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Assessing localised rainfall and water table depth relationships in agricultural grassland peat soils

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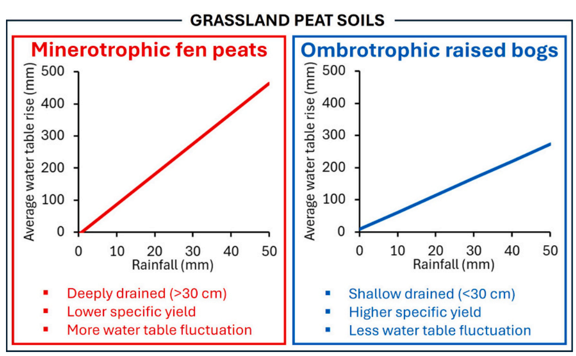
HIGHLIGHTS

- Water table management on grassland peat soils is a carbon farming action.
- At lowland sites in Ireland, fens are more deeply drained than raised bogs.
- Fens had strong correlations between rainfall and water table rise.
- Hydrologic differences such as water storage capacity exist within peat soil types.
- Site-specific analysis is key for water table management.

GRAPHICAL ABSTRACT



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ABSTRACT

Actively managing the water table position, which dictates the carbon storage dynamics of grassland peat soils, is an important tool to reach European Union (EU) climate neutrality goals by 2050. Understanding water table and rainfall relationships at peat sites will aid in future water table management. Across six sites, four fen and two raised bogs (RB), a total of 30 fully screened monitored dipwells were installed, and hourly precipitation was measured for one year from September 2023 to August 2024. For each site, the correlation between water table rise and event rainfall and the soil's specific yield (S_Y) were calculated. Results showed that peat soil type has an impact on the drainage depth and that fen peat sites were more deeply drained (average water table depths ranging from 114.1 cm–41.3 cm) than RB sites (average water table depths of 15.7 cm and 12.2 cm), despite similar drainage system design. There were also larger water table fluctuations due to rainfall inputs at the fen sites than at the RB sites. An event-based analysis was used to correlate water table rise with rainfall at each site and for each peat classification type and it was found that the fen sites exhibited a stronger correlation between water table rise and event rainfall ($R^2 = 0.79$) than the RB sites ($R^2 = 0.59$). This type of analysis highlights the differences across peat soil types under grassland management and emphasises the need for individualised management on these areas to align with climate policy objectives.

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1. Introduction

Peat forms under waterlogged conditions due to the incomplete decomposition of peat-forming vegetation, resulting in significant levels of carbon (C) storage (Evans et al., 2021; Offermanns et al., 2023). Although peat soils cover only approximately 3 % of global land area, they can store around 30 % of global C stocks (Liu et al., 2020), making them important sinks for C. There are many names and definitions used for areas of peat soils (Lourenco et al., 2023). For this study, the terms 'raised bog' (RB) and 'fen peats', used to define these lands in Ireland, are utilised. In lowland areas, ombrotrophic RB develop due to the influence of precipitation, while the development of minerotrophic fen peats is controlled by topography and the influence of groundwater (Hammond, 1981). Raised bog and fen peats are not considered as soils but rather as landscape units which contain the parent materials (different peat types) from which organic soils are formed (Hammond, 1981). Within the European Union (EU), 2.8 million ha of peat soils are estimated to be under permanent grassland management (Martin and Couwenberg, 2021). Permanent grassland is land which is used to produce grass for several consecutive years, and which can be used for grazing, mown for silage and hay, or used for renewable energy production (EU, 2004). For this study, the term 'grassland peat' refers to permanent grassland as defined by the EU that have been cultivated in lowland areas of organic soils that are considered drained (i.e., shallow (average annual water table position is <30 cm below ground level) or deep (average annual water table position is >30 cm below ground level)) (IPCC, 2014).

In Ireland, RB and fen peats in lowland areas have been drained, actively managed (Tiemeyer et al., 2024) and are also potentially associated with domestic or industrial extraction of peat (Carey, 1971; Hammond, 1981). Often the precise history of these sites is not captured in terms of their exact drainage and maintenance history (Tuohy et al., 2023), agricultural management and cutaway status. Following disturbances such as installation of land drainage for agricultural use (i.e., open drainage ditches of various depths and associated in-field pipes), emissions of carbon dioxide (CO_2) and water quality issues from peat soils increase as the water table drops (Evans et al., 2021). This is due to the breakdown of organic material that occurs when oxygen is introduced into the system (Leifeld and Menichetti, 2018). To mitigate these negative impacts, reduced management intensity on organic soils drained for grassland (European Commission, 2012) forms part of the strategy created to meet the targets set forth in EU climate change mitigation policy (European Commission, 2021). Raising the water table to a level that will maximise C storage potential while minimising the emission of other greenhouse gases (GHGs) is another potential mitigation measure.

Understanding the relationship between water table dynamics and rainfall in grassland peat soils is important when considering future water table management strategies at a site, i.e., open drainage ditch blocking. These grassland peat soils will have different histories in terms of how the soil was formed and what artificial drainage and farm management has occurred at the site. It is difficult to both gather this information for a site (e.g., in some countries, such as Ireland, there is no drainage register, and land drainage maps were not recorded) and to understand how exactly these parameters will affect the water table behaviour at the site. Climate change has increased rainfall variability significantly, which impacts water table levels as well as greenhouse gas emissions (Guo et al., 2024). Since these areas are targeted for active water table management, it is essential to understand the initial water table behaviour at these sites so that their potential response to water table management efforts can be understood. This is because some sites may be more difficult, or impossible, to influence through traditional

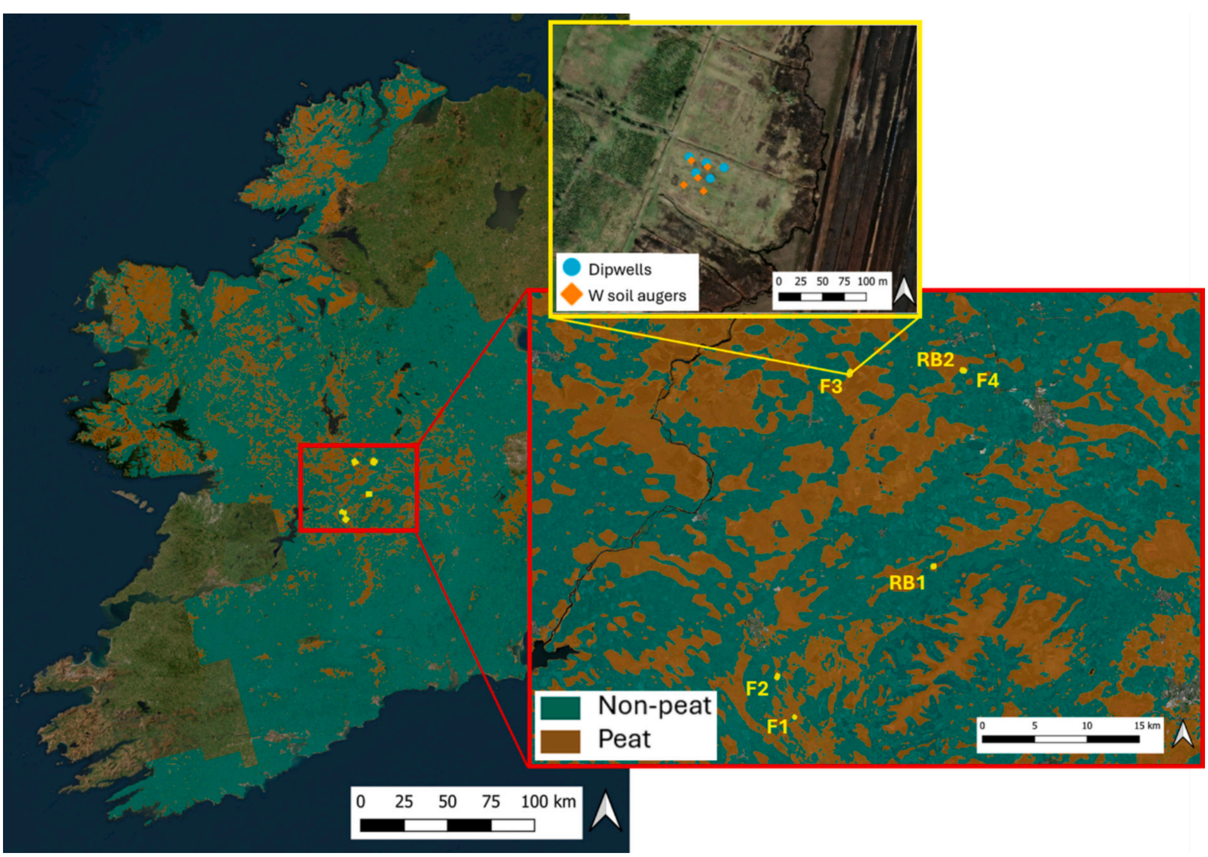

Fig. 1. Map of the lowland grassland site locations on the island of Ireland showing non-peat and peat soil distribution. The sites are generally located on the edges of peat soil areas in the transition zone from organic to mineral soils (peat/non-peat base map from O'Leary et al. (2025)).

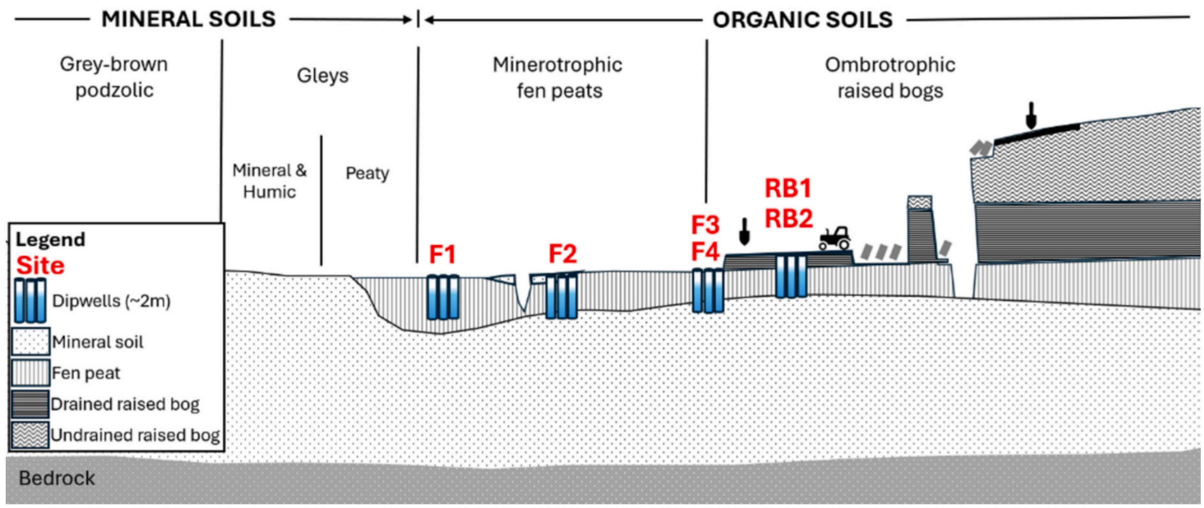

Fig. 2. Landscape schematic (not to scale) based on Hammond (1981) illustrating mineral to organic soil transition, as well as fen peat and RB areas. The notional locations of study sites are shown within this transition along with their associated peat type and their dipwell configuration, which monitor only the water table level within 2 m of the ground surface and may not be indicative of the regional water table. Abbreviations used: F1–F4 are fen sites 1–4; RB1–RB2 are raised bog sites 1–2. See Table 1 for details.

water table management methods, such as blocked surface drains. Methods that correlate rainfall and the water table have been used previously to examine these relationships (Baird and Low, 2022; Ferlatte et al., 2015; Tiemeyer et al., 2024). For example, in Germany, Ahmad et al. (2020) found that there was a much smaller water table response to rainfall inputs at a rewetted fen site than there was at a nearby drained fen site. In Canada, monthly water cumulative water table increases were calculated and compared with monthly precipitation amounts and were found to have strong correlations in seven ombrotrophic peatlands (Bourgault et al., 2019). This study expands on these previous works by comparing the relationship between rainfall and the water table in different peat types (RB and fen peats) under similar land management.

Specific yield (S_Y) is a ratio that defines the water storage capacity of the soil, essentially describing the amount of water that can be drained from a volume of soil. For example, in peat soils S_Y decreases with depth within the top metre of soil, which influences fluctuations in the water table (Bourgault et al., 2018, 2019; Moore et al., 2015). As the depth to the water table increases, smaller amounts of rainfall are needed to raise the water table. When the water table is shallower, larger amounts of rainfall are needed to raise the water table until the point where no additional water storage is available (Bourgault et al., 2019). The high S_Y associated with peat soils means that these soils are less influenced by flooding and drought, as the larger storage capacity of the soil provides a buffer function (Bourgault et al., 2017; Ahmad et al., 2020). This storage capacity is changed when the peat soils are drained and degraded. Decreasing S_Y with depth suggests that there will be less capacity for storage of water in more deeply drained peat soils and that smaller rainfall amounts may raise the water table in these areas. Therefore, it is proposed that interpretation of spatial and temporal rainfall event and water table rise relationships, together with soil profile depth-specific S_Y at grassland sites within transitional peat soil zones (e.g., where one finds a mineral to organic soil transition, as well as fen peat and RB areas), will help aid targeted decisions regarding water table management in these complex and high heterogeneous landscape units.

The objective of this study is to investigate rainfall and water table relationships at agricultural grassland sites on peat soils over a one-year period to: (1) examine similarities and differences in these relationships within and across peat soil types; (2) calculate depth-specific S_Y for each of the sites, and (3) combine (1) and (2) to determine localised hydrological patterns and responses that can be used to aid in the classification of these and other sites to establish future water table management potential. For this study, six sites on commercial grassland throughout the midlands of Ireland were selected, instrumentation was installed, and these sites were monitored from September 2023 through August 2024.

Table 1
Site name, location, management and other pertinent information.

Site	County	Management	Soil pH range[a]	Average peat depth (cm)	Peat classification
F1	Offaly	Beef; moderate intensity	6.00–6.01	238	Fen
F2	Offaly	Sheep; low intensity	5.98–6.02	218	Fen
F3	Offaly	Not currently grazed	5.80–6.50	122	Fen
F4	Offaly	Dairy; high intensity	4.20–6.69	106	Fen
RB1	Laois	Beef; low intensity	6.20–6.50	165	RB
RB2	Offaly	Beef; low intensity	4.43–6.20	210	RB

Abbreviations used: F = fen; RB = raised bog.
[a] pH range indicative of samples from 0 to 1 m which will include both mineral and peat soil in places.

2. Materials and methods

2.1. Site selection and description

Six lowland grassland farms were selected in the midlands of Ireland (Fig. 1) and a field within each farm was selected and monitored from September 2023 through August 2024. The sites were also selected due to their proximity to one another so that they would experience similar amounts of rainfall. Most of the farms in this study exhibit a clear transition between landscape units represented by glacial drift, river flood plains and RB (a characteristic that was considered in their selection). The soil transition comprises both mineral and organic soils. Within the mineral soils, grey-brown podzolics and gleys dominate and underlie the neighbouring organic soils. The locations of the field sites vary in their exact position along this mineral-to-organic soil transition (Fig. 2). For example, the fen landscape unit is found in river flood plains (F2), poorly drained hollows (F1) and on the periphery of raised bogs (F3-F4).

In terms of establishing baseline conditions, peat depths were determined by a combination of rodding and coring (Table 1). The soil in each field was characterised chemically and physically using soil depth-specific samples from soil augers (n = 5 in a W pattern as suggested by Wall and Plunkett, 2020) and a soil profile pit excavated at the central W position, respectively. The auger samples were divided into 0–10 cm, 10–20 cm, 20–30 cm, 30–60 cm and 60–100 cm depth intervals. The soil at each depth in the augers was composited and analysed for pH, nitrogen and C content. In the soil profile pit, sample rings were extracted from each depth or at the middle of the depth interval for 30–60 cm and 60–100 cm. These samples were used to determine dry bulk density in the laboratory (BS 1377: Part 5, BSI, 1990).

History for each site was gathered by talking with landowners, walking the sites and interrogation of old orthophotography and satellite archives (e.g., GeoHive Hub, 2025). All sites were previously artificially drained and reclaimed for grassland using a combination of deep open ditches and in-field pipes that discharge into open ditches. Except for at F1, drainage systems installed at the sites in previous decades have not been well maintained. The F1-monitored site is at the base of a poorly drained hill (consisting of mineral soils) where the footslope of the hill consists of a hollow filled with peat soils. Overland flow from the hill runs onto this flat area. The site is now bounded by deep open ditches connected to a maintained drainage outlet. Within this flat grassland area, recently installed in-field pipe drainage (80 mm corrugated pipe) at approx. 1 m depth has been installed and back-filled to the field surface with stone aggregate. This system is fully maintained, connected to the adjoining open ditch and deemed functional. F2 is situated in a river flood plain (see Fig. 2) and has a layer of deep fen peat soil that is overlain by mineral soils in some areas that have been deposited from the river after flooding. This site is bounded on two sides by deep open ditches and on one side by a river. F3 is located near the edge of an industrial cutaway zone and RB has been harvested by hand from the area of the site. Due to this history, the site consists of a layer of fen peat overlain with remnant RB in some areas. This site has a series of open ditches located along two sides, as well as other connected drainage ditches to the north of the site. F4 is characterised by a shallow layer of peat and is drained by open ditches along the field borders. RB1 is drained by a deep in-field ditch located to the southwest of the dipwells. RB2 is connected to the same open ditch drainage network as F4, but is characterised by a layer of deeper, more uniform RB peat. At F1 all of the dipwells are encased in the organic soil layer, while at F4 all of the dipwells puncture through the organic soil layer into the mineral soil below. At the remaining sites (F2, F3, RB1, RB2), at least one of the dipwells punctures through the organic soil layer into mineral soil below, while other dipwells are fully within the organic soil layer. Sub-peat mineral soils are common across sites but variable in extent (Carey, 1971). It is best described here as glacial drift, relatively uniform with >60 % carboniferous limestone fragments, with smaller amounts of shale, sandstone, dolomite and chert.

2.2. Field instrumentation and drainage history

Five fully screened dipwells constructed of high-density polyethylene and measuring 32 mm (outer diameter) with 0.3 mm slots were installed at the each of the sites to monitor the water table depth (WTD). Dipwell position varies within each farm and numbers were randomly assigned to each dipwell (1–5). The installation depth and design ensured the water table position was always within the screened interval, as each dipwell was installed to about 2 m depth. This was deeper than the WTD in these areas, allowing for the continuous monitoring of the water table position within the dipwell. Each dipwell was instrumented with a Seametrics LevelSCOUT level logger (Seametrics, United States) to measure WTD and temperature every 15 min over the study period. The sensor was affixed to a wire and held in a static position above the base of the dipwell. Each site had a Seametrics BaroSCOUT pressure sensor installed to correct the water level readings for barometric pressure. Compensation of the water level readings with the barometric pressure was done in the Aqua4Plus control software, provided by Seametrics. Sites are classified as in Table 1.

Water table depth was calculated by subtracting the compensated submergence value from the dipwell length and is presented as a positive value (Baird and Low, 2022). A negative value of WTD recorded in any of the dipwells indicates ponding of water on the ground surface or flooding in the field and should not be interpreted as a measured height of water above the ground surface. All depths presented in this study are referenced from the ground surface (0 cm).

Precipitation at sites F1, F2, F3 and RB1 was measured using a PRONAMIC Rain-O-Matic tipping bucket rain gauge (PRONAMIC, Denmark) that was connected to a DataHub (Flux Enviro, Ireland). The rain gauges were mounted on a 50 cm mounting pole and were installed at a distance from any obstructions that may adversely affect the accuracy of the measurements. Rainfall was recorded every 15 min over the study period to align with the WTD measurements. Sites F4 and RB2 use the rain gauge that was installed at site F3 due to the three sites' proximity. At times that local rainfall data were not available due to installation date or equipment failure, the next closest local rain gauge or a nearby Met Éireann weather station was utilised.

2.3. Data analysis

All data were collected during the study period of September 2023 through August 2024. To analyse and visualise the data collected at each site, Microsoft Excel and MATLAB were used. Excel was used to create hydrographs from daily water table and rainfall data. Using MATLAB, analyses that correlated water table rise and rainfall on an event basis were completed. An event was defined as a period of rainfall that had at least 12 h of no rainfall before and after the first and last measured precipitation, after Tuohy et al. (2018). Periods when the water level in the dipwells was measured within 1 cm of the ground surface or higher (e.g., when the water table was at or above the ground surface) were excluded from the event-based analysis since water table rise in this situation could not be accurately measured during the rainfall event. Specific dipwells were excluded from an event if they met any of the criteria for exclusion during that event, which means that the averages depicted for a site may or may not include all five dipwells for any given event.

The parameters described above were used to identify events that occurred during the study period and the maximum water level rise was calculated during each event based on the water table elevation at the beginning of the event and the highest water table elevation during the event. The total rainfall during each event was also calculated. The water table rise and rainfall for each event were correlated for each of the five dipwells at the six sites, and an average of each site's five dipwells was also calculated and correlated. Another output of the event-based analysis was the lag time for each well to reach its maximum water table level, which was measured as the time from the start of the event to the time of the maximum water table level.

The analysis also calculated S_Y using the water table fluctuation method (Bourgault et al., 2017) to estimate the water storage capacity of the soil:

$$S_Y = P/\Delta h \tag{1}$$

where P (mm) is the total precipitation during the event and Δh (mm) is the water table rise during the event. This capacity is expected to decrease with depth and the S_Y for peat soils have been found to range from 0.01 to 1 within the top 50 cm of the soil (Bourgault et al., 2017). Larger S_Y near the surface of peat soils allows for these areas to store more water and therefore react more slowly to rainfall inputs than mineral soils and peat soils at depth that have lower S_Y. S_Y was calculated for all dipwells when the water table level was within the peat layer in the dipwell during all events that met the criteria for event-

Table 2
Site total annual rainfall, average and individual dipwell (1–5)[a] water table depths (WTD) and drainage status.

Site	Total annual rainfall (mm)	Average annual water table depth (cm)	1-WTD range (cm)[b]	2-WTD range (cm)[b]	3-WTD range (cm)[b]	4-WTD range (cm)[b]	5-WTD range (cm)[b]	Drainage status
F1	844	41.8	90.3–47.9	79.1 to −5.7	78.8–4.5	77.1 to −10.4	71.5–12.4	Deep
F2	942	41.3	72.7 to −4.5	95.7–2.8	91.9–2.5	93.8–0.2	81.9 to −4.6	Deep
F3	998	69.7	157.2–41.0	117.8–11.0	146.4–20.2	125.4–5.0	101.4–10.8	Deep
F4	998	114.1	188.7–43.3	205.9 to −8.5	204.3–44.0	206.8–57.0	198.8–88.0	Deep
RB1	913	12.2	57.6 to −1.1	44.8 to −97.6	35.5 to −19.0	50.0 to −32.9	34.0 to −11.3	Shallow
RB2	998	15.7	65.2–6.9	41.5 to −6.2	60.2 to −7.7	41.9 to −7.8	56.0–4.7	Shallow

[a] Dipwells are numbered 1–5 at random at each site. There is no correspondence between wells with like numbers.
[b] Negative water table values indicate ponding of water on the ground surface or flooding in the field and should not be interpreted as a measured height of water above the ground surface.

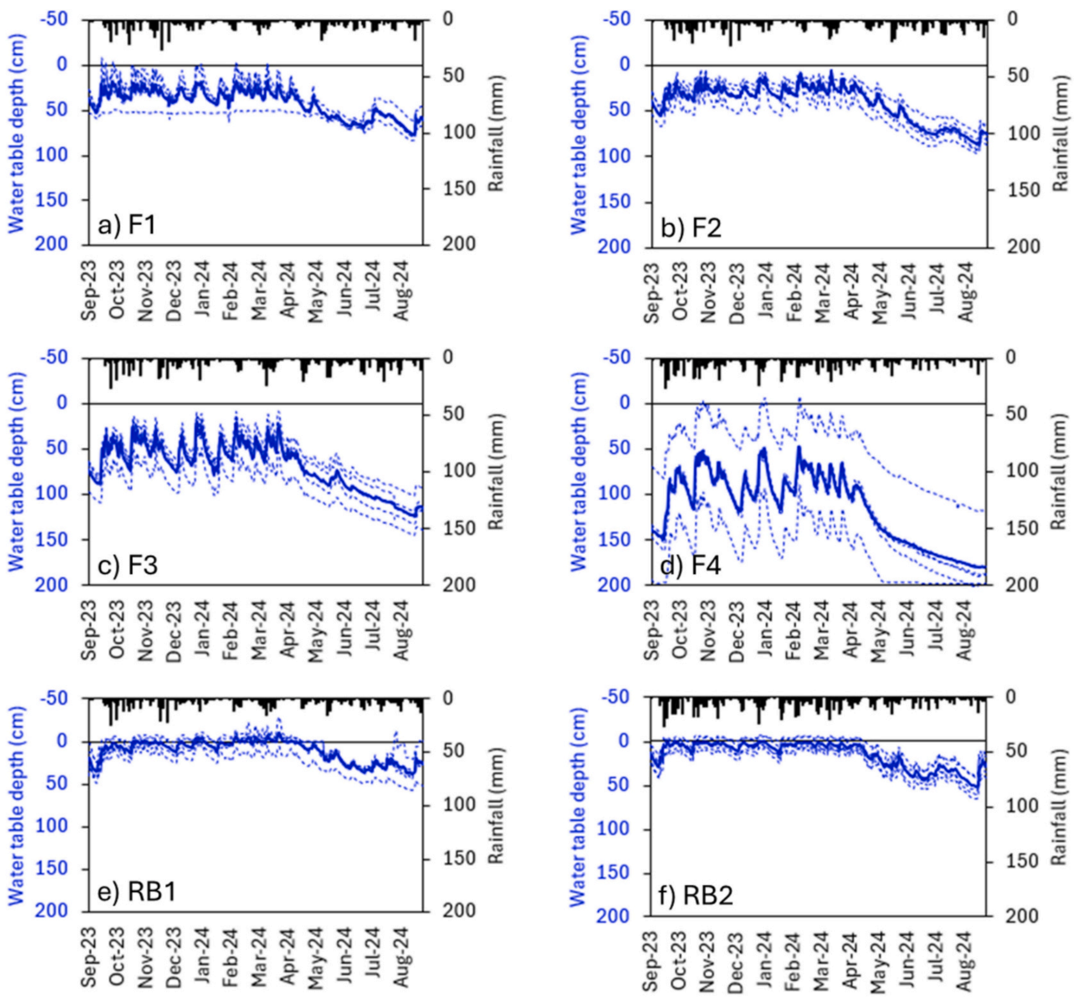

Fig. 3. Site water table depths and rainfall, where the black lines at 0 cm represent the ground surface. Thick blue lines show the average water table depth at each site; thin, dashed blue lines show each individual dipwell at the site (five per site). Negative water table depth indicates ponding at field surface. Abbreviations used: F = fen; RB = raised bog.

based analysis at each of the study sites. Instances where the S_Y was calculated to be >1 were excluded due to not meeting the assumption that no rainfall would be lost as runoff during an event (Bourgault et al., 2017). Another assumption of this method is that a significant volume of water is not retained by the soil in the unsaturated zone (Ahmad et al., 2020). Because of this assumption, this method has the tendency to overestimate S_Y in deeply drained soils and therefore S_Y was only calculated for the top 50 cm of soil (Lv et al., 2021). Due to these assumptions, this method can only be used as an indication of the S_Y of the soil.

3. Results

3.1. Similarities and differences in annual rainfall and water table positions

The total annual rainfall, average annual WTD, ranges of WTD measured in each of the five dipwells and drainage status (IPCC, 2014) are summarised for each site in Table 2. Rainfall amounts ranged from 844 mm (F1) to 998 mm (at F3, F4) for the fens and from 913 mm (RB1) to 998 mm (RB2) for the raised bogs. Average WTD for fens were all deeper than for the RB sites, but with noticeable differences within fen

Table 3
Event-based[a] analysis outputs for each site: the total number of rainfall events that met the criteria for event-based analysis and the minimum, maximum, and averages for rainfall, water table rise, lag time, and specific yield (S_Y) during the events at each site.

Site	Events	Rainfall (mm) Min–max (avg.)	Water table rise (cm) Min–max (avg.)	Lag time[b] (h) Min–max (avg.)	S_Y[c] Min–max (avg.)
F1	163	0.2–39 (5.2)	0–73.1 (4.8)	0–101 (15.1)	0.00–0.94 (0.16)
F2	163	0.2–42 (5.9)	0–37.1 (4.4)	0–87.5 (13.6)	0.01–0.96 (0.16)
F3	163	0.2–50 (5.9)	0–53.7 (5.1)	0–168 (12.9)	0.00–0.96 (0.21)
F4	164	0.2–50 (5.9)	0–67.1 (4.3)	0–122.3 (13.0)	0.01–0.84 (0.16)
RB1	162	0.2–45.4 (5.1)	0–26.5 (3.4)	0–137.8 (11.3)	0.00–0.97 (0.23)
RB2	164	0.2–50 (5.9)	0–52.6 (2.5)	0–129.5 (12.4)	0.00–0.99 (0.31)

[a] An event was defined as a period of rainfall that had at least 12 h of no rainfall before and after the first and last measured precipitation.
[b] The time from the start of the event to the time of the maximum water table level.
[c] Calculated using the water table fluctuation method ($S_Y = P / \Delta h$, where P (mm) is the total precipitation during the event and Δh (mm) is the water table rise during the event).

sites: F1 and F2 had similar average WTD of 41 cm, F3 had a deeper average WTD of 70 cm and F4 had a very deep average WTD of 114 cm. These data suggest that the four fen sites have a deep drainage status with an average annual WTD > 30 cm, while the two RB sites have shallow drainage status i.e., average annual WTD < 30 cm.

3.2. Similarities and differences in rainfall and water table relationships

Hydrographs of the six sites visualise the relationship between the WTD measured in the five dipwells at each site, the average WTD for the site and local rainfall (Fig. 3).

For each rainfall event, the total rainfall, maximum water table rise, lag time from event start to maximum water table position, and S_Y were calculated. A summary of these results from the event-based analysis is included in Table 3. Due to the close proximity of the sites, the average event rainfall was consistent across the six sites, but the water table rise varied with the largest average rise occurring at F3 (5.1 cm) and the smallest average rise occurring at RB2 (2.5 cm). Average lag times at the sites were fairly consistent and ranged from 11.3 to 15.1 h.

The correlations between water table rise and rainfall on an event basis (Fig. 4) show variability among the sites (e.g., F1 – F4 have different slopes and intercepts (positive and negative)) and do not indicate that these correlations can be used to group the sites based on their peat soil type. The R^2 values at F1 (0.60), RB1 (0.64) and RB2 (0.63) indicate moderate correlation between event-based water table rise and rainfall. Sites F2 (0.84), F3 (0.91) and F4 (0.81) have the strongest correlation between water table fluctuations and rainfall.

The slopes of the linear regressions, an indication of how much the water table will rise based on the amount of rainfall, were also considered. F3 and F4 had the highest slope values (10.7 and 10.1, respectively). The RB sites had the lowest slope values (6.6 for RB1 and 4.7 for RB2). This was the expected relationship based on the average water table fluctuations at the sites; the deeply drained fen sites (F1 – F4) had the largest water table fluctuations and therefore the highest slope values, while the RB sites had the smallest water table fluctuations and the lowest slope values (Table 3).

The four fen sites (sites F1, F2, F3 and F4) were grouped together to see what a general 'fen' correlation for similar sites would be. The R^2 value of the fen group was 0.79 (Fig. 5). The two RB sites showed a moderate correlation when grouped together. The R^2 value of the RB group was 0.59 (Fig. 5). The RB group also had a much smaller trendline slope (5.3 compared to 9.4 for the fen site group).

3.3. Depth specific S_Y

S_Y ranges at the sites were consistent, apart from F4, which had the smallest range (0.01–0.84). The largest average S_Y occurred at RB2 (0.31) and the smallest average S_Y occurred at F1, F2 and F4 (0.16, Table 3). The two RB sites (RB1 and RB2) had the highest average S_Y (0.23 and 0.31, respectively, Table 3) and show a pattern of higher S_Y at shallower depths and lower S_Y at deeper depths. All the fen sites show a pattern of clustered low S_Y values at shallower depths, with a wider distribution of S_Y and higher S_Y at deeper depths (Fig. 6).

4. Discussion

4.1. Similarities and differences in rainfall and water table relationships

Although the six sites chosen for this study are in close geographical proximity to one another and each is a managed grassland on peat soil, the characteristics of the sites had similarities and differences in terms of the water table and rainfall relationships within and across sites classified as fens and RB. Comparing the relationship between rainfall and the water table in fen and RB sites under grassland management provides new insight into how these peat soils behave after undergoing drainage and modification in order to be used as agricultural grasslands.

Visual analysis of the hydrographs showed similarities between sites F1 and F2, sites F3 and F4, and sites RB1 and RB2 (Fig. 3). Sites F1 and F2 are deep fen peats and have shallower water tables that appear to react similarly to rainfall. Sites F3 and F4 are fen peats with deeper water tables that have more dramatic fluctuations throughout the year. The sites showed variability in their average water table rise during events (Table 3). At F3, the site with the largest average water table rise, due to the deeper water table position at the site, allowing for more fluctuation with rainfall inputs. Sites RB1 and RB2 have water tables that are at or near the ground surface for much of the year. The site with the smallest average water table rise, RB2, has a consistently high water table and therefore smaller water table fluctuations. The other RB site, RB1, had the second smallest average water table rise.

The sites in this study are representative of transitional landscapes as depicted in Fig. 2. These areas are modified, drained and managed so that in most cases they barely resemble their peat soil parent type. The intense management and degradation of peat of these sites means that differences among peat types could be attributed to different management techniques, such as the installation of field drains, ploughing or nutrient use on the different sites. The data show that three sites in particular have weaker correlations between rainfall and water table rise (i.e., F1, RB1 and RB2), as shown by their lower R^2 values (Fig. 4). In these cases there are valid reasons for this discrepancy. To understand these relationships more information or knowledge is needed about the site, which necessitates a greater understanding of site landscape position, overland flow dynamics, recent drainage history pertaining to design (e.g. spacing, depth, materials used) and maintenance. In the case of F1, this is due to the influence of recently installed and fully functional in-field drains, which are believed to be influencing two of the dipwells (3 and 4 in Fig. 7) that show no correlation between rainfall and water table rise. This is likely due to the siphoning off of infiltrating drainage water to the open ditches during and after rainfall events. There may also be some input of water from the in-field drain system during very high rainfall events if water becomes backed up into the field drain system from the surface drain and leaches out into the surrounding soil. Another dipwell, 1, located very close to the intersection of the two surface drainage ditches that border the field, consistently recorded a WTD of around 50 cm which may indicate the efficacy of the surface drains at close distances.

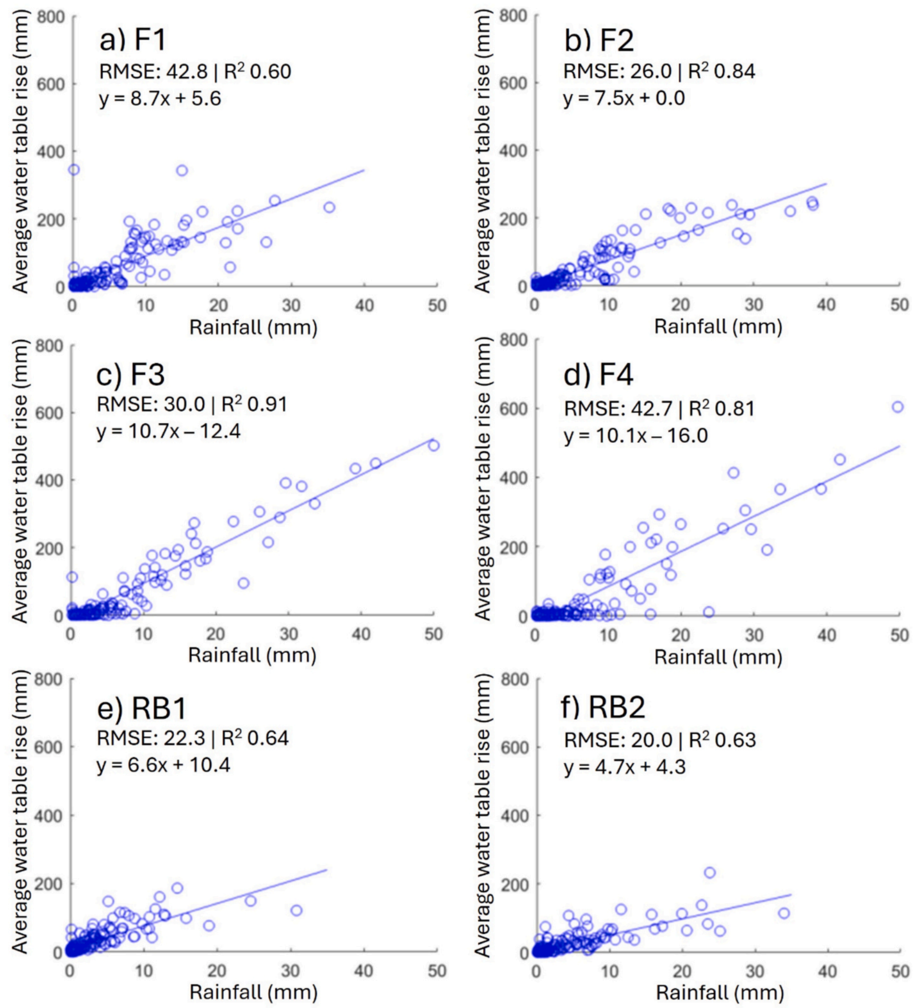

Fig. 4. Event-based average water table rise in all five dipwells at each site vs. rainfall correlations. Each blue circle indicates an event that met the criteria for analysis over the study period and the blue line indicates the corresponding correlation. Root mean squared error (RMSE) and R^2 values are included for each correlation. Abbreviations used: F = fen; RB = raised bog.

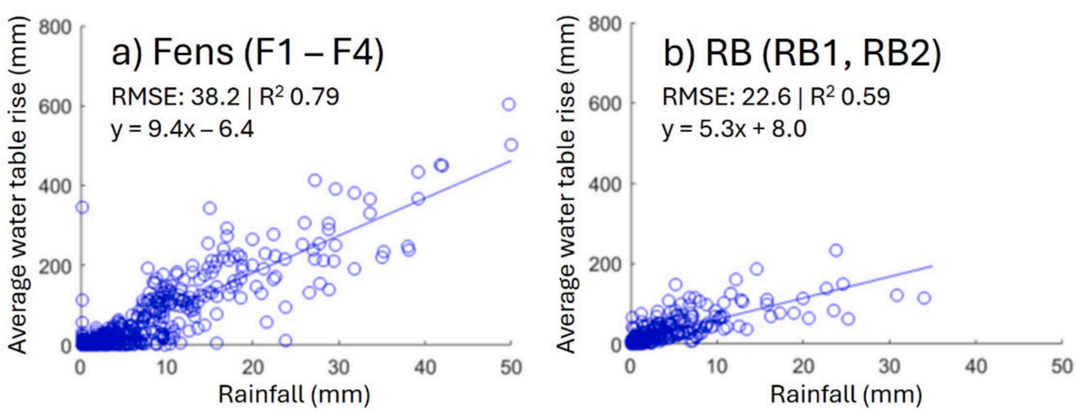

Fig. 5. a) Event-based average water table rise in the five dipwells at each of the fen sites (F1–F4) vs. rainfall correlation. b) Event-based average water table rise in the five dipwells at the two RB sites (RB1 and RB2). Each blue circle indicates an event that met the criteria for analysis over the study period and the blue line indicates the corresponding correlation. The R^2 value of the correlation and equation for the linear regression are shown.

In the cases of RB1 and RB2, the lower R^2 values may be due to higher water tables present at the RB sites. Due to the nature of peat soil, the surface can be very wet, and ponding can occur frequently when the water table is at or above the ground surface in one or more of the dipwells, instances that were excluded from the event-based analysis. These excluded events were more likely to be those with higher rainfall amounts, meaning that the remaining data to be analysed is skewed towards smaller rainfall events. Additionally, these sites had shallow

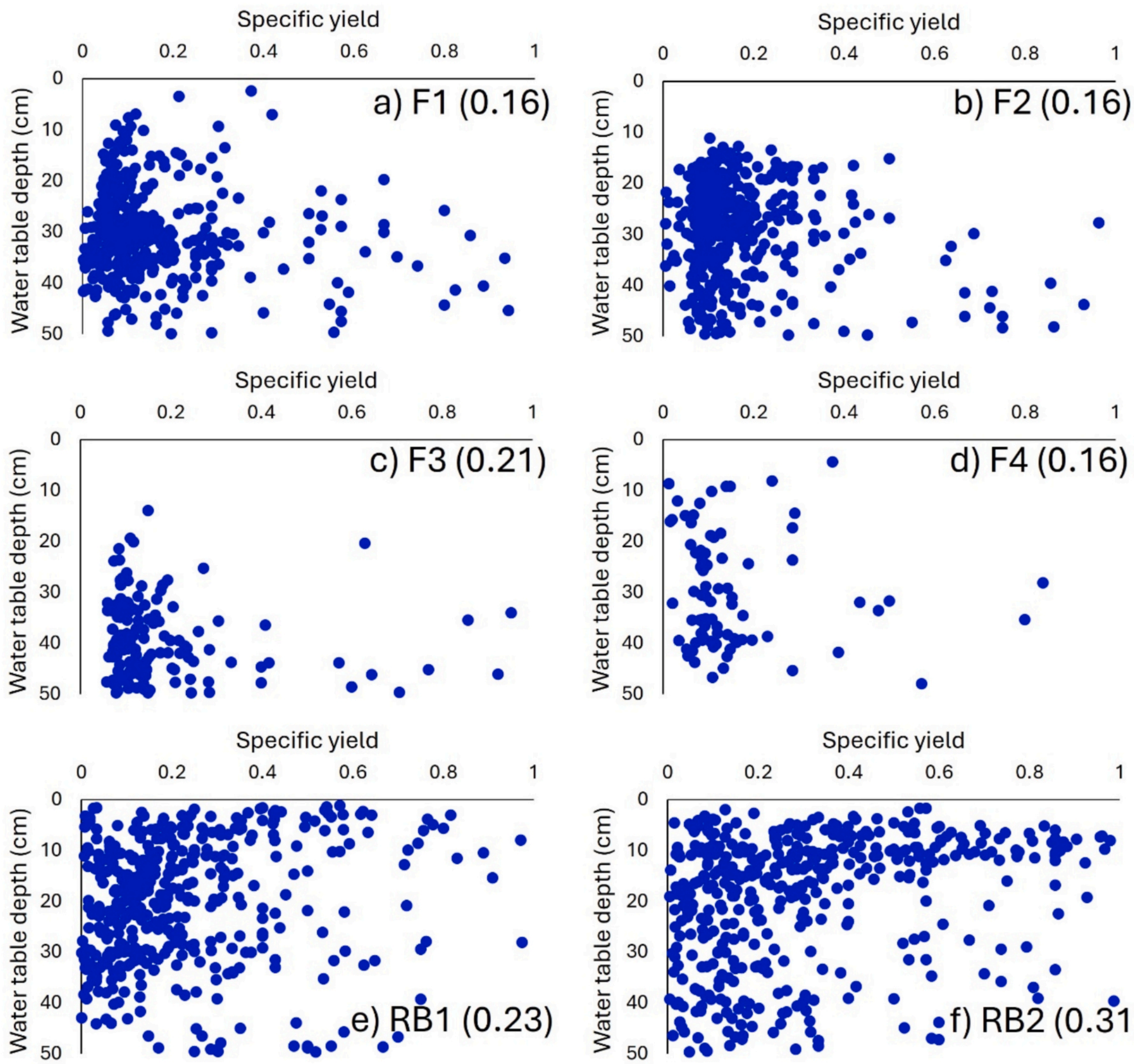

Fig. 6. Distribution of specific yield (S_Y) in each dipwell at each site. Each blue dot represents the S_Y calculated in peat soil in each dipwell. The site's average S_Y value is shown in parentheses after the site name. Abbreviations used: F = fen; RB = raised bog.

water tables that did not allow for much fluctuation during events, leading to a flatter sloped correlation and possibly contributing to the lower R^2 values at these sites. Incorporating data over a longer time period may improve the correlation at this site. Therefore, drainage or drainage impedance can both influence the relationship between rainfall and water table dynamics.

In the present study, F1 has been shown to be an outlier when compared to its partner fen sites, and such information should be taken into account for future water table management endeavours at the site. The F1 site may react similarly to the rest of the fen group if the in-field drainage was blocked or removed. However, this effect may not be immediate as other studies have demonstrated that it can take peat soils years to recover after rewetting efforts (Holden et al., 2011). Sites RB1 and RB2, although classified as drained grassland peat soils, had an average WTD of 12.2 cm and 15.7 cm, respectively, and therefore according to the IPCC (2014) definition, are considered ‘rewetted’ and would not require further management intervention to raise the water table. More monitoring should be done to determine if the average annual water table remains above 30 cm even during years with less rainfall than the study period. Therefore, an important aspect to consider at any site is the location of dipwells with respect to existing land drainage infrastructure (i.e., in terms of distance away from open drainage ditches and in-field drains) and landscape position (i.e., avoid areas where run-on or low permeability could induce ponding conditions) that may interfere with rainfall-water table rise correlations and interpretations.

Sites F2, F3 and F4 were the sites with the strongest correlation between rainfall and water table rise, which is consistent with their larger water table fluctuations. These were deeply drained fen sites where smaller amounts of rainfall resulted in larger rises in the water table. When the fen sites were grouped together, they showed an overall moderately strong correlation between rainfall and water table rise. Sites F2 and F3 may be the most appropriate to target for restoration efforts since they have relatively deep peat soil profiles and drainage depths that are not significantly deeper than 30 cm, especially F2 which had an annual WTD of 41.3 cm. Site F4 had shallower peat across the site and a much deeper average annual WTD (114.1 cm) and therefore may need more extreme water table management interventions in order to raise the average annual WTD to above 30 cm.

4.2. *Depth-specific S_Y*

Larger S_Y values are expected closer to the ground surface in peat soils, with declining S_Y values expected with depth (Bourgault et al., 2017). This is seen in the RB sites (RB1 and RB2) which have larger S_Y values and high, stable water tables with small fluctuations (Fig. 6). This

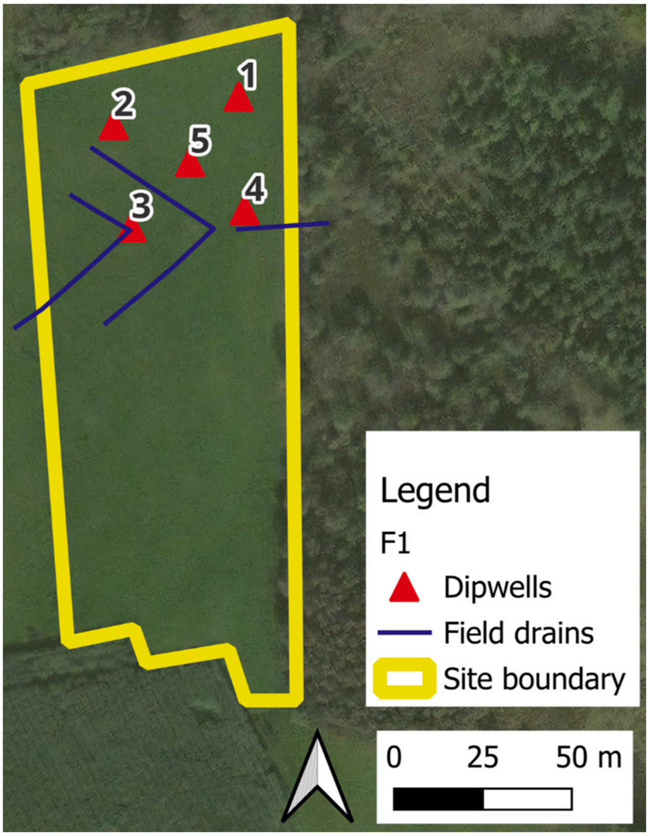

Fig. 7. Map of F1 showing the location of the dipwells, evidence of field drains that is visible on the ground surface and site boundaries. The northern and eastern site boundaries shown are surface drainage ditches.

was not seen for the fen sites (F1 – F4), which all showed a clustering of lower S_Y values at shallower depths and wider ranges of S_Y values at deeper depths. The S_Y values at the fen sites (F1 – F4) are lower (Fig. 6). Lower S_Y values occur where there are large water table fluctuations and are associated with drainage in peat soils (Loisel and Gallego-Sala, 2022). There is a bias towards overestimation of S_Y using this calculation especially at deeply drained sites that have deeper water tables. When water table position is deeper in the peat soil profile, some of the rainfall measured during an event will remain in the upper horizons of the wet soil or be taken up by plants before causing a rise in the water table. The total rainfall amount for the event, which is used to calculate S_Y, includes this amount retained by the soil which does not affect water table fluctuation and therefore one disadvantage of this method in peat soils is that it can overestimate S_Y (Lv et al., 2021). Therefore, the average S_Y values may be overestimated at the deeply drained fen sites as they have deeper water tables (Fig. 6). To reduce this bias towards higher S_Y at deeper water table depths, S_Y was only calculated when the water table was within 50 cm of the ground surface.

The apparent S_Y values calculated at the sites indicate that the shallow drained RB sites and the deeply drained fen sites behave differently. The S_Y values indicate that the RB sites are acting more like natural peat soils, with higher S_Y values closer to the ground surface and declining values at depth, and that these sites have a larger storage capacity for water. Such high values limit water table fluctuations maintaining near saturation values. It also means that it would take larger rainfall inputs to see larger rises in the water table at these sites since their reaction to external influences are buffered. The lower S_Y values in the deeply drained fen sites indicate that there is less storage capacity at these sites and smaller rainfall amounts therefore result in larger increases in the water table. Raising the water table at the deeply drained fen sites may increase the storage capacity at these sites, however this may only be apparent after a significant length of time has passed. A period of 20 years of rewetting was found to be sufficient to increase storage capacity of a previously drained fen in Germany (Ahmad et al., 2020). Once rewetting has occurred over a sufficient period at the deeply drained fen sites to increase their S_Y values, this increased storage capacity will help buffer these sites from external influences as seen in the RB sites and these areas should become less susceptible to artificial drainage efforts, droughts and flooding. Since the fen sites have lower storage capacities and are linked to the regional groundwater table, these areas may be difficult to raise the water table on consistently and may require more intervention than just drain blocking, such as subsurface irrigation in addition to drain blocking (Heller et al., 2025).

When considering both the rainfall and water table dynamics and the S_Y at these sites, it emerges that the RB and fen sites behave differently. The rainfall and water table rise relationships at sites were influenced by factors such as the presence of field drains and surface drains at the sites, which in some instances made it difficult to classify the sites into two groups hydrologically. However, including the calculated S_Y at sites helped to both explain the rainfall and water table relationships that were observed and enable the sorting of the sites into two distinct groups based the distribution of S_Y at depth that were observed at the six sites.

5. Conclusions

The relationship between rainfall and water table depths and the S_Y in different lowland grassland peat soils revealed differences between and within peat soil parent types. Sites that were classified based on their soil characteristics as fen peats emerged as a distinct group hydrologically from the sites that were classified as RB. There were also differences found within the group of four sites that were classified as fens.

This study demonstrates that even with similar drainage techniques and maintenance, RB are more difficult to effectively drain than fen peat sites, demonstrated by the consistently higher water tables at these sites despite a similar drainage design to nearby fens. A very high drainage intensity is needed at RB sites to control the water table depth and the lateral water table effect from open ditches is limited. This observation is supported by the larger S_Y values calculated at the RB sites, which buffer these areas from external influences and therefore they are less reactive to rainfall, drought and artificial drainage. In terms of water table management, these attributes for restoration purposes are advantageous since these sites already maintain shallow WTD even with drainage and therefore may not need any intervention in order to meet the criteria for rewetted peat soils. The fen peat sites were able to be more deeply drained and had deeper water tables that were more reactive to rainfall inputs with correspondingly lower S_Y. In terms of water table management, these fen sites may also be more difficult to manage as they are connected to the regional water table and have seasonally variable water table depths. However, there is an opportunity at these sites which are considered deeply drained, but which have deep peat soil profiles and average annual WTD that are not much deeper than 30 cm, to potentially alter the drainage status to raise the average annual WTD to above 30 cm.

As grassland peat soils are being targeted for active water table management to raise the water table to an average depth of within 30 cm of the soil surface, the present study has shown that understanding site specific relationships between rainfall and the water table are important criteria for establishing eligibility and baseline conditions for any site. Some lands may be more suitable for these rewetting efforts based on these relationships. Before any water table management is carried out, the methodology presented herein should be deployed at a site to give further insights to whether it has potential for restoration or not. This methodology will show if a site is similar or different to other sites both within the same peat type or across peat types. This will enable the targeting of specific types of restoration efforts to specific sites and may also show that some sites which may be considered deeply drained already have WTD that remain above 30 cm and therefore do not require further water table management.

CRediT authorship contribution statement

Hilary Pierce: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Owen Fenton:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Eve Daly:** Writing – review & editing, Supervision, Funding acquisition. **Asaf Shnel:** Resources, Data curation. **David O'Leary:** Writing – review & editing, Software, Data curation. **Mark G. Healy:** Writing – review & editing, Supervision, Funding acquisition. **Patrick Tuohy:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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