivity of the HYDRUS models to K_{sat} values was explored, since site-specific K_{sat} values were not measured in Word et al. (2022) and we instead used mean fitted parameters from Eggleston et al. (2018): 1678.9 cm/h in Upper Peats and 30.48 cm/h in Lower Peats. We generated HYDRUS models for Sites 2, 5 and 9 with both the K_{sat} typical of their stratum position, and with the entire profile having Lower Peat K_{sat}, which allowed us to evaluate the sensitivity of our modelled profiles to variable K_{sat} values.

To expand beyond our study system and further test the limits of the assumption of hydrostatic equilibrium, we generated HYDRUS models using reported hydraulic properties and K_{sat} values from three different peat types. These three peats were a moderately decomposed woody peat (MDWP) and an undecomposed moss peat (UMP) from Verry et al. (2011) and a fen peat (FP) from Simhayov et al. (2018). The models were run using the same 7-weeks of meteorological data applied at the GDS sites.

2.3.2 | Water table-based method

Assuming hydrostatic equilibrium, we determined burn depth potentials as the closest height above the water table that exceeded the tension required to reach $s_{smolder}$ ($h_{smolder}$, cm) for each depth sample at each site (see example of $h_{smolder}$ in Figure 4c). For each depth sample at the six sites modelled in HYDRUS (Sites 2, 5, 9, MDWP, UMP, and FP), $h_{smolder}$ was derived from their MRCs (Figure 2b). The soil profiles for the water table-based method were evenly discretized, as in the HYDRUS approach to reflect the number of depth samples and their depths collected at each site. Burn depth potentials could not skip across depth sample layers (i.e., if a modelled burn did not move through the entirety of Upper-1, it could not reignite in Upper-2, even if a position in Upper-2 was further from the water table than $h_{smolder}$ for that depth sample).

2.3.3 | Comparison between water table-based and HYDRUS methods

To enable a direct comparison between the two methods, we estimated burn depth potential with the water table-based approach using the HYDRUS-simulated water tables at all modelled sites. We used the HYDRUS-simulated water tables because Sites 2 and 5 had water table observations above ground surface for the duration of the

7-week modelling period. To ensure that simulations would be under a threat of burning, we set initial water table depths equal to the initial observation depth for Site 9 or $h_{smolder}$ for each site's Upper-1 sample, whichever was deeper, to correct for water table observations that were above the ground surface during the model period. By taking this approach, we systematically generated initial conditions for our sites and the three peats from the literature. Hourly modelled burn depth potentials from the two different approaches were compared for each modelled peat using Spearman's correlation analyses. We also compared the frequency of burn events between methods. Difference in hourly burn depth predictions (Δ_{burn}) were calculated to separately assess periods when HYDRUS predicted greater ($+\Delta_{burn}$) or shallower burn depths ($-\Delta_{burn}$) than the water table-based method (see example in Figure 4c). Results from this analysis allowed us to identify situations in which peat properties or climatic events rebuke the necessary assumption of rapid hydrostatic equilibration for the water table-based method, thus indicating that the HYDRUS approach may be more appropriate.

2.4 | Simulating burn depth potentials across sites

In comparing burn depth simulations from the two approaches, we found that the water-table based approach was reasonable for our Upper Peats. Thus, we applied the simpler water table-based approach across all 11 sites to compare burn depth potentials for the entire water table record (27 April 2017–17 September 2019). Differences among sites was assessed using a non-parametric Kruskal–Wallis test and a pair-wise, post-hoc Wilcoxon rank sum test ($\alpha = 0.05$).

To better understand the factors that influence burn risk, we conducted correlation analyses between site-mean burn depths and site variables. We identified surrogate variables for short- and long-term controls, specifically mean water table position for short-term and soil capillary length as an indicator for long-term. Soil capillary length was calculated via our MRCs following Stewart and Najm (2018). This metric was chosen as it is a single parameter that captures moisture release functions in soils. Additionally, we tested for collinearity between these site variables since hydrology explained much of the variation between the hydraulic properties of peats in Word et al. (2022). We ran either Spearman's rank correlation or simple linear regression, depending on the shape of the relationship, and calculated the coefficients of determination. All statistical tests and comparisons were done in R 4.0.2 (R Core Team, 2020).

3 | RESULTS

3.1 | Water table-based method versus HYDRUS for burn depth predictions

Calibration of HYDRUS modelled water tables to observed water levels at Site 9, was optimized by setting the ratio of ET to PET at 80% and interception loss at 0.11 cm, (Figure 3b, $R^2 = 0.93$). This strong correlation coefficient provided confidence that HYDRUS applications would accurately represent the soil moisture profiles at other GDS sites. The minor disagreement between the observed and modelled values is likely due to the heterogeneity of precipitation events over such a large area, as evidenced by the mismatch of initial water table increases around the 1000 h mark and the magnitude around the 600 h mark (Figure 3a).

The six peats chosen for model comparison varied in their hydraulic properties, namely $h_{smolder}$ and K_{sat}, with noticeable influences on the degree of divergence between methods (Δ_{burn}) and the frequency at which they were under threat of burning (Table 1). When modelled with the K_{sat} values that corresponded with their stratum, Sites 2, 5 and 9 all had a close agreement between methods (median $\pm\Delta_{burn}$ values <1 cm, ρ-values ≥0.94). The strong degree of correlation is

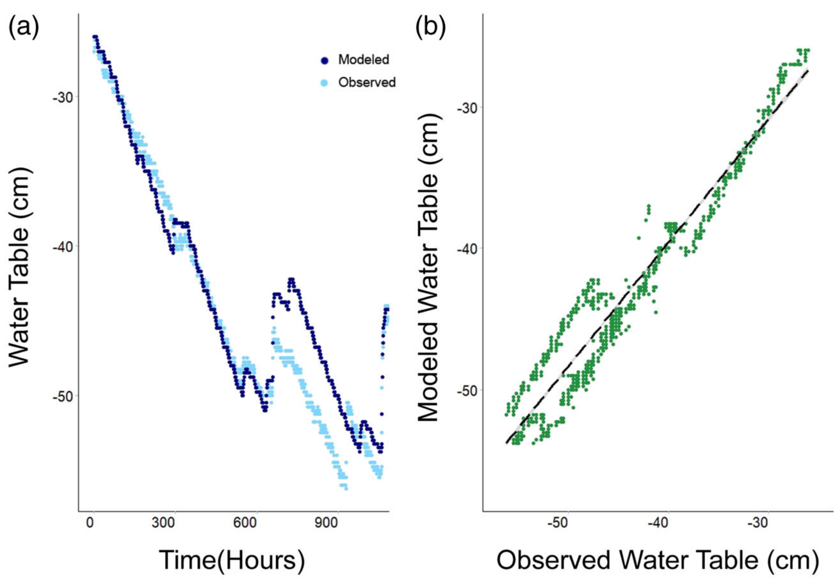

FIGURE 3 (a) Modelled and observed hourly water tables relative to ground surface for Site 9. (b) Modelled versus observed water tables for Site 9, dashed black line is a line of best fit ($R^2 = 0.93$)

TABLE 1 Comparisons between modelled burn depth potentials from HYDRUS and water table-based methods

Peat	$h_{smolder}$ (cm)	K_{sat} (cm/h)	Burn depth ρ	$+\Delta_{burn}$ (cm)	$-\Delta_{burn}$ (cm)	% time at burn risk via HYDRUS
Site 2	1.00	1678.9	1.00	0.3 (0)	0 (0)	100
Site 2	1.00	30.48	1.00	0.3 (0)	0 (0.7)	99.7
Site 9	16.15	1678.9	0.99	0.2 (0.1)	0.1 (0.7)	99.8
Site 9	16.15	30.48	0.88	1.4 (0.5)	0.9 (4.2)	96.0
Site 5	65.66	1678.9	0.94	0.7 (0.8)	0.1 (3.1)	98.3
Site 5	65.66	30.48	0.38	13.4 (3.2)	8.3 (5.0)	90.7
MDWP	60.34	17.86	0.75	4.1 (1.6)	3.2 (6.3)	95.7
UMP	1.71	137.16	0.99	0.2 (0)	0 (0)	100
FP	84.85	106	0.92	0.6 (0.6)	0.8 (3.8)	98.1

Note: Reported $h_{smolder}$ is for the Upper-1 samples, and Upper Peat K_{sat} is listed for sites with multiple stratum. Spearman's ρ from the correlation between burn depth predictions are noted. Δ_{burn} is the difference in burn depth predictions between methods, where $+\Delta_{burn}$ denotes HYDRUS burning deeper than the water table-based method. Medians and standard deviations, in parenthesis, provided for both. Only % time at burn risk is shown for HYDRUS simulations because modelled water tables remained at depths greater than $h_{smolder}$ for all sites, resulting in 100% time at burn risk for water table-based predictions. MDWP is moderately decomposed woody peat, UMP is undecomposed moss peat both from Verry et al. (2011) and FP is fen peat from Simhayov et al. (2018).

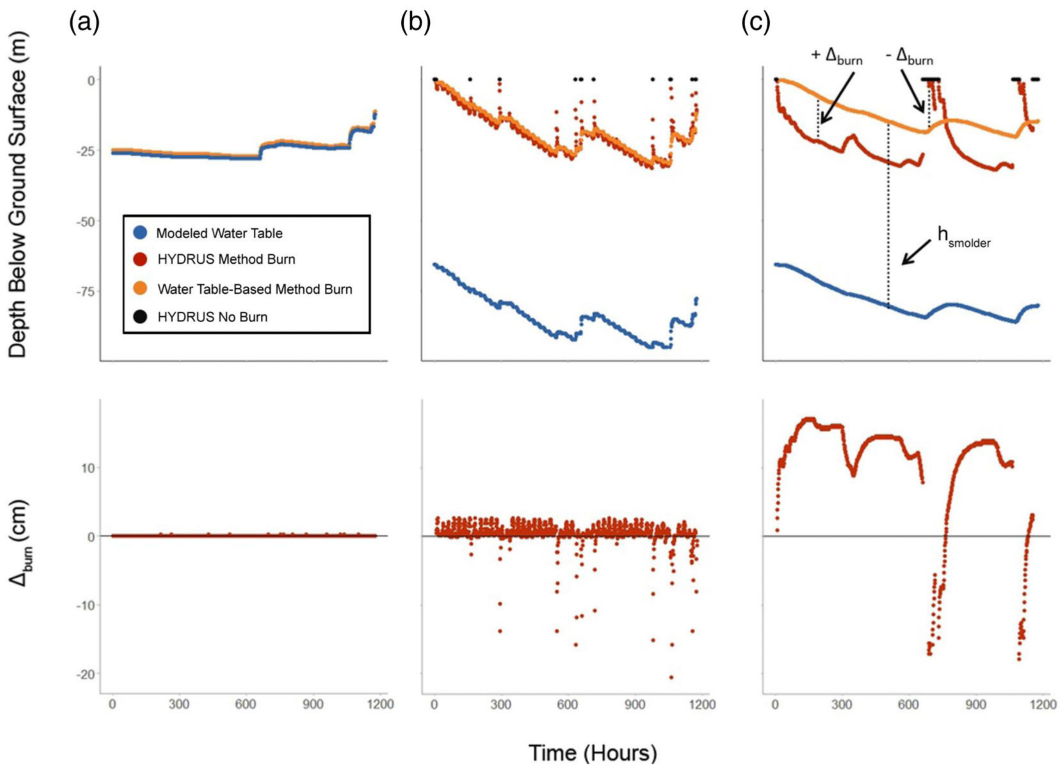

FIGURE 4 Modelled water tables from HYDRUS and corresponding modelled burn depths from both HYDRUS and water table-based approaches (upper panels). No burn events from the HYDRUS approach shown in black. Difference in hourly burn depth predictions between methods (Δ_{burn}) (lower panels). (a) Site 2 with layer appropriate K_{sat}. (b) Site 5 with layer appropriate K_{sat}. (c) Site 5 with Lower K_{sat} only

predictable for Site 2 given its low water retention, but less expected for Sites 5 and 9, which had higher capillary lengths (Figure 2a). Site 2 had near complete agreement between the two methods (Figure 4a), as compared to some minor divergence at Site 5 (when applying stratum appropriate K_{sat}). That divergence was driven by diurnal ET and precipitation events (Figure 4b). When modelled entirely with the K_{sat} values reported for Lower Peat (30.48 cm/h), however, Sites 5 and 9 had much larger Δ_{burn} values than Site 2, demonstrating the varying level of influence K_{sat} had across sites that differed in water retention. For sites 5 and 9 there was strong divergence during drying events when HYDRUS predicted deeper burn depths ($+\Delta_{burn}$), reflecting greater and sustained ET-induced soil

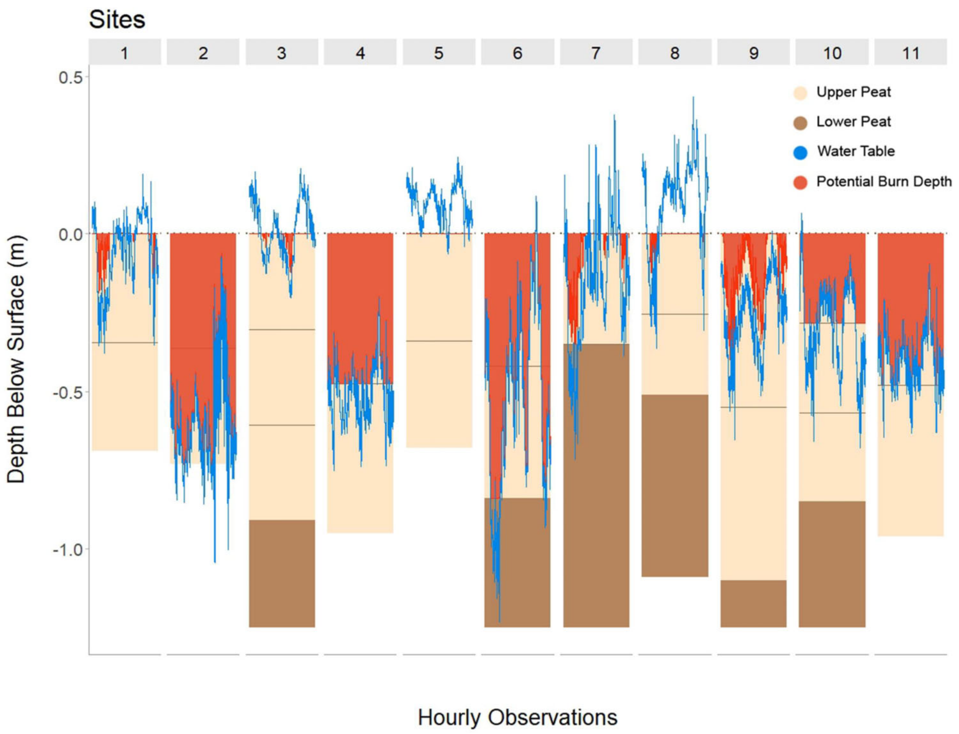

FIGURE 5 Burn depth potentials modelled by the water table-based method and observed water tables relative to ground surface across the 11 sites from April 2017–September 2019. Total depth of Upper stratum shown. Lower stratum, where present, are truncated to 1.25 m below ground surface; Sites 1, 2,4, 5, and 11 had no Lower Peat present. In Site 2, the water table periodically dropped into the mineral layer. The discretization of depth samples is noted with horizontal lines

moisture declines. That divergence is also apparent during precipitation-induced wetting fronts where HYDRUS burn depth predictions were shallower than the water table-based approach ($-\Delta_{burn}$) (Table 1, Figure 4c). The influence of K_{sat} on peats with higher water retention can also be seen in MDWP, which has a low K_{sat} value and high $h_{smolder}$ value and similarly demonstrated a notable degree of divergence from hydrostatic equilibrium (Table 1). Despite the differences between model results for peats with high water retention and low K_{sat} values, the disagreement between model predictions never exceeded 15 cm for any of the peats (Figure 4c).

3.2 | Simulating burn depth potentials across sites

Water table depths, while exhibiting similar temporal patterns, differed among sites (e.g., 3 and 9) as did their hourly burn depth potentials (Figure 5). Relatedly, the duration of burning risk varied among sites, with some under constant risk (e.g., Site 4) and others never at risk (e.g., Site 5). Further, differences in $h_{smolder}$ values between depth samples within a site created some situations where fires would burn up to a depth sample limit regularly (see horizontal line for Site 4 in Figure 5), and others routinely vacillating across depth sample boundaries (e.g., Site 6). The mean depth of burn was also highly varied, with some sites burning shallowly on average (e.g., Site 1, mean = 1.6 cm) and others deeply (e.g., Site 2, mean = 59.6 cm) (Figure 6). Similarly, some sites exhibited a large range in burn depth potentials (e.g., Site 6, interquartile range = 44.7 cm) whereas others had a much smaller range (e.g., Site 4, interquartile range = 2.7 cm).

The relationship between mean burn depth and mean water table position was positive, linear, and significant (Figure 7a; $R^2 = 0.92$, p-value <0.001). Mean burn depth also had a positive, non-linear, significant relationship with the site-specific Upper-1 soil capillary length (Figure 7b; Spearman's $\rho = 0.81$, p-value $= 0.003$). Notably, there was a significant correlation between these two controlling variables (Spearman's $\rho = 0.81$, p-value $= 0.003$).

4 | DISCUSSION

In this study, we used soil property and hourly water table data to develop and verify a method of predicting burn depth potentials in the peats of GDS. We were able to model soil moisture in the vadose zone and predict depth of burn potentials across 11 sites by combining depth-varying MRCs and hourly water table data with a known moisture-to-ignition threshold. This method was validated by comparing results against those from a more complex, process-based soil moisture model, HYDRUS-1D. Our findings demonstrate that the water table-based method has similar performance, particularly for lower water retention soils with high K_{sat} values. Water table position was the primary control on burn dynamics in our system, regardless of if a state of hydrostatic equilibrium is assumed or not. Peat-specific water retention properties also exerted a degree of influence on burn depths. These findings highlight the impact that drainage, and hydrologic restoration, may have on peatland fire risk and severity. Our study adds to the understanding of peat fire drivers and provides land managers and planners with an approach for assessing wildfire risk and prioritizing hydrologic restoration efforts.

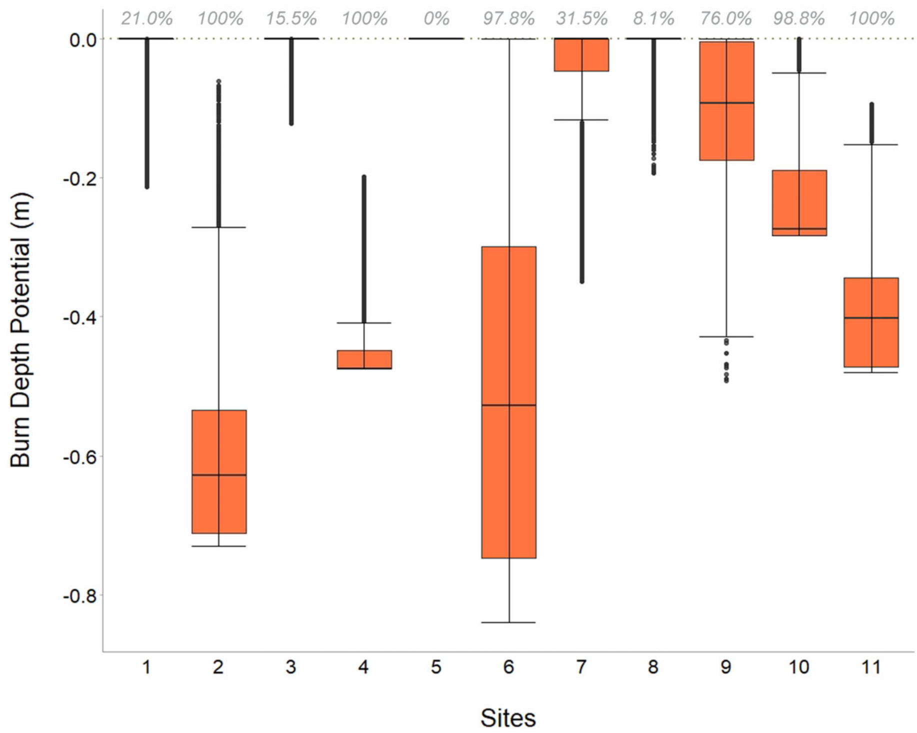

FIGURE 6 Burn depth potentials across the 11 sites from April 2017 to September 2019, with percentage of time at risk of burning noted above each site

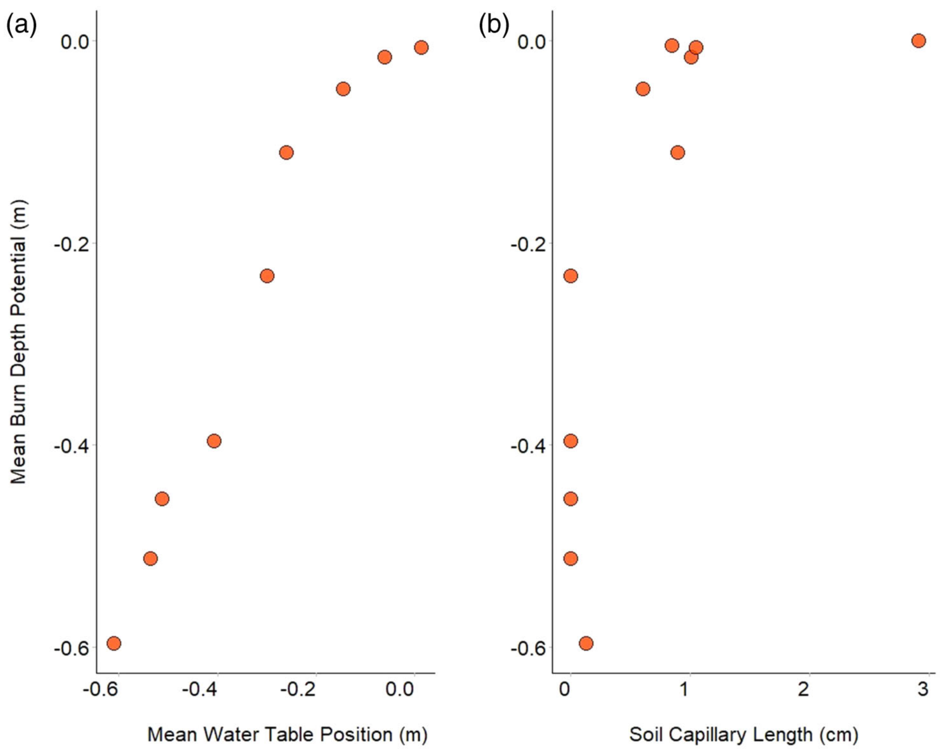

FIGURE 7 (a) Relationship between the mean burn depth potential modelled by the water table based-approach from April 2017 to September 2019 against mean water table position ($R^2 = 0.92$, p-value <0.001) and (b) against soil capillary length for the Upper-1 sample (Spearman's $\rho = 0.81$, p-value $= 0.003$)

4.1 | Approaches to model burn depth potential

Given the need for accurate yet feasible soil moisture models, we sought to create a new, accessible approach. In order to validate our modelling method, we compared the simpler water table-based approach to HYDRUS, a process-based model of soil water redistribution. HYDRUS requires known soil hydraulic properties, meteorological data, and a degree of calibration. While peat property data for HYDRUS has been used in previous studies for a variety of peat types and may be available (Kettridge et al., 2015; Mccarter & Price, 2014;

Price & Whittington, 2010), we reemphasize the large variability in hydraulic properties both among and within peatlands (Table 1, Benscoter et al., 2011) and thus the need for site-specific data. HYDRUS simulations should be calibrated with measured water level or soil moisture data for accurate applications (Dettmann et al., 2014). Similarly, publicly available meteorological data may suffice, but model error may arise during spatially variable precipitation events in predominantly rain-fed systems as ours (as demonstrated by the offset of initial water table increases around the 1000 h mark in Figure 3a). Adjustments to hydrologic input and output rates (e.g., ET:PET ratios and interception) may also be necessary depending on study region and vegetation cover. An additional issue to modelling soil moisture in peatlands with HYDRUS is that it has been shown to have trouble describing preferential and non-equilibrium flows during wetting periods as it fails to account for macropores (Dettmann et al., 2014). Nonetheless, HYDRUS has been shown to provide a good model of soil moisture in peats (Price & Whittington, 2010), which made it useful for comparison in our study. In situations where water table data are not available but meteorological data are, HYDRUS may be the best method to model moisture regimes in organic soils.

Compared to HYDRUS, coupling known MRCs to water table data offers a simpler approach and one easier to implement across sites and time. Employing this method still requires known hydraulic properties as HYDRUS does, but then solely relies on water table dynamics without the need for meteorological data, calibration, and more complex modelling. However, the water table-based method is only appropriate where hydrostatic equilibrium occurs rather rapidly, as was the case with our Upper Peats. In situations without rapid hydrostatic equilibration (i.e., in peats that have relatively low hydraulic conductivities), HYDRUS, or other process-based models may still be needed, depending on modelling objectives (e.g., accuracy needs and temporal resolution). Our comparison of methods suggests this may be the case for some of our Lower Peats (Figure 4c) and peats like the MDWP (Table 1). The water table-based approach may be valuable to assess soil moisture in drained peatlands, and future work should investigate the limits of the assumption of hydrostatic equilibrium across a variety of other organic soils.

Last, we acknowledge the uncertainty in two key parameters, K_{sat} and $s_{smolder}$. We had to rely on previous K_{sat} estimates for the HYDRUS simulations, which were different for our Upper (1678.9 cm/h) and Lower (30.48 cm/h) Peats. When adjusting K_{sat}, however, it is apparent that the extent of its influence is inherently linked to water retention. That is, sites with lower retention (e.g., Site 2) were substantially less impacted by adjustments to K_{sat} than high water retention peats (e.g., Site 5, MDWP) (Table 1). Other studies using HYDRUS to model peat moisture have similarly found that K_{sat} is a key control in high water retention peats (Kettridge et al., 2015). Difficulty in quantifying $s_{smolder}$ values leads to large uncertainty, as evidenced by the value from Schulte et al. (2019) applied here ($s_{smolder} = 71.2\%$ with a standard deviation of 77.0%). Additional uncertainty exists around this term as the moisture content required for extinction of smouldering can be much higher than the limit for peat ignition (Huang & Rein, 2015). Moreover, substantial variation in $s_{smolder}$ values exists among peat types (Frandsen, 1997). Regardless of modelling approach used, the soil moisture threshold is a necessary parameter for any smouldering predictions, so we stress the importance of site-specific values where possible.

4.2 | Approaches to model burn depth potential

By applying the water table-based approach to all 11 sites, we were able to model burn depth potentials over a large area (Figure 1) for a 2.5-year period of water table data (27 April 2017–09 September 2019). Our modelling window for the water table-based approach was a during a prolonged period of lowered water table elevations, where the average lake stage position for Lake Drummond was 10 cm lower than the average for a 17-year period of recorded values (Figure 8).

Across our sites, the site means and variances of the burn depth potentials both differed (Figure 6). The variation exhibited by our 11 sites serves to reemphasize that risk assessments should be local rather than landscape-wide, with implications for a range of management efforts in GDS and other peatlands. The standard procedure to assess peat fire risk in the field is to use point-specific soil moisture data gathered by handheld sensors (Prior et al., 2020; Robichaud et al., 2004), which is applicable only for the time of measurement and not linked to potentially site-varying moisture-to-ignition thresholds. A stronger understanding of soil moisture dynamics and their specific ignition thresholds would help land managers plan prescribed burns or adjust wildfire suppression priorities around easily accessible data (i.e., water table depth), which has been of interest in wetlands similar to GDS (Fire Environment Working Group, 2009). Further, knowledge on how the degree of risk varies spatially would help land managers prioritize sites for hydrologic restoration. Thus, future work, spanning a multitude of different peatland types, should compare modelled burn depth predictions with laboratory or in situ burns to further evaluate the utility of modelling approaches.

The second objective was to explain the drivers of burn depth potential. The variation in water table depths across sites (Figure 5) ultimately drove their variable burn depth predictions, clearly implicating contemporary water level regimes as the primary control of smouldering fire risk (Figure 7a). However, the strong influence that individual peat properties play on burn depth potentials, both among sites and at multiple depths within sites, further underscores the importance of site-specific soil data for accurate burn depth and fire risk predictions (Figure 7b).

The collinearity between the two main controls on peat fire risk, water retention properties and mean water table position, demonstrates the multifaceted consequence of drainage. In the short term, a deeper water table means drier, and therefore more flammable peat. In the long term, drainage can alter peat pore structure and associated water retention properties (Peng et al., 2007; Peng & Horn, 2007; Schwärzel et al., 2002). At GDS, previous work suggested that drainage resulted in lower water retention and higher macroporosity in Upper Peat layers (Word et al., 2022). Consequently, we found that

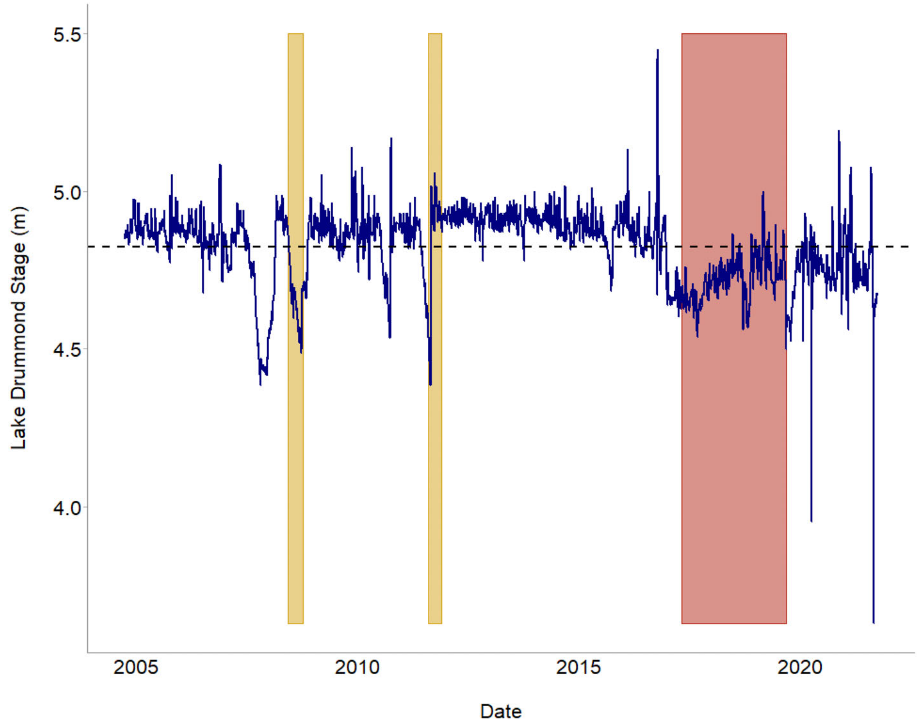

FIGURE 8 Lake Drummond stage (shown in meters above sea level NAVD88) from 10 October 2004 thru 30 September 2021 in navy. Modelling period for this study highlighted in red (27 April 2017–09 September 2019). Duration of South One (09 June 2008–07 October 2008) and Lateral West Fires (04 August 2011–22 November 2011) highlighted in orange. Average Lake Drummond stage marked with black, dashed line

some of our sites had such poor water retention capacities that the $h_{smolder}$ values in their Upper-1 samples were <1 cm (Figure 2b). A logical extension of the combined impact of these drainage effects would be that fires in degraded peats at GDS can regularly be expected to burn down to the water table, which was the assumption historically made by land managers at similar peatlands but refuted by other studies (Reardon et al., 2007). That extension (that drained peats may always be under threat of burning to the water table) may be a convenient shorthand assessment for risk at GDS, and is bolstered by the findings that $s_{smolder}$ values for extinction are often greater than that for ignition (Huang & Rein, 2015). However, that conclusion may not be universal, as studies in drained northern bogs and fens have observed lower macroporosities (and therefore higher water retention) as compared to undisturbed peats (Kennedy & Price, 2005; Price & Schlotzhauer, 1999). These contrasting results once again emphasize the importance of site-specific assessments, particularly where past land use has altered peats.

Considering the observed relationship between water table position and water retention properties from another perspective, our results suggest that restored peats at GDS may have fire risks more similar to undisturbed conditions. If true, hydrologic restoration efforts at GDS, and potentially other peatland systems, could be an effective strategy to decrease fire vulnerability by enhancing both the short-term controls (available soil moisture) and long-term controls (water retention properties). As an example, Site 5 underwent hydrologic restoration (Balentine, 2020), has a soil capillary length within the range of the Lower Peats (Figure 2a), and during our observation window was never under risk of burning (Figure 6). Moreover, work comparing the properties of Upper and Lower Peats in GDS found that Upper Peats that experienced consistent saturation had hydraulic properties more comparable to undisturbed Lower Peats (Word et al., 2022). As further evidence, given that there is a relationship between pore size distribution and K_{sat} (Bouma & Anderson, 1973), K_{sat} for a peat like Site 5 may more closely align with the Lower Peat value used here (30.48 cm/h), further reducing fire risk via slower water redistribution (Table 1). Given this, we echo the call from Rochefort and Andersen (2017) that future studies should focus on the response of peat soils to rewetting efforts. Those investigations should pay particular attention to the multiple properties (i.e., water retention, soil moisture-ignition thresholds) that drive peat flammability and if their responses to rewetting are consistent across different peatland types. Such coupled restoration and research efforts are vital to peatland revitalization (Rochefort & Andersen, 2017) and would have numerous positive benefits beyond reducing wildfire risk (Zedler & Kercher, 2005).

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CONFLICT OF INTEREST

The authors have no conflicts of interest to report regarding the contents of this research and subsequent manuscript.

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 can be found online in the Supporting Information section at the end of this article.

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