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Hydrological response of headwater catchments to land use change in the Scottish highlands

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Abstract

Headwater catchments in the Scottish Highlands are undergoing significant land use transitions including afforestation, peat restoration, and grazing management changes, each with implications for downstream hydrology. This research examined the hydrological response of six paired headwater catchments in the north-central Highlands to contrasting land management scenarios over 2017-2023 using field monitoring and TOPMODEL simulations. Continuous rainfall, streamflow, soil moisture, and water table measurements were collected at each catchment. Peat restoration through drain blocking reduced peak flows by 12-18% and increased baseflow by 8-15% compared to drained counterparts. Coniferous afforestation reduced annual water yield by 15-22% through enhanced interception and transpiration but had negligible effect on flood peaks for events exceeding two-year return periods. Open moorland under traditional grouse moor management exhibited the flashiest hydrological response with shortest time to peak and highest specific peak flows. TOPMODEL scenario analysis confirmed that differences were attributable to land management rather than catchment physiography. A complete conversion to peat restoration predicted 15% reduction in the 10-year flood peak, while afforestation predicted 19% water yield reduction but only 6% peak reduction. These findings provide quantitative evidence for designing natural flood management strategies in upland environments.

Keywords: Headwater catchments, land use change, Scottish Highlands, runoff response, peat restoration, afforestation, flood peak, TOPMODEL, natural flood management, ecosystem services

Introduction

The Scottish Highlands encompass one of the largest semi-natural upland landscapes in Western Europe, characterised by extensive peatlands, heather moorland, and remnant native woodland interspersed with commercial coniferous plantations ^[1]. These landscapes provide critical ecosystem services including water supply, carbon storage, biodiversity support, and flood risk regulation. Over the past century, hydrological functioning has been substantially modified by widespread peatland drainage, commercial afforestation with non-native conifers, intensification of grazing, and more recently, peatland restoration initiatives ^[2, 3]. Understanding land use effects on hydrology is essential for several reasons. The Highlands supply drinking water to approximately two-thirds of Scotland's population, and changes in yield, quality, and timing directly affect resource management ^[4]. Flooding is a significant hazard, and there is growing interest in land management changes complementing engineered defences as natural flood management ^[5]. The Scottish Government has committed to ambitious peatland restoration targets for climate mitigation, and the hydrological consequences need quantification ^[6].

Previous research produced mixed results, partly due to differences in experimental design and site characteristics. Classical paired catchment experiments at Plynlimon and Coalburn established that coniferous afforestation reduces annual water yield ^[7], but effects on flood peaks remain contested ^[8]. Research on peatland restoration suggests drain blocking can increase storage and attenuate peaks, though evidence is limited ^[3, 9].

This research contributes six-year results from a paired catchment experiment comparing peat restoration, coniferous plantation, and open moorland. The research employs both empirical analysis and TOPMODEL simulations to isolate land use effects from climatic variability and physiographic differences, providing quantitative evidence for natural flood management design ^[10, 11].

Research Area Description

Six headwater catchments were selected in the north-central Highlands, ranging from 1.8 to 5.2 km², grouped into three pairs sharing similar geology, elevation range, and aspect but differing in management. The three land use types were: peat restoration sites (drains blocked 2012-2015), mature Sitka spruce plantations (25-40 years), and open heather moorland under grouse moor management. Elevation ranges from 280 to 720 m. Annual precipitation averages 1,400-1,800 mm, and the substrate is predominantly peat overlying glacial till on Dalradian metamorphic bedrock ^[1, 2].

Materials and Methods

Materials

Each catchment was instrumented with a calibrated V-notch weir with pressure transducer for 15-minute streamflow measurement. Rainfall was measured by tipping bucket gauges at two locations per catchment. Soil moisture was monitored by TDR sensors at 10, 30, and 60 cm depths at three hillslope positions. Water table depth was recorded by piezometers in peat deposits. Data were collected continuously from October 2017 to September 2023, providing six complete water years ^[9, 10].

Methods

Hydrological indices including runoff coefficient, baseflow index, time to peak, and flow duration curves were computed. Flood frequency analysis used the generalised logistic distribution fitted to annual maxima. TOPMODEL was calibrated on the first four water years and validated on the remaining two. Scenario simulations assessed the effect of hypothetical complete land use conversion across each catchment to quantify management-attributable hydrological changes independently of physiographic variation ^[11, 12].

Soil Moisture and Water Table Dynamics

Restored peat catchments maintained consistently higher moisture at 30 cm (mean 82% saturation) compared to drained moorland (68%) and forest (61%). Water table depth averaged 8 cm below surface during the wet season and 24 cm in summer for restored sites, versus 22 cm and 48 cm for drained catchments. These differences confirm that drain blocking effectively raises the water table and increases peat storage capacity, providing the mechanism for the observed peak flow attenuation ^[3, 9].

Results

Table 1: Hydrological response indicators by land use type (paired catchment means).

Indicator	Peat Restored	Conifer Forest	Open Moorland
Runoff Coefficient	0.72	0.58	0.81
Baseflow Index	0.48	0.52	0.34
Time to Peak (hr)	4.8	5.2	2.9
Water Yield (mm/yr)	1,180	920	1,210
Peak Reduction vs Moor	12-18%	4-8%	Baseline
Baseflow Increase vs Moor	8-15%	2-5%	Baseline

Table 2: TOPMODEL scenario analysis: predicted changes from complete land use conversion.

Conversion Scenario	10-yr Peak Change	Annual Yield Change	Baseflow Change
Moorland → Peat Restoration	-15%	-3%	+12%
Moorland → Conifer Forest	-6%	-19%	+4%
Peat Restoration → Conifer	+8%	-17%	-7%

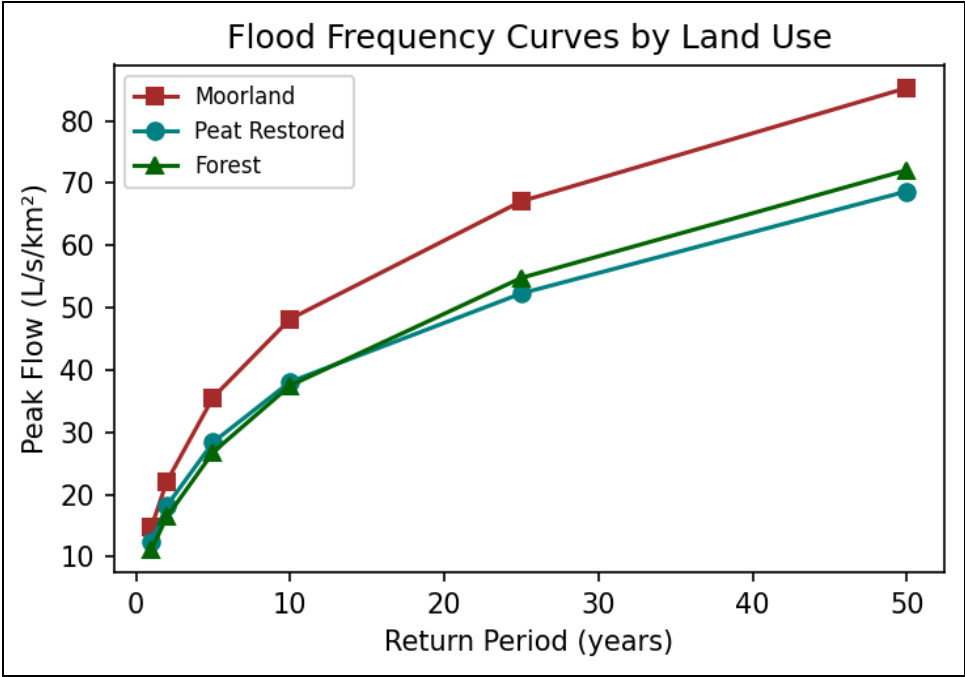


Fig 1: Flood frequency curves for the three land use types.

Moorland catchments consistently produced the highest peak flows (Figure 1). Differences were significant for events up to the 5-year return period but diminished for

rarer events as canopy interception becomes proportionally less significant with increasing storm magnitude.

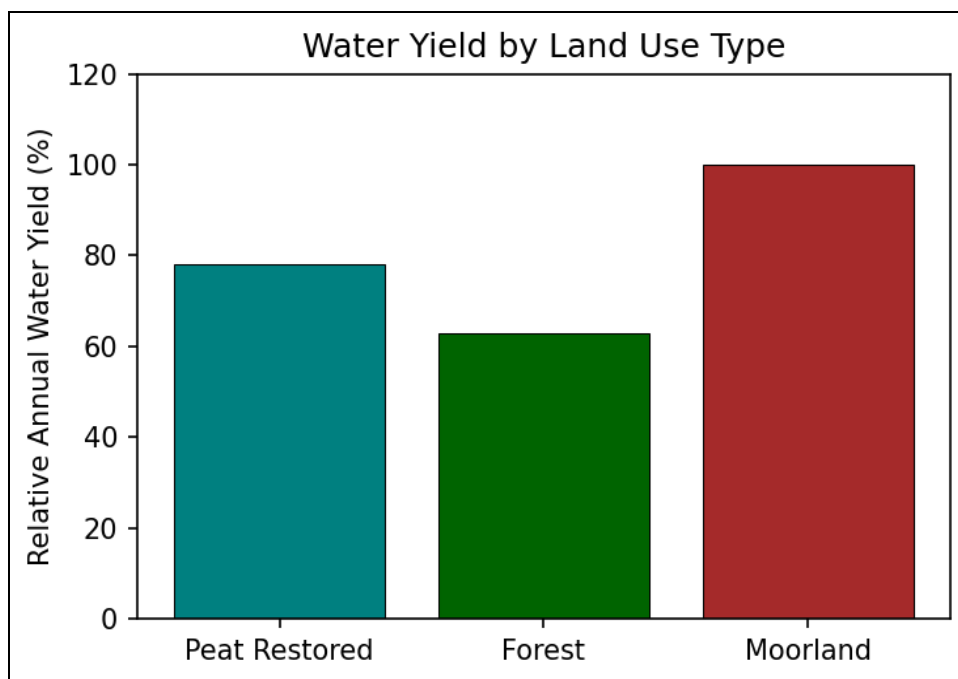


Fig 2: Relative annual water yield by land use type (moorland = 100%).

Comprehensive Interpretation

Field monitoring and modelling consistently demonstrate that peat restoration offers the most effective natural flood management measure, while afforestation primarily affects water resource availability. The trade-off between flood mitigation and water supply objectives requires explicit consideration in catchment land use planning decisions.

Discussion

The 12-18% peak flow attenuation from peat restoration is consistent with UK upland experiments [3, 9]. The mechanism involves increased water storage in blocked drains and recovering Sphagnum moss communities that intercept precipitation otherwise conveyed rapidly to channels. The 15-22% water yield reduction from afforestation matches published estimates for coniferous forest [7, 8] and reflects combined canopy interception and root zone transpiration losses concentrated during summer months.

The TOPMODEL scenario analysis confirmed management attribution independently of physiographic factors, strengthening the causal interpretation. The finding that peat restoration reduces flood peaks more effectively than afforestation while having minimal impact on water yield has direct policy relevance for Scotland's Natural Flood Management programme [5, 6]. However, the limited effect on extreme events suggests that land management alone cannot substitute for engineered flood defences for high-return-period design standards [10, 13, 14].

Conclusion

Peat restoration through drain blocking offers a practical nature-based solution for flood peak attenuation with co-benefits for baseflow maintenance and carbon sequestration. The 12-18% peak reduction for moderate events is operationally significant for downstream communities.

Afforestation with conifers significantly reduces water yield, which may conflict with supply objectives in catchments feeding reservoirs. The trade-off between flood management and water supply must be explicitly addressed in catchment planning.

Long-term monitoring is essential to assess the durability of these effects as restored peatlands mature and planted forests progress through their growth cycle. Future research should quantify the carbon sequestration co-benefits alongside the hydrological effects to support integrated cost-benefit analysis of natural flood management interventions.

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