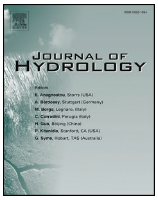
Journal of Hydrology 664 (2026) 134498

Contents lists available at ScienceDirect

Journal of Hydrology

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



Research papers

The influence of plantation forest legacy on blanket bog hydrology

Muhammad Jehanzaib[a], Raymond Flynn[a], Vicky Preece[a], Hannah Lehnhart-Barnett[b], Devin F. Smith[c], Oisín Leonard[b], Tiernan Henry[b], W. Berry Lyons[c], Anne E. Carey[c,*], Peter Croot[b]

[a] School of the Natural and Built Environment, Queen's University Belfast, Belfast BT9 5AG, United Kingdom
[b] Earth & Ocean Sciences, School of Natural Sciences, University of Galway, Galway H91 TK33, Ireland
[c] School of Earth Sciences, The Ohio State University, Columbus, OH 43210-1398, United States

ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Michael Bruen, Associate Editor

Keywords:
Blanket bogs
TOPMODEL
Clear-felling
Streamflow
Hydrological modelling
Ireland

ABSTRACT

Human activities in headwater blanket bogs can lead to downstream flooding due to changes in land cover; however, the effects of the geographic distribution of these land cover modifications, especially the role of legacy of plantation forestry on hydrological regime, remains poorly characterized. Therefore, the focus of this research is to estimate the impact of legacy of plantation forestry on streamflow in small (21 ha) blanket bog catchment of Ireland. A network of groundwater monitoring and hydro-meteorological stations were installed to collect high-resolution (15 min to 1 h) hydro-meteorological and groundwater level data. Generalized Multistep Dynamic (GMD) TOPMODEL was calibrated using high resolution (1 m × 1 m) Light Detection and Ranging (LiDAR) and hydro-meteorological data in intact blanket bog watershed. The calibrated model was validated before simulating in degraded (legacy of plantation forestry) catchment. The effect of legacy of plantation forestry on streamflow was examined by comparing observed and simulated streamflow series at various timescales (monthly, seasonal, and yearly). The results indicated that streamflow increased by 106 % annually due to legacy of plantation forestry, with the highest monthly increase recorded in February (275 %) and the lowest in September (16 %) when compared to intact blanket bog. Seasonal analysis revealed an increase in streamflow attributed to legacy of plantation forestry, with the highest increase observed in winter (237 %) and the lowest in summer (24 %). Minimal interception losses, reduced evapotranspiration, and compact bog contribute to elevated runoff relative to undisturbed conditions. The results of this study assist water managers, stakeholders, and policymakers in facilitating effective planning and decision-making.

1. Introduction

Peatlands cover almost 3 % of the Earth's terrestrial surface, are found in over 180 nations, and are recognized as ecologically significant globally (Yu et al., 2010; Xu et al., 2018). They act as biodiverse habitats that also serve as carbon sinks (Bonn et al., 2016). Peatlands are predominantly developed in environments characterized by high and frequent precipitation (>1250 mm/year and number of rainy days/year >200) (Mitchell and Ryan 1997), including highland areas in temperate and boreal zones or lowland regions where gentle slopes, impermeable substrates, or topographic convergence can maintain saturation (Holden et al., 2004). They are classified based on two fundamental factors: source of water and nutrient source (Wheeler and Proctor, 2000).

Blanket bogs are known as ombrotrophic peatlands that depend on precipitation for water and nutrient supply, while fens (minerotrophic peatlands) are more reliant on groundwater for water and nutrient supply (Johnson and Dunham, 1963). Blanket bogs are the most widespread peatland type in the United Kingdom and Ireland, accounting for approximately 20 % of the global blanket bog resource (Wildlife Trusts, 2021). This includes mountainous regions, where blanket bog has formed on various substrates, ranging from low permeable glacial clays to limestone aquifers (Geological Survey of Ireland, 2024). Furthermore, throughout Great Britain and Ireland, blanket bog catchments serve as a significant supply of potable water owing to substantial and frequent precipitation, coupled with low pollution pressures, hence assuring high raw water quality in considerable quantities (Xu et al., 2018).

Intact bogs are vital for maintaining hydrological stability and mitigating climate-related water challenges. They have been reported to

---

* Corresponding author.
E-mail address: carey.145@osu.edu (A.E. Carey).

https://doi.org/10.1016/j.jhydrol.2025.134498
Received 24 February 2025; Received in revised form 9 October 2025; Accepted 27 October 2025

serve as natural reservoirs providing a consistent water release particularly during dry spells (Holden et al., 2004). They can mitigate flood risks caused by heavy rainfall by absorbing and slowly releasing water, while also maintaining base flows in rivers and streams (Gao et al., 2015). A waterlogged environment and low fertility restrict blanket bog's ability to produce traditional economic products in its intact state (Flynn et al., 2022). This has resulted in considerable drainage activity to lower the water table and convert bog to different land uses (Flynn et al., 2022). According to Biancalani and Avagyan (2014), peatland drainage is the main cause of environmental degradation. This can be attributed to several factors, including increased carbon loss, biodiversity loss, increased frequency of fires, land degradation, and increased susceptibility to soil erosion. The drainage and removal of vegetation during peat extraction have a significant influence on blanket bog hydrology, biological functioning, and soil water chemistry (Heikkinen et al., 2018). Moreover, the rainfall-runoff processes are also influenced by afforestation in peatland catchments (Heal et al., 2004). Drainage, interception by tree canopy, evapotranspiration, and shrinkage of peat, afforestation, grazing, and burning all modify the hydrological regime of afforested peat watersheds (Holden et al., 2004). Furthermore, degraded bogs have been reported to intensify flooding by diminishing their water retention capacity, resulting in accelerated runoff and elevated peak flows downstream (Goudarzi et al., 2024). Knowledge of hydrological dynamics in relatively intact blanket bogs provides a scientific foundation for establishing attainable restoration objectives for degraded areas.

At the start of the 20th century, total forested (natural and afforested) areas accounted for 1 % of total land cover in Ireland (Eaton et al., 2008). Since 1950, successive Irish governments have pursued a program of increasing forest cover; the figures for 2022 indicate that forest cover is at 11.6 % (with plans to increase this to 17 % by 2030) (Department of Agriculture, Food and the Marine, 2024). The majority of afforestation in recent decades has taken place on peatlands that were traditionally unsuitable for agricultural use. This has altered hydrological regimes. Drainage is typically carried out prior to plantation using a combination of closely spaced plough furrows and deeper, more widely-spaced ditches (Department of Agriculture, Food and the Marine, 2024). Land cover changes including afforestation have a substantial influence on storm hydrographs in blanket bogs (Grayson et al., 2010). Interception losses are one of the most important factors in influencing the rainfall-runoff response of a forested peatland watershed. Several studies have documented greater interception losses in forested peatlands (Anderson et al., 1990; Heal et al., 2004; Johnson, 1990; Sottocornola and Kiely, 2010). Anderson et al. (1990) observed a 38 % loss from canopy interception and 12 % from transpiration on afforested peatlands in the UK. Johnson (1990) discovered an average interception loss of 28 % over the course of three years from a 50-year-old Sitka spruce forest in the Scottish Highlands. Heal et al. (2004) conducted research in Scotland's Sitka spruce-forested peatland and discovered that interception loss exceeded 50 % of yearly precipitation. Evapotranspiration (ET) observed for a period of 5 years to be 15.5 % of the total precipitation in pristine blanket bog in southwest Ireland (Sottocornola and Kiely, 2010). All these investigations indicate that ET rises, and stream flow decreases in afforested blanket bogs. By contrast, loss of the canopy is suspected to lead to a subsequent rise in stream flow and fall in interception in deforested blanket bogs.

Hydrological modelling techniques can simulate and quantify the effects of land cover on streamflow in peatlands. Different land cover scenarios can be developed and simulated using hydrological models, with each scenario can be simulated under similar meteorological conditions. Simulations generated by these scenarios can help in understanding the influence of various land cover types on blanket bog hydrology. Many hydrological models that can simulate mineral soils are not well adapted for peatlands (Beven and Kirkby, 1979; Reggiani et al., 2000). However, others have proven more promising. Dunn and Mackay (1996) utilized SHETRAN hydrological model to study the impact of ditches on peatlands, while Lane et al. (2004) adapted TOPMODEL to incorporate high-resolution Digital Terrian Model and applied it to a 13.8 km^2 upland catchment in the United Kingdom. Lane and Milledge (2013) combined the Network Index version of TOPMODEL with spatially distributed unit hydrograph (SDUH) routing to account for water supply time from various catchment areas to the outlet. Ballard et al. (2011) implemented a physical-based model to study streamflow and water table responses under various drainage scenarios, and they discovered that the model performed better in wet conditions. Lewis et al. (2013) studied the impact of afforestation on annual streamflow and ground water level using GEOtop model. They found that annual streamflow was 20 % lower and groundwater levels were 20 cm lower than observed. Land cover changes in sensitive areas of uplands, such as riparian zones, can have a greater impact on flow peaks than in headwater regions (Gao et al., 2016).

Despite these advances, the contrast in modelling techniques applied offers potential for inconsistent approaches and outputs. However, many studies employed TOPMODEL to simulate runoff response on different land cover as it offers wide range of benefits such as it uses topographic index, and it factors out the impact of topography (Lane et al., 2004; Gao et al., 2015; Gao et al., 2016; Goudarzi et al., 2021; Goudarzi et al., 2023; Goudarzi et al., 2024). Moreover, its open access status facilitates more widespread use, including in programmes with limited financial resources. TOPMODEL is employed in current research based on its widespread usage and robustness.

Most studies stated in the literature were conducted on large (> 10 km^2) blanket bog watersheds and examined the influence of various land cover changes on streamflow in blanket bogs (Gao et al., 2016; Gao et al., 2018; Lane et al., 2004; Lewis et al., 2013). However, no study has been conducted to investigate the influence of legacy of plantation forestry on streamflow in blanket bogs in smaller (10 s-100 s ha) catchment. In this text “legacy” refers to areas that have been clear felled with few or any intact trees remaining, and with stumps, furrows, and brash left *in situ*, as observed widely in commercial plantations. This study is a comprehensive investigation of the influence of intact and degraded (legacy of plantation forestry) blanket bogs on streamflow. The aim of this work is to assess the impact/influence of legacy of plantation forestry on the runoff regime of a small blanket bog catchments in the west of Ireland. Additionally, the relative impacts of legacy of plantation forestry on monthly, seasonal, and annual runoff regime are examined.

2. Material and methods

2.1. Description of study area

The blanket bog hydrology research site Letterunshin is located in the Ox Mountains Bogs, Special Areas of Conservation (Latitude 54.185° and Longitude −8.911°) in Co. Sligo, Republic of Ireland (Ireland) (Fig. 1). The total catchment area is 2.14 km^2 including 1.93 km^2 of relatively intact blanket bog and 0.21 km^2 (21 ha) of degraded area (legacy of plantation forestry). This is part of a much larger area of elevated blanket bog that forms the headwaters of the River Easkey. Ground elevations range from 107 to 149 m above mean sea level (AMSL) and majority of the study catchment lies within the range of 130 to 145 m AMSL (Fig. 1). Long-term (1991–2020) average annual rainfall in Letterunshin is approximately 1503 mm (Curley et al., 2023).

The Letterunshin site is dominated by several types of sphagnum mosses and other species such as *Eriophorum angustifolium, Narthecium ossifragum, Calluna vulgaris, Eriophorum angustifolium*, and certain areas are covered with *Rhynchosporion* vegetation (Perrin et al., 2013). On the relatively flat upland portions of the site, there are several dystrophic pool systems and widespread piping was observed at headwaters. Vertical shafts and swallow holes in the bog surface indicate the presence of a network of naturally formed peat pipes that discharge at the ground surface to create the source of the Fiddanduff River that drains the site (Flynn et al., 2022). Geological Survey of Ireland (2022) Mapper

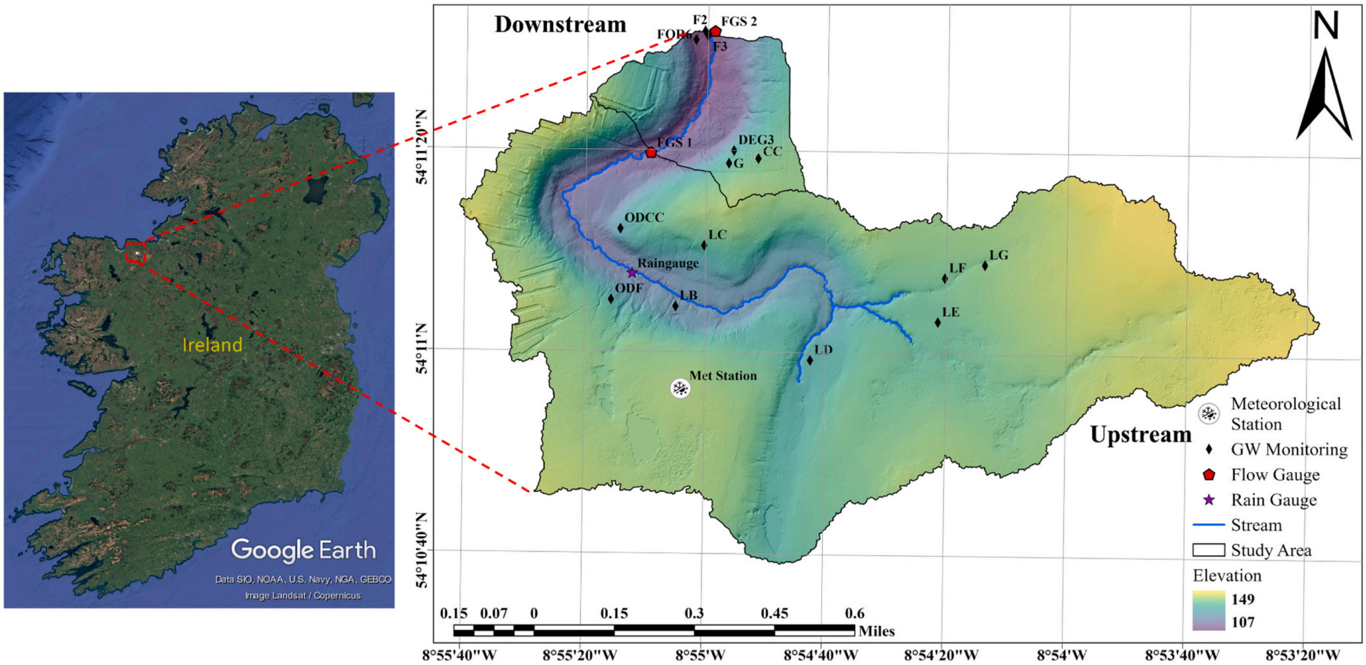


Fig. 1. Location of study area showing elevation of the terrain and location of hydro-meteorological stations (Google Earth, 2024). Upstream area is intact (1.93 km^2) and downstream area is degraded (0.21 km^2).

Quaternary Geomorphology landform maps designate the Fiddanduff River as a glacial meltwater channel. The study catchment is underlain by the Lower Carboniferous (Dinantian) Upper Ballina Limestone Formation, which is designated as a regionally important karstified aquifer, implying potentially high transmissivity rates.

Perrin et al. (2013) state that although there is evidence of previous burning at this site and some small-scale peat extraction at the edges, the land is mainly free of artificial drainage and is still in a reasonably intact state. Coniferous forestry was planted in early 1990 s at the lower end of the watershed in furrow ridge plantation system, and it was clear-felled between December 2022 and January 2023. The slopes on either side of the stream in the lower end of the catchment are now clear felled. Fig. 2 shows the land cover change before and after the end of 2022/start of 2023 in the Fiddanduff River's watershed.

2.2. Data

A network of hydro-meteorological instruments was installed across the catchment as part of this and previous studies (Flynn et al., 2022) to record meteorological, hydrological and hydrogeological data. A Davis Instrument, Vantage Pro-plus Weather Station (Davis, California) was installed at 142 m AMSL, recording rainfall, temperature, wind speed, solar radiation, humidity, atmospheric pressure and evapotranspiration (ET) at 30-minute intervals. A sensor error at this station meant that there was a temporal gap in ET data collection, so ET data at daily timestep was obtained from the closest Met Éireann autographic station at Belmullet (https://www.met.ie/climate/available-data/historical-data). A second rain gauge (EML ARG314) was installed at 119 m AMSL to assessment of precipitation variability across the catchment (rainfall was recorded here at 15-minute intervals). Four flumes were installed in the study area, but that for this study only the data from two are being used. Two flumes having dimension (2.5 m length × 1.5 m width × 1.0 m depth) were erected at the stream headwater to provide continuous monitoring of stream flow at the outlets of both intact and degraded catchments with varying land use patterns. A CS451 Pressure Transducer (Resolution = 0.00035 m, accuracy = +/- 0.1 %) was installed in a stilling well adjacent to flume near the intact catchment's outlet, measuring stage at 15 min time interval. Similarly, stage measurements were made possible at the outlet of degraded catchment by installing CS451 Pressure Transducer inside a standpipe next to a stream section with a fixed cross section. Rating curves were developed by employing tracer injection technique using OTT Hydromet (Kempten, Germany) sensor for each flume as provided in supplementary file (Fig. S1 and S2). Each rating curve was divided into three parts based on stage values (0–0.255 m, 0.256–0.61 m, >0.61 m) and three rating equations were formulated to convert stage into streamflow. The lower end of rating curve (0–0.255 m) was also validated using volumetric method (Fig. S1 and S2) and assumed the derived rating equations are correct. Groundwater levels were recorded on an hourly basis in piezometer clusters at 15 catchment locations. Topographical data are a key in hydrological modelling. In 2017, Bluesky International conducted airborne LiDAR (Light Detection and Ranging) surveys of Letterunshin employing an Optech Galaxy LiDAR Sensor. The minimum point density was 8 ppm, with an estimated vertical accuracy of +/- 0.15 m. A high resolution (1 m × 1 m) Digital Terrain Model (DTM) was provided in ASCII format. Previous studies (Mackin et al., 2017; Regan et al., 2019) have shown that this resolution is appropriate for ecohydrological modelling of peatlands in Ireland.

2.3. Hydrological modelling

TOPMODEL, developed by Beven and Kirkby (1979), and its variants are widely used in rainfall-runoff modelling of blanket bog catchments (Lane et al., 2004; Gao et al., 2016; Goudarzi et al., 2021). Lane et al. (2004) proposed a Network Index variant of TOPMODEL that routes the interconnected segments of saturated areas as overland flow; however, this enhancement inadequately elucidates the flood generation process. The majority of TOPMODEL variants are of semi-distributed nature; to reduce calculation time, they combine the sections of a catchment are likely to yield the same runoff response to the same rainfall. The lumped sections are called Hydrologically Similar Units (HSU), and the "similarity" is measured using a Topographic Index (TI) value that is particular to each catchment and computed for each Digital Elevation Model (DEM) cell. Goudarzi et al. (2021) suggested that semi-distributed TOPMODEL can be used to model landcover changes in micro-catchments. Goudarzi et al. (2023) proposed a generalized multistep

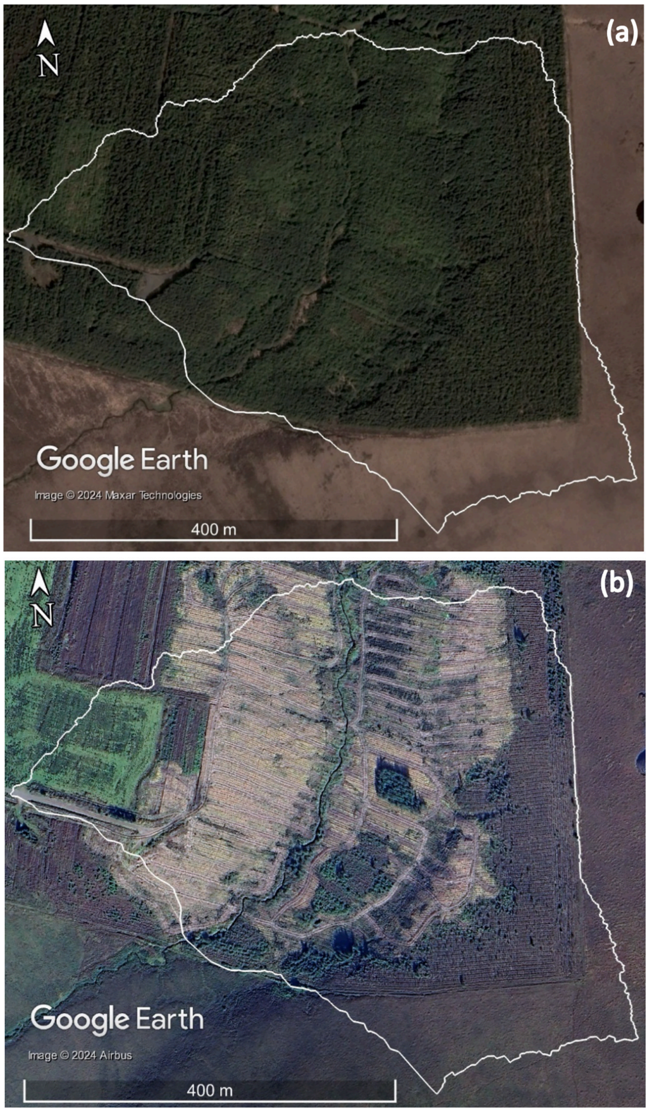


Fig. 2. Depiction of landcover variation in degraded watershed: a) planted forest in early 1990 s (image taken in April 2011), b) deforested area or dead forest (legacy of planted forest) after early 2023 (image taken in September 2024) (Google Earth, 2024).

dynamic (GMD) TOPMODEL with additional improvements, including the addition of an *iso*-basin discretisation layer to limit spatially distributed information. Iso-basins are sub-catchments within a large catchment representing distinct landcover. The improved GMD-TOPMODEL proposed by Goudarzi et al. (2023) and Goudarzi et al. (2024) was used in this study to model the response of legacy of plantation forestry on streamflow. The modified GMD-TOPMODEL includes six calibration parameters presented in Table 1.

The model parameters were calibrated using the Generalized Likelihood Uncertainty Estimation (GLUE) framework (Beven and Binley, 1992). Parameter ranges were defined based on literature review and by using Latin Hypercube method (Goudarzi et al., 2021), and 80,000 parameters sets were made. TOPMODEL ran 80,000 times on a High-Performance Computer (HPC) to test the performance efficiency of each parameter set. Only parameter combinations that optimised the objective function and demonstrated a realistic association between the observed and simulated streamflow were retained (Jehanzaib et al., 2020). The TOPMODEL was evaluated based on Kling-Gupta efficiency (KGE) (Gupta et al., 2009), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), and Root Mean Square Error (RMSE).

Table 1
Calibration parameters of GMD-TOPMODEL.

Parameter symbol	Unit	Detail	Range
$\widehat{\boldsymbol{d}}$	–	Exponent of decay of transmissivity with depth	10 – 14
$\widehat{\boldsymbol{T}}_{\boldsymbol{o}}$	m/s	Maximum transmissivity, that is, at the surface	10^{-5} – 0.1
$\widehat{\boldsymbol{e}}_{\boldsymbol{p}}$	mm/day	Annual average daily potential evapotranspiration rate	0.005 – 0.1
$\widehat{\boldsymbol{S}}_{\boldsymbol{m}}$	m	Maximum rootzone storage	10^{-6} – 0.01
$\widehat{\boldsymbol{n}}_{\boldsymbol{hs}}$	s/m$^{1/3}$	Hillslope Manning’s roughness coefficient	0.1 – 4
$\widehat{\boldsymbol{n}}_{\boldsymbol{ch}}$	s/m$^{1/3}$	Channel Manning’s roughness coefficient	– 2

$$KGE = 1 - \sqrt{(1-\gamma)^2 + (1-\alpha)^2 + (1-\beta)^2} \tag{1}$$

where, γ is the correlation coefficient, α is the variability, and β is the bias ratio between observed and simulated streamflow.

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{N}\left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(Q_{sim,i} - Q_{obs,i}\right)^2}{N}} \tag{3}$$

where, Q_{obs} is the observed streamflow, $\overline{Q_{obs}}$ is the mean of observed streamflow, Q_{sim} is the simulated streamflow, and N represent number of observations. The values of KGE and NSE assess the overall goodness-of-fit between observations and simulations. When the simulations fully correspond to the observations, the values of KGE and NSE equal one, and RMSE equals zero.

2.4. *Quantification of relative impact of legacy of plantation forestry on streamflow*

To model the impact of legacy of plantation forestry on streamflow, GMD-TOPMODEL was calibrated on the intact blanket bog catchment using GLUE framework. This calibrated model (employing intact blanket bog catchment parameters) was then used to simulate streamflow on the degraded catchment. The streamflow simulations made by the calibrated TOPMODEL were compared with the observed streamflow at the degraded catchment outlet to gauge the impact of the legacy of plantation forestry. To investigate the relative impact of legacy of plantation forestry on a monthly, seasonally and yearly basis, observed and simulated streamflow were converted to monthly, seasonal and yearly time series as these timescales are mostly used in literature for comparison (Zou et al., 2018; Achite et al., 2023).

3. Results

Stream stage data recorded at 15-minutes intervals between December 2023, and November 2024 were converted to streamflow values. Details of the hydrometry data are provided in Table 2. The annual rainfall for this period was 1368 mm (less than the 30-year long-term average rainfall of 1503 mm). LiDAR data (1 m × 1 m) was extracted according to intact and degraded watershed boundaries in ArcGIS Pro software prior to its application in TOPMODEL.

3.1. *Calibration and validation of TOPMODEL*

TOPMODEL is based on the concept of topographic index (TI). The TI values for individual DEM cells were calculated for both intact and degraded watersheds (Fig. 3). The cells having high TI values indicate

Table 2

Statistics of monthly hydro-meteorological dataset. T, PET, Q, and GW stand for temperature, potential evapotranspiration, streamflow, and groundwater, respectively.

Hydrometry	Statistics				
	Mean	Standard Deviation	Kurtosis	Skewness	Range
Precipitation (mm)	114.02	47.90	2.89	1.72	171.60
Mean T	10.67	2.80	−1.50	−0.02	8.33
PET (mm)	44.93	24.34	−1.74	0.15	61.20
Intact Q (m^3/s)	130.37	73.15	1.12	0.78	254.90
Degraded Q (m^3/s)	37.14	34.01	4.02	1.96	117.59
GW (mm)	−117.04	38.23	−0.98	−0.48	113.26

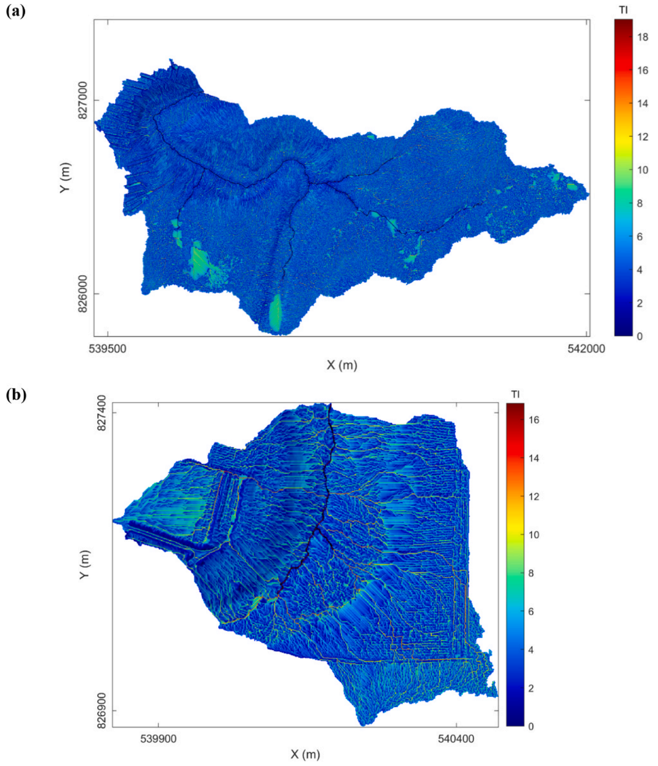


Fig. 3. Topographic Index values calculated via TOPMODEL: a) intact watershed and b) degraded (plantation forest legacy) watershed.

open heathland areas that are relatively flat and more likely to be saturated while cells having low TI values are more well-drained regions found on steep slopes. Cells lying on the stream channel have high TI value indicated by black colour in Fig. 3.

TOPMODEL was calibrated in the intact watershed using observed streamflow data for the period February 17, 2024, to August 31, 2024. The scatter plot in Fig. 4(a) shows good agreement between observed and simulated flow during calibration period with KGE = 0.92, NSE = 0.88, RMSE = 12.64 m^3, correlation coefficient = 0.95, and R^2 = 0.89 (Table 3). Fig. 4 illustrates that points above the 1:1 line represent model overestimations, whereas points below the line indicate underestimations. The loop formations in Fig. 4 reflect the correspondence between observed and simulated streamflow responses, arising from plotting high-resolution (15-minute) streamflow series on a scatterplot. TOPMODEL simulated peaks very well during the calibration period, with a small number of peak flows overestimated or underestimated (Fig. 5(a)). Fig. 6(a) is a cumulative plot of simulated streamflow during calibration period that shows a close correspondence with the observed flow, exhibiting a difference of 0.04 %, as indicated in Table 3. Calibrated TOPMODEL was validated between the period September 1, 2024, and November 20, 2024 and shows good correspondence with simulated flow (Fig. 4(b)). It underestimated two flow peaks (October 18 and November 17, 2024) but overall goodness of fit in validation period was satisfactory as shown in Fig. 5(b) and indicated by goodness of fit criteria provided in Table 3 (KGE = 0.88, NSE = 0.82, RMSE = 15.84 m^3, correlation coefficient = 0.92, and R^2 = 0.85). The cumulative plot (Fig. 6(b)) between simulated and observed flow during validation period indicated that TOPMODEL simulated 4.97 % less flow than observed. TOPMODEL simulations were further validated by comparing them with observed flow at various time intervals, with discrepancies remaining within a ±5 % range. The comparison of TOPMODEL simulations with observed flow over several times, specifically from March 14, 2024, to April 17, 2024, March 14, 2024, to July 06, 2024, June 1, 2024, to July 4, 2024, March 11, 2024, to May 31, 2024, and March 22,

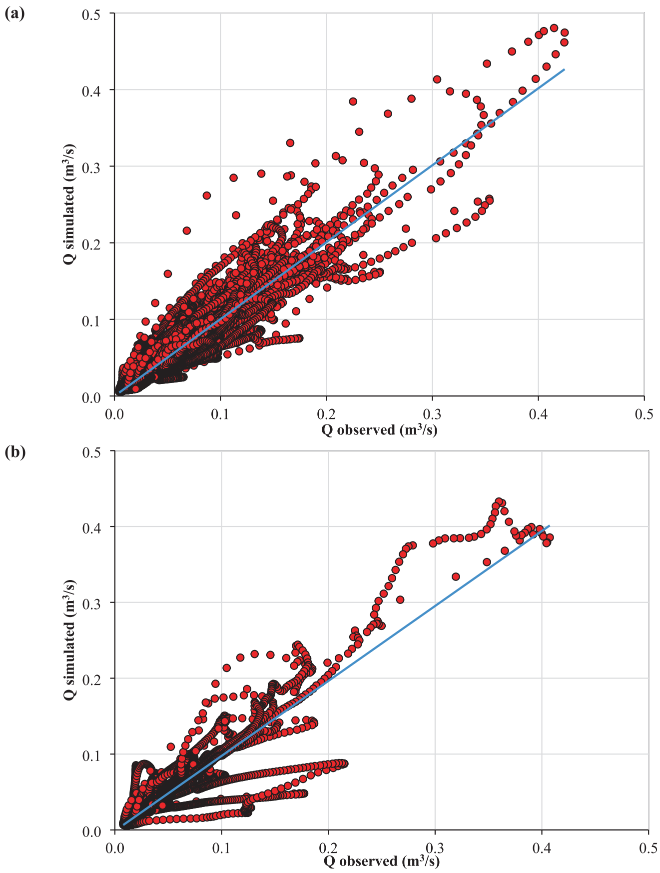


Fig. 4. Scatterplot of TOPMODEL showing model performance: a) calibration and b) validation at intact watershed. Solid blue line presents 1:1 line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

Performance evaluation of TOPMODEL during calibration and validation period.

Performance Indicators	Calibration	Validation
KGE	0.92	0.88
Correlation	0.95	0.92
NSE	0.88	0.82
R^2	0.89	0.85
RMSE (m^3)	12.64	15.84
Diff (m^3)	213.59	−11331.42
Percentage	0.04	−4.67
Fraction	1.00	0.95

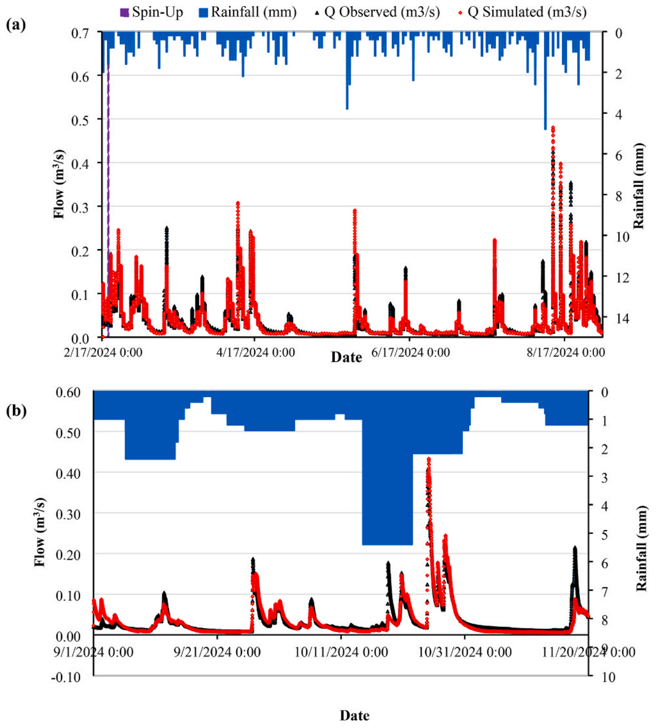


Fig. 5. TOPMODEL simulations during a) calibration period and b) validation period. Spin-up period is the warm-up period for model.

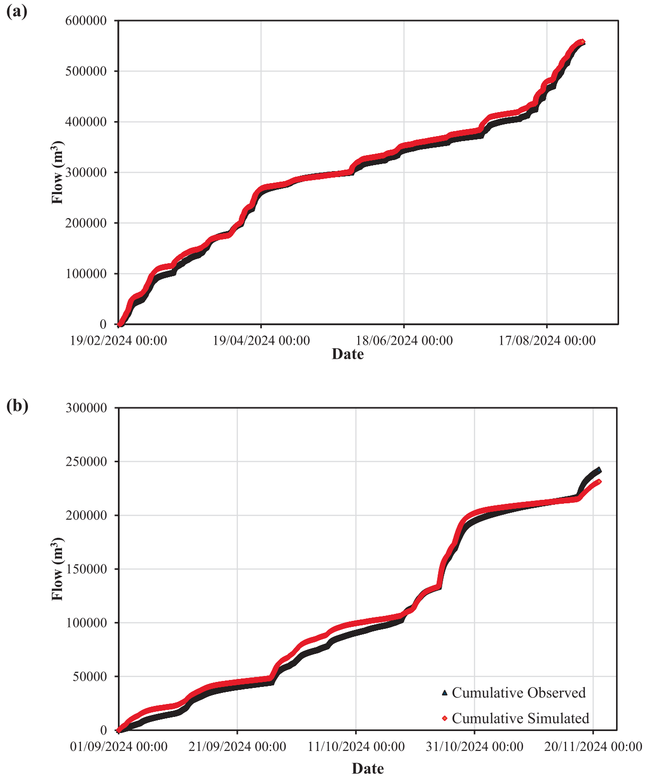


Fig. 6. Cumulative streamflow simulated by TOPMODEL during a) calibration period, and b) validation period.

2024, to June 10, 2024, yields discrepancies of −5%, −1.5 %, 0.5 %, −2.1 %, and −1.4 %, respectively (**Table S1**).

3.2. Impact of legacy of plantation forestry on streamflow

The calibrated TOPMODEL generated using data from the intact catchment was used to make simulations in degraded catchment for the year December 1, 2023 to November 30, 2024. The results suggest that TOPMODEL simulations generated lower flow than the observed streamflow (Fig. 7 **(a)**). A drastic increase was observed between observed and simulated flow in the winter period (December to February) compared to other seasons. Fig. 7 **(b)** shows that TOPMODEL simulated 56 % less flow than the observed values. These finding suggested that streamflow increased significantly due to legacy of plantation forestry in blanket bogs. It was also observed that flood peaks in intact condition are lower compared to degraded conditions. Fig. 7 **(a)** shows that flood peaks (in the wetter winter period and in response to discrete heavy rainfall events) are significantly higher in degraded conditions.

Month wise increases in streamflow between intact and degraded watershed were investigated. December was the wettest month (233 mm) with the lowest ET (16.4 mm), and high stream flows were recorded in both the intact and degraded watersheds. The second highest rainfall (183 mm) was observed in August, but less streamflow was observed due to increase in ET during this month. Results of month-wise comparison between streamflow in intact and degraded conditions are shown in Fig. 8 **(a)**. Seasonal analysis suggested that streamflow generation in winter was highest (largest rainfall, low ET and high groundwater table), whereas streamflow is very low in summer due to high ET, and low ground water table, more infiltration is required to recharge groundwater table. Seasonal streamflow trend shows Winter > Spring > Autumn > Summer as shown in Fig. 8 **(b)**.

Percentage change analysis between intact and degraded streamflow shows that highest percentage increase was observed in February (275 %) and lowest percentage increase was observed in September (16 %). Seasonal analysis showed that streamflow in degraded watershed was 237 %, 116 %, 24 % and 42 % higher than intact conditions in winter,

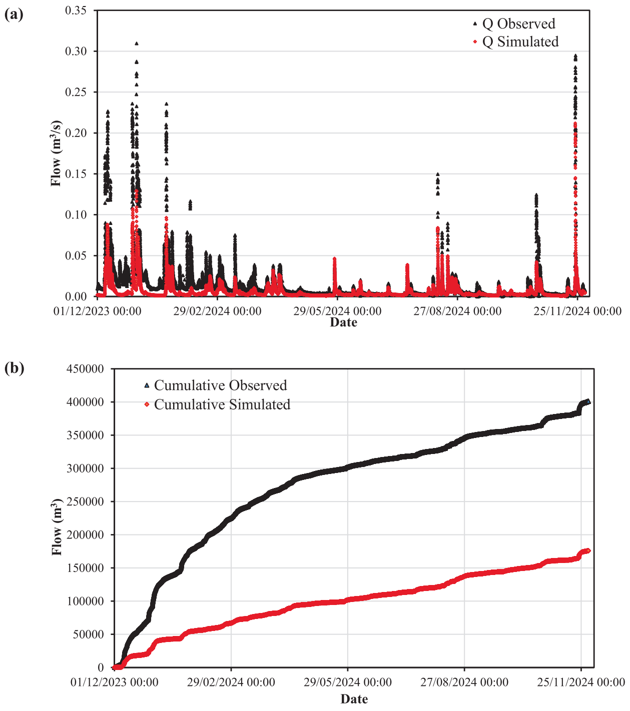


Fig. 7. Simulations produced by calibrated TOPMODEL in degraded watershed: a) simulations and b) cumulative flow.

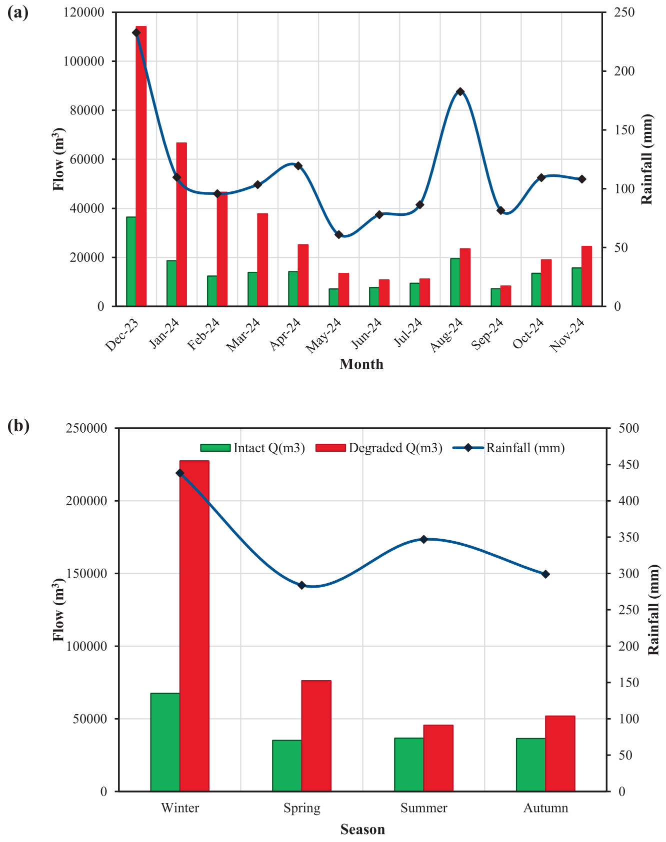


Fig. 8. Streamflow comparison between intact and degraded watershed and rainfall variability: a) monthly, and b) seasonally.

spring, summer and autumn season, respectively. The reduction in percentage increase between degraded and intact condition is due to the fact that losses resulting from ET are less in winter, while losses of water from ET and infiltration to recharge groundwater are higher in summer as shown by the monthly and seasonal percentage analysis in Fig. 9. Overall, outcomes of this study suggested that streamflow is increased significantly in plantation forest legacy blanket bog watershed, even in typically drier summer conditions.

4. Discussion

Most blanket bog rainfall –runoff studies found in the literature address the impact of afforestation, burning, grazing, and drainage on hydrological regime in blanket bogs (Anderson et al., 1990; Holden et al., 2004; Ballard et al., 2011; Lewis et al., 2013; Gao et al., 2015; Gao et al., 2016; Flynn et al., 2022). This research evaluated the relative influence of legacy of plantation forestry on hydrological regime in blanket bogs compared to an area of intact blanket bog. In the studied degraded watershed, the forest was planted in early 1990s but was clear-felled by the start of 2023. Overall performance of TOPMODEL was good: it overestimated a small number of peaks in calibration and validation period. Beven and Kirkby (1979) described that TOPMODEL assumes steady-state subsurface flow, which can overestimate runoff in dynamic rainfall events. The analysis herein revealed an increase in streamflow within the legacy of plantation forestry watershed, underscoring the substantial hydrological effects of land-use alterations in the area. Monthly comparative analysis revealed that the most significant percentage increase in streamflow occurred in February, coinciding with the peak groundwater table, whereas the smallest percentage increase was in September, attributed to a low groundwater table and elevated evapotranspiration rates (Fig. 9 **(a)**). Seasonal percentage analysis indicated that highest streamflow was observed in winter and lowest was observed in summer. The increase in streamflow in a degraded catchment results from interception losses due to the removal of canopy cover, which typically captures and holds rainfall (Calder, 1998; Bruijnzeel, 2004). This increases direct precipitation reaching the ground, leading to higher surface runoff. Moreover, water uptake in a clear-felled site is negligible, and prior plantation on blanket bog associated with drainage leads to peat shrinkage and compression reduce its water holding capacity, resulting in more surface runoff generation (Institute of Hydrology, 1991; Holden et al., 2004). Furthermore, streamflow generation on bare peat is typically more intense as compared to intact peatland. Additionally, drains in degraded watershed exhibit increased connectivity due to elevated groundwater levels in winter, leading to greater streamflow contributions. The findings presented here compare with previous studies which were on afforestation impact on streamflow in blanket bogs (Institute of Hydrology, 1991; Anderson et al., 2000; Heal et al., 2004). Anderson et al. (2000) observed that afforestation reduced runoff generation by 7 % compared to unforested drained control peatlands in Scotland. Heal et al. (2004) discovered that interception losses in Sitka spruce forested wetlands exceed 50 % of yearly precipitation, resulting in a substantial decrease in streamflow. Those research studies indicated that afforestation leads to an increase in evapotranspiration and a decrease in streamflow (Anderson and Pyatt, 1986; Anderson et al., 1990; Johnson, 1990; Institute of Hydrology, 1991; Anderson et al., 2000; Heal et al., 2004; Sottocornola and Kiely, 2010). Moreover, Bruijnzeel (1990) and Critchley and Bruijnzeel (1996) stated that deforestation diminishes infiltration and enhances runoff, thereby elevating flood risk and sediment load. Our findings also suggested that flow peaks in degraded (legacy of plantation forestry) watershed are much higher than intact

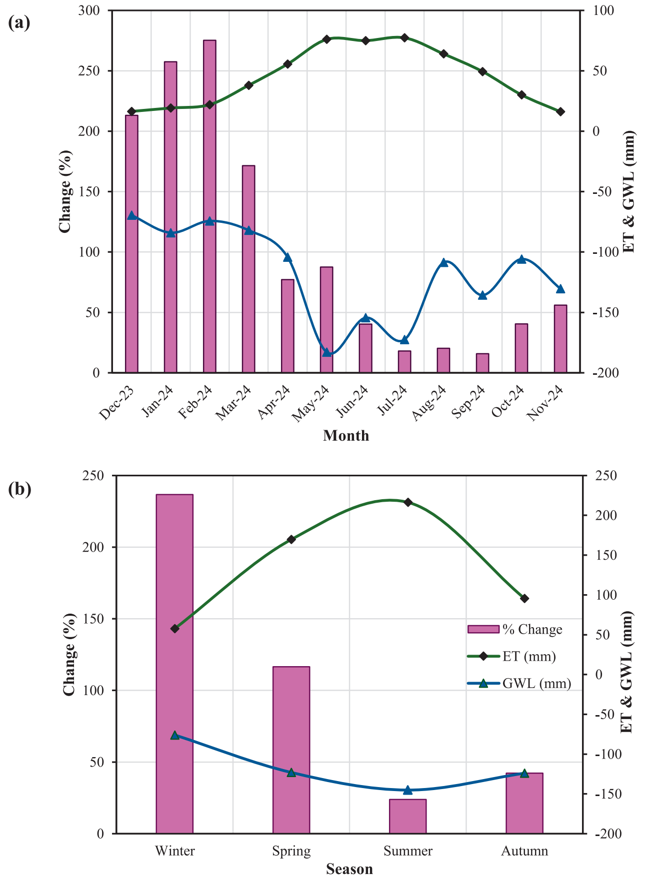


Fig. 9. Percentage increase in streamflow in degraded watershed as compared to intact watershed, variation is evapotranspiration and groundwater level (GWL): a) monthly, and b) seasonally.

conditions which elevates a risk of flooding downstream.

5. Conclusions

This study investigated the impact of legacy of plantation forestry, a human activity, on streamflow within a small blanket bog watershed (21 ha). The outcomes underscore the substantial influence of legacy of plantation forestry on the hydrological regime of the watershed. The key findings are summarised below.

1. The TOPMODEL efficiently simulated streamflow in the intact watershed with Nash-Sutcliffe efficiency (NSE), Kling-Gupta efficiency (KGE), and Coefficient of determination (R^2) more than 85 % both in calibration and validation period.
2. Relative contribution of streamflow increased by 106 % due to legacy of plantation forestry, which highest increase observed in February (275 %) and lowest increase was observed in September (16 %).
3. Seasonal analysis revealed that legacy of plantation forestry increased streamflow, with the highest increase in winter (237 %) and the lowest increase in summer (24 %).
4. A significant increase in flood peaks was observed in degraded (legacy of plantation forestry) watershed as compared to intact conditions.

Deforestation markedly diminishes interception losses by eliminating effects of canopy cover that usually capture and retains precipitation. The decrease in interception enhances direct precipitation on the ground, resulting in increased surface runoff and related hazards, including soil erosion and flooding. Prior forest plantation on blanket bog associated with drainage leads to peat shrinkage and compression reduce it water holding capacity, resulting in more surface runoff. Further research is required to quantify the impact of legacy of plantation forestry on water quality on a monthly and seasonal scale in blanket bogs. The outcomes of this analysis should assist the peatland research community, stakeholders and water managers for flood risk assessments.

CRediT authorship contribution statement

Muhammad Jehanzaib: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Raymond Flynn:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Vicky Preece:** Writing – review & editing, Validation, Data curation. **Hannah Lehnhart-Barnett:** Writing – review & editing, Data curation. **Devin F. Smith:** Writing – review & editing, Data curation. **Oisín Leonard:** Writing – review & editing, Data curation. **Tiernan Henry:** Writing – review & editing, Validation, Project administration, Funding acquisition, Data curation. **W. Berry Lyons:** Supervision, Project administration, Funding acquisition. **Anne E. Carey:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Peter Croot:** Writing – review & editing, 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.

Acknowledgments

The Sensor Application to Peatland Hydrology in Remote Environments (SAPHIRE) project is supported by USI 177 research grant from the Department for the Economy, Northern Ireland Research Ireland/Science Foundation Ireland (21/US/3724), and US National Science Foundation GEO EAR 2114028 under the US-Ireland R&D Partnership Programme.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2025.134498.

Data availability

Data will be made available on request.

References

Achite, M., Katipoğlu, O.M., Jehanzaib, M., Elshaboury, N., Kartal, V., Ali, S., 2023. Hydrological drought prediction based on hybrid extreme learning machine: Wadi Mina Basin Case Study, Algeria. Atmosphere 14 (9), 1447. https://doi.org/10.3390/atmos14091447.

Anderson, A.R., Pyatt, D.G., 1986. Interception of precipitation by Pole-Stage Sitka Spruce and Lodgepole Pine and Mature Sitka Spruce at Kielder Forest, Northumberland. Forestry 59 (1), 29–38. https://doi.org/10.1093/forestry/59.1.29.

Anderson, A., Pyatt, D., Stannard, J., 1990. The effects of clearfelling a Sitka spruce stand on the water balance of a peaty gley soil at Kershope Forest, Cumbria. Forestry: Int. J. Forest Res. 63 (1), 51–71. https://doi.org/10.1093/forestry/63.1.51.

Anderson, A.R., Day, R., Pyatt, D.G., 2000. Physical and hydrological impacts of blanket bog afforestation at bad a' Cheo, Caithness: the first 5 years. Forestry 73 (5), 467–478. https://doi.org/10.1093/forestry/63.1.51.

Ballard, C., McIntyre, N., Wheater, H., Holden, J., Wallage, Z., 2011. Hydrological modelling of drained blanket peatland. J. Hydrol. 407 (1–4), 81–93. https://doi.org/10.1016/j.jhydrol.2011.07.005.

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrol. Sci. J. 24 (1), 43–69. https://doi.org/10.1080/02626667909491834.

Beven, K., Binley, A., 1992. The future of distributed models: model calibration and uncertainty prediction. Hydrol. Process. 6 (3), 279–298. https://doi.org/10.1002/hyp.3360060305.

Biancalani, R., Avagyan, A., 2014. Towards climate-responsible peatlands management.

Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R., 2016. Peatland Restoration and Ecosystem Services: Science, Policy and Practice. Cambridge University Press.

Bruijnzeel, L.A., 1990. Hydrology of moist tropical forests and effects of conversion: a state of knowledge review.

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agr. Ecosyst. Environ. 104 (1), 185–228. https://doi.org/10.1016/j.agee.2004.01.015.

Calder, I.R., 1998. Water-resource and land-use issues. SWIM Paper, vol. 3. International Water Management Institute, Colombo Sri Lanka.

Critchley, W.R., Bruijnzeel, L.A., 1996. Environmental impacts of converting moist tropical forest to agriculture and plantations.

Curley, M., Coonan, B., Ruth, C.E., Ryan, C., 2023. Ireland's Climate Averages 1991-2020 (No. 22). Climatological Note.

Department of Agriculture, Food and the Marine, 2024. Forest Statistics Ireland 2024. Department of Agriculture, Food and the Marine, Wexford, Ireland.

Dunn, S., Mackay, R., 1996. Modelling the hydrological impacts of open ditch drainage. J. Hydrol. 179 (1–4), 37–66. https://doi.org/10.1016/0022-1694(95)02871-4.

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P., Kiely, G., 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. Clim. Change 91, 317–334. https://doi.org/10.1007/s10584-008-9412-2.

Flynn, R., Mackin, F., McVeigh, C., Renou-Wilson, F., 2022. Impacts of a mature forestry plantation on blanket peatland runoff regime and water quality. Hydrol. Process. 36 (2), e14494. https://doi.org/10.1002/hyp.14494.

Gao, J., Holden, J., Kirkby, M., 2015. A distributed TOPMODEL for modelling impacts of land-cover change on river flow in upland peatland catchments. Hydrol. Process. 29 (13), 2867–2879. https://doi.org/10.1002/hyp.10408.

Gao, J., Holden, J., Kirkby, M., 2016. The impact of land-cover change on flood peaks in peatland basins. Water Resour. Res. 52 (5), 3477–3492. https://doi.org/10.1002/2015WR017667.

Gao, J., Kirkby, M., Holden, J., 2018. The effect of interactions between rainfall patterns and land-cover change on flood peaks in upland peatlands. J. Hydrol. 567, 546–559. https://doi.org/10.1016/j.jhydrol.2018.10.039.

Geological Survey of Ireland, 2022. Geological Survey Ireland Spatial Resources (arcgis.com) https://dcenr.maps.arcgis.com/apps/MapSeries/index.html?appid=a30af518e87a4c0ab 2fbde2aaac3c228. Accessed 18 September 2024.

Google Earth 7.3.6 2024, Letterunshin, County Sligo, Ireland, 54°11'15"N 8°54'49"W, elevation 116m. [software]. Accessed 15 December 2024.

Goudarzi, S., Milledge, D., Holden, J., 2023. A generalized multistep dynamic (gmd) topmodel. Water Resour. Res. 59 (1), e2022WR032198. https://doi.org/10.1029/2022WR032198.

Goudarzi, S., Milledge, D., Holden, J., Evans, M., Allott, T., Johnston, A., Shuttleworth, E., Kay, M., Brown, D., Rees, J., 2024. Natural flood management through peatland restoration: Catchment-scale modeling of past and future scenarios in Glossop, UK. Water Resour. Philos. Phenomenol. Res. 60 (8), e2024WR037320. https://doi.org/10.1029/2024WR037320.

Goudarzi, S., Milledge, D.G., Holden, J., Evans, M.G., Allott, T.E., Shuttleworth, E.L., Pilkington, M., Walker, J., 2021. Blanket peat restoration: Numerical study of the underlying processes delivering natural flood management benefits. Water Resour. Res. 57 (4), e2020WR029209. https://doi.org/10.1029/2020WR029209.

Grayson, R., Holden, J., Rose, R., 2010. Long-term change in storm hydrographs in response to peatland vegetation change. J. Hydrol. 389 (3–4), 336–343. https://doi.org/10.1016/j.jhydrol.2010.06.012.

Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. J. Hydrol. 377 (1–2), 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003.

Heal, K.V., Stidson, R., Dickey, C., Cape, J., Heal, M.R., 2004. New data for water losses from mature Sitka spruce plantations in temperate upland catchments/Nouvelles données pour les pertes d'eau de plantations adultes de sapins de Sitka en bassins versants tempérés d'altitude. Hydrol. Sci. J. 49 (3). https://doi.org/10.1623/hysj.49.3.477.54344.

Heikkinen, K., Karppinen, A., Karjalainen, S., Postila, H., Hadzic, M., Tolkkinen, M., Marttila, H., Ihme, R., Kløve, B., 2018. Long-term purification efficiency and factors affecting performance in peatland-based treatment wetlands: an analysis of 28 peat extraction sites in Finland. Ecol. Eng. 117, 153–164. https://doi.org/10.1016/j.ecoleng.2018.04.006.

Holden, J., Chapman, P., Labadz, J., 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. Prog. Phys. Geogr. 28 (1), 95–123. https://doi.org/10.1191/0309133304 pp403ra.

Institute of Hydrology., 1991. Effects of upland afforestation on water resources: the Balquhidder experiment 1981–1991. Report no. 116, Institute of Hydrology, Wallingford, UK.

Jehanzaib, M., Shah, S.A., Yoo, J., Kim, T.W., 2020. Investigating the impacts of climate change and human activities on hydrological drought using non-stationary approaches. J. Hydrol. 588, 125052. https://doi.org/10.1016/j.jhydrol.2020.125052.

Johnson, G.A.L., Dunham, K.C., 1963. The geology of Moor House: a national nature reserve in north-east Westmorland. HM Stationery Office.

Johnson, R., 1990. The interception, throughfall and stemflow in a forest in highland Scotland and the comparison with other upland forests in the UK. J. Hydrol. 118 (1–4), 281–287. https://doi.org/10.1016/0022-1694(90)90263-W.

Lane, S.N., Brookes, C.J., Kirkby, A.J., Holden, J., 2004. A network-index based version of TOPMODEL for use with high-resolution digital topographic data. Hydrol. Process. 18 (1), 191–201. https://doi.org/10.1002/hyp.5208.

Lane, S.N., Milledge, D.G., 2013. Impacts of upland open drains upon runoff generation: a numerical assessment of catchment-scale impacts. Hydrol. Process. 27 (12), 1701–1726. https://doi.org/10.1002/hyp.9285.

Lewis, C., Albertson, J., Zi, T., Xu, X., Kiely, G., 2013. How does afforestation affect the hydrology of a blanket peatland? a modelling study. Hydrol. Process. 27 (25), 3577–3588. https://doi.org/10.1002/hyp.9486.

Mackin, F., Flynn, R., Barr, A., Fernandez Valverde, F., 2017. Use of geographical information system-based hydrological modelling for development of a raised bog conservation and restoration programme. Ecol. Eng. 106 (A), 242–252. https://doi.org/10.1016/j.ecoleng.2017.04.067.

Mitchell, F., Ryan, M., 1997. Reading the Irish Landscape. Town House.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I— a discussion of principles. J. Hydrol. 10 (3), 282–290. https://doi.org/10.1016/0022- 1694(70)90255-6.

Perrin, P., Roche, J., Barron, S., Daly, O., Hodd, R., Muldoon, C., Leyden, K., 2013. National survey of upland habitats (Phase 3, 2012–2013). Site Report No. 10: Ox Mountains Bogs cSAC (002006), Cos. Mayo and Sligo. National Parks and Wildlife Service, Dublin.

Reggiani, P., Sivapalan, M., Hassanizadeh, S.M., 2000. Conservation equations governing hillslope responses: exploring the physical basis of water balance. Water Resour. Res. 36 (7), 1845–1863. https://doi.org/10.1029/2000WR900066.

Regan, S., Flynn, R., Gill, L., Naughton, O., Johnston, P., 2019. Impacts of groundwater drainage on peatland subsidence and its ecological implications on an Atlantic raised bog. Water Resour. Res. 55 (7), 6153–6168. https://doi.org/10.1029/2019WR024937.

Sottocornola, M., Kiely, G., 2010. Energy fluxes and evaporation mechanisms in an Atlantic blanket bog in southwestern Ireland. Water Resour. Res. 46 (11). https://doi.org/10.1029/2010WR009078.

Wheeler, B.D., Proctor, M.C.F., 2000. Ecological gradients, subdivisions and terminology of north-west european mires. J. Ecol. 88, 187–203. https://doi.org/10.1016/j.scitotenv.2023.162890.

Wildlife Trusts., 2021. Blanket bog. https://www.wildlifetrusts.org/habitats/wetlands/blanket-bog. Accessed 18 September 2024.

Xu, J., Morris, P.J., Liu, J., Holden, J., 2018. Hotspots of peatland-derived potable water use identified by global analysis. Nat. Sustainability 1 (5), 246–253. https://doi.org/10.1038/s41893-018-0064-6.

Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W., Hunt, S.J., 2010. Global peatland dynamics since the last Glacial Maximum. Geophys. Res. Lett. 37 (13). https://doi.org/10.1029/2010GL043584.

Zou, L., Xia, J., She, D., 2018. Analysis of impacts of climate change and human activities on hydrological drought: a case study in the Wei River Basin, China. Water Resour. Manage. 32 (4), 1421–1438. https://doi.org/10.1007/s11269-017-1877-1.