HYDROLOGICAL PROCESSES
*Hydrol. Process.* (2012)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9486

# How does afforestation affect the hydrology of a blanket peatland? A modelling study

Ciaran Lewis,[1]* John Albertson,[2] Tan Zi,[2] Xianli Xu[1] and Gerard Kiely[1]

[1] *Centre for Hydrology, Micrometeorology and Climate Change, Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland*
[2] *Department of Civil and Environmental Engineering, Duke University, Durham, NC, USA*

## Abstract:

Over the last century, afforestation in Ireland has increased from 1% of the land area to 10%, with most plantations on upland drained blanket peatlands. This land use change is considered to have altered the hydrological response and water balance of upland catchments with implications for water resources. Because of the difficulty of observing these long-term changes in the field, the aim of this study was to utilize a hydrological model to simulate the rainfall runoff processes of an existing pristine blanket peatland and then to simulate the hydrology of the peatland if it were drained and afforested. The hydrological rainfall runoff model (GEOtop) was calibrated and validated for an existing small (76 ha) pristine blanket peatland in the southwest of Ireland for the 2-year period, 2007–2008. The current hydrological response of the pristine blanket peatland catchment with regard to streamflow and water table (WT) levels was captured well in the simulations. Two land use change scenarios of afforestation were also examined, (A) a young 10-year-old and (B) a semi-mature 15-year-old Sitka Spruce forest. Scenario A produced similar streamflow dynamics to the pristine peatland, whereas total annual streamflow from Scenario B was 20% lower. For Scenarios A and B, on an annual average basis, the WT was drawn down by 16 and 20 cm below that observed in the pristine peatland, respectively. The maximum WT draw down in Scenario B was 61 cm and occurred in the summer months, resulting in a significant decrease in summer streamflow. Occasionally in the winter (following rainfall), the WT for Scenario B was just 2 cm lower than the pristine peatland, which when coupled with the drainage networks associated with afforestation led to higher peak streamflows. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS peatland; rainfall runoff model; afforestation; hydrology

*Received 23 September 2011; Accepted 4 July 2012*

## INTRODUCTION

Peat is an organic soil composed of partially decomposed plant matter (Hoag and Price, 1995) with depths that range from 30 cm to as much as 1000 cm. Peatlands cover 400 million hectares of the earth's surface and store between 33% and 50% of the world's soil carbon pool (Holden, 2005), which has been estimated at 25%–50% of the current carbon held in the atmosphere (Frolking and Roulet, 2007). This vast store of carbon is considered to be vulnerable to climate change (Oechel *et al*., 2000; Sottocornola and Kiely, 2010), artificial drainage (Holden *et al*., 2004) and land use change (Limpens *et al*., 2008). More than 80% of these peatlands are located in temperate-cold climates in the northern hemisphere particularly in Canada (Letts *et al*., 2000), Russia, USA and parts of northern Europe (Limpens *et al*., 2008). In all regions of these northern peatlands, there have been vast areas that have undergone drainage for commercial forestry (Waldron *et al*., 2009). An estimated 500 000 ha of peatland was afforested between the 1950s and 1980s in the UK (Hargreaves *et al*., 2003). This land use change and drainage is considered to have had a profound effect on vegetation, water and carbon dynamics of peatlands (Strack *et al*., 2006).

From a regional perspective, much of Ireland's native forestry had been felled over the centuries so much so that by the beginning of the twentieth century, forestry accounted for only 1% of the total land cover in Ireland (Pilcher and Mac an tSaoir, 1995; Eaton *et al*., 2008). However, since the 1950s, it has been the policy of successive Irish governments to increase forest cover, and by 2007, the national forest area had risen to 10% (NFI, 2007) with a planned increase to 18% by 2020 (Dept. of Agriculture, 1996).

Much of this afforestation over that past five decades has taken place on peatlands that were traditionally considered unsuitable for agricultural use. An estimated 49% of the afforestation between 1990 and 2000 was carried out on peat soils (Black *et al*., 2008). The principal tree species used in peatland afforestation in Ireland were Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and lodgepole pine (*Pinus contorta* Dougl.) (Byrne and Farrell, 2005). Sitka spruce is non-native to Ireland but is favoured because of its rapid growth in the temperate humid Irish climatic conditions and its ability to survive in difficult terrain. An estimated 57% of the national forest stock is Sitka spruce (Horgan *et al*., 2004). Although Sitka spruce is able to thrive under the moist

*Correspondence to: Ciaran Lewis, Centre for Hydrology, Micrometeorology and Climate Change, Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland.
E-mail: c.lewis@student.ucc.ie

Irish weather conditions (Horgan *et al.*, 2004), its root development when planted on peat soils is limited to the aerated top section of the peat profile (Lees, 1972). Peatlands, and particularly blanket peats, in Ireland are environments with the water table (WT) at, or close to, the surface for long periods of the year (Iritz *et al.*, 1994; Bragg, 2002; Holden and Burt, 2002; Hogan *et al.*, 2006; Laine *et al.*, 2007). Sottocornola and Kiely (2010) found that in a pristine blanket peatland in southwest Ireland, the daily averaged WT never fell further than 16 cm below the bog surface for the period 2002–2010. This is in contrast to blanket peatlands in places such as Canada where the WT falls as much as 60 cm below the surface. This makes Irish peatlands unsuitable for afforestation in their natural undrained (high WT) condition, which can result in stunted root development and vulnerability to wind throw.

For afforestation purposes, peatlands are typically drained prior to planting with drainage normally being carried out using a combination of closely spaced plough furrows and deep (0.5–2.0 m) but more widely spaced ditches (Holden *et al.*, 2004). Frequently, this results in a change in streamflow, both in the short term while the drains are active and in the long term when the forest becomes established (Holden *et al.*, 2004). These drains, although beneficial for the development of the forest, have also been linked with higher peak streamflows (Robinson, 1986). In an early study by Burke (1975), the streamflow : rainfall ratio from an undrained peatland in Glenamoy, Ireland, was 23.4% compared with 79.2% from a drained catchment. Conway and Millar (1969) found that artificially drained peats produced rapid streamflow in the north Pennines (UK). Ahti (1980) found that the flood peak increased after drainage in Scandinavian peatlands. However, investigations by Holden *et al.* (2006) in the same peatlands as the Conway and Millar (1969) study found that overland flow was greatly reduced following drainage, whereas subsurface flow was greatly increased within the Moor House blanket peatlands. Investigations by Iritz *et al.* (1994) on a selection of forested Scandinavian peatland catchments found that peak flows decreased following drainage. Prevost *et al.* (1997) reported an increase in stream base flow following drainage in a Canadian peatland. Although there have been conflicting conclusions drawn from different international studies, this is likely due to limited data and the diversity of ground conditions (e.g. natural variation of WT depth), which is seen as critical to the amount of storage available and surface runoff production in peatlands (Holden *et al.*, 2006). Furthermore, the type of drainage will impact the degree of change in hydrology. Deep closely spaced drains cause a peat catchment to respond differently to shallow widely spaced drains. Holden *et al.* (2011) observed that in an intact blanket bog in Oughtershaw Moss in northern England, whereas the seasonal range of WT depth was 0–20 cm, the spatially weighted mean WT depth was only 5.8 cm. In the same bog, they found for a drained section that whereas the depth of the seasonal WT ranged from 0 to 40 cm, the spatially weighted mean WT depth was 11.5 cm. The natural WT depth varies from lows of ~10 cm in Irish blanket peatlands to highs of ~60 cm in Canadian and Scandinavian blanket peatlands (Koehler *et al.*, 2011). Whereas drainage always precedes blanket peat afforestation in Ireland, this is not necessarily so in Canada and Scandinavia.

The rainfall runoff response of a peatland catchment changes once it becomes afforested (Hudson *et al.*, 1997; Anderson *et al.*, 2000; Heal *et al.*, 2004). Drainage (WT lowering), peat shrinkage and compression, tree canopy interception and evapotranspiration (ET) all contribute to a changed hydrological (and hydrochemical) regime of a peatland when afforested (Institute of Hydrology, 1991; Iritz *et al.*, 1994; Holden *et al.*, 2004; Ballard *et al.*, 2011b). Anderson *et al.* (2000) in a study investigating the effects of blanket bog afforestation on the physical properties of the peat soil and on the quantity and timing of runoff found a reduction of 7% in streamflow after afforestation in a Scottish peatland relative to an unforested drained control. They noted that the reduction in streamflow was predominantly in the spring and summer, possible linked with higher ET from the forest canopy. Compared with the drained control, peak flows were increased by afforestation, whereas the baseflow component of the total flow was reduced.

One of the major contributing factors in changing the rainfall runoff response of an afforested peatland is the change in interception losses. ET from a pristine blanket peatland in southwest Ireland was observed over 5 years to be 15.5% of the total precipitation representing an annual average of 394 mm (Sottocornola and Kiely, 2010). However, many studies reported far greater interception losses in afforested peatlands. Studies in areas that may be considered to have similar climates to south west Ireland such as the Heal *et al.* (2004) study in Scotland found the that interception losses in a Sitka spruce forested peatland were reported to be greater than 50% of the annual precipitation. An investigation by the Institute of Hydrology (1991) into the water resources of two upland catchments also in Scotland found significant interception losses amounting to 38% of the precipitation. Anderson *et al.* (1990) in UK afforested peatland reported 38% canopy interception and 12% transpiration loss in UK afforested peatland. Johnson (1990) found that in a 50-year-old Sitka spruce forest in the Scottish highlands on peat and peaty gley soils, the average interception over a 3-year period was 28% with the greatest interception occurring in the summer months and the least in winter. A 25-year-old Sitka spruce forest on a peaty gley soil in Northumberland, UK was observed to have an average interception loss of 48% of the precipitation (Anderson and Pyatt, 1986). These studies demonstrate that ET increases and stream runoff decreases after afforestation of peatlands (Table I). A review by Hudson *et al.* (1997) of the studies carried out on a number of catchments including the Plynlimon and Lanbrynmair catchments in Wales concluded that afforested upland catchments (on a mixture of Peaty



DOI: 10.1002/hyp

Table I. A number of water table (WT) depths, streamflows and evapotranspiration values from literature

| Ecosystem | Location | Notes | Average annual precipitation (mm) | Annual evapotranspiration (mm) | Average WT depth (cm) | Average streamflow (mm) | Reference |
|---|---|---|---|---|---|---|---|
| Boreal raised bog | Canada | 5 years data | 910 | 351 | >0.25 (varies considerably) | 560 | (Lafleur *et al.*, 2005) |
| Mire | Sweden | 2 years data | 683 | 238 | 10 | 445 | (Nilsson *et al.*, 2008) |
| Blanket peatland | Ireland | pristine 2003–2007 | 2597 | 394 | 4 | ~2000 | (Sottocornola and Kiely, 2010) |
| Blanket peatland | Scotland | Drained peatland | 943 | 362 | 12 | 581 | (Anderson *et al.*, 2000) |
| Afforested peatland | Scotland | Sitka spruce 5 years old | 943 | 401 | 19 | 541 | (Anderson *et al.*, 2000) |
| Afforested peatland | Scotland | Sitka spruce 50 years old | 2130 | 597 | – | 1533 | (Johnson, 1990) |
| Afforested peatland | Scotland | Sitka spruce 37 years old | 2912 | 1375 | – | 1726 | (Heal *et al.*, 2004) |

Gleys, Brown Earths and Podzols soils) had higher ET than similar grassland covered catchments. It was further noted by Hudson *et al.* (1997) that in the wet windy climate of the British uplands, 15%–20% of rainfall is lost by transpiration from grasslands, whereas 30%–40% is lost from forested areas.

Peatlands can serve as important regulators of river flow and hydrochemistry (Koehler *et al.*, 2011), because of their location and high precipitation. Many rivers (at least in Ireland, Scotland and Wales) rise in areas of upland blanket peat with high precipitation (because of elevation). In upland blanket peatlands where the WT is perennially close to the surface (as occurs in north west Europe), flash floods occur because there is very little storage potential in the peat (Bay, 1969; Bragg, 2002; Holden and Burt, 2002; Holden and Burt, 2003; Baird *et al.*, 2008; Lewis *et al.*, 2011). A recent concept (Lapen *et al.*, 2005) suggests that a layer of lower hydraulic conductivity at the margins of peatlands is responsible for maintaining higher WTs in the centre of the bog. Recent field tests by (Baird *et al.*, 2008) on a raised bog and Lewis *et al.* (2011) on a blanket bog support this idea. However, to the authors' knowledge, this spatial variation of hydraulic conductivity has yet to be incorporated into hydrological models.

Although there are several hydrological models capable of simulations on mineral soils (Beven and Kirkby, 1979; Abbott *et al.*, 1986; Arnold *et al.*, 1998; Reggiani *et al.*, 2000), the same cannot be said for peat soils as many hydrological models are not well suited to wetlands (Price *et al.*, 2005). A model parameterization for Canadian peatlands was developed by Letts *et al.* (2000) for a soil vegetation atmosphere transfer scheme. SHETRAN was employed by Dunn and Mackay (1996) to investigate how peatlands are affected by ditches. Lane *et al.* (2004) modified TOPMODEL (Beven and Kirkby, 1979) for use with Digital Elevation Models of high resolution, as these high resolution models can lead to many saturated areas that are unconnected to the drainage network. Lane *et al.* (2004) also noted that TOPMODEL may not accurately represent the lateral movement of water in soils of low hydraulic conductivity into open drains. More recently, Ballard *et al.* (2011a) developed a simplified physics-based model to investigate flow and WT responses to different drainage scenarios. The model was found to perform well under wet conditions capturing the peak flows well, with a poorer performance under drier conditions.

The general objective of this study was to use a 2-year hydrological data set at a blanket peatland catchment and a process-based rainfall runoff model to explore the hydrological response, if the peatland were to be drained and afforested. Specifically the aims were (1) to calibrate and validate the hydrologic rainfall runoff model GEOtop for a small scale blanket peatland catchment in southwest Ireland by using 2 years of observations, (2) to investigate the catchment hydrological response for the scenario of a drained pre-afforested condition with a 50-cm WT lowering and (3) two afforestation scenarios: A, a 10-year-old Sitka spruce afforestation simulation, and B, a 15-year-old Sitka spruce afforestation simulation.

## MATERIALS AND METHODS

### *Site description*

The study site is a pristine Atlantic blanket bog near Glencar in County Kerry, southwest Ireland (latitude: 51°58N, longitude 9°54W) at an elevation of approximately 150 m (Figure 1) and is typical of Atlantic blanket bogs in the coastal regions of northwest Europe in terms of both vegetation and water chemistry (Sottocornola *et al*., 2009). The study site is part of a larger pristine bog of approximately 121 $km^2$. A small stream (~1 m wide) runs through the centre of the bog and drains approximately 76 ha; 85% of which is intact blanket bog (see Figure 1).

The surface of the bog is a mosaic of microforms that differ in relative altitude, plant composition and WT depth. Four vegetation microform classes were distinguished in relation to their difference in WT level: hummocks, high lawns, low lawns and hollows that cover 6%, 62%, 21% and 11% of the study site, respectively (Laine *et al*., 2007; Sottocornola *et al*., 2009). Vascular plants cover about 30% of the study site area with the most common species being *Molinia caerulea* (purple moorgrass) and *Calluna vulgaris* (common heather). About 25% of the bog surface is covered by bryophytes with the dominant species being a brown moss, *Racomitrium lanuginosum*. The vegetation of the study site has been described in detail by Sottocornola *et al*. (2009).

### *Site instrumentation*

At the outfall of the 76-ha catchment (Figure 1), the stream height was recorded every 30 min by using a pressure transducer (1830 Series, Druck Limited, UK). Stream height was converted to discharge by using a rating curve (Equation 1) built up from stream height and stream velocity measurements taken over 2 years.

$$\begin{aligned} Q &= 0.6946 * (h - 0.08071)^{1.441} \\ r^2 &= 0.9986, \mathrm{RMSE} = 0.005 \end{aligned} \tag{1}$$

where $Q$ is the instantaneous discharge in $m^3\,s^{-1}$ and $h$ is stream height in m. The rating curve was established from manual measurements of instantaneous discharge carried out at a range of stream heights by using an OTT current metre (OTT Messtechnik GmbH & Co KG, Germany).

The meteorological station (Figure 1) was established in 2002 and includes two tipping bucket rain gauges (an ARG100, Environmental Measurements Ltd., UK and

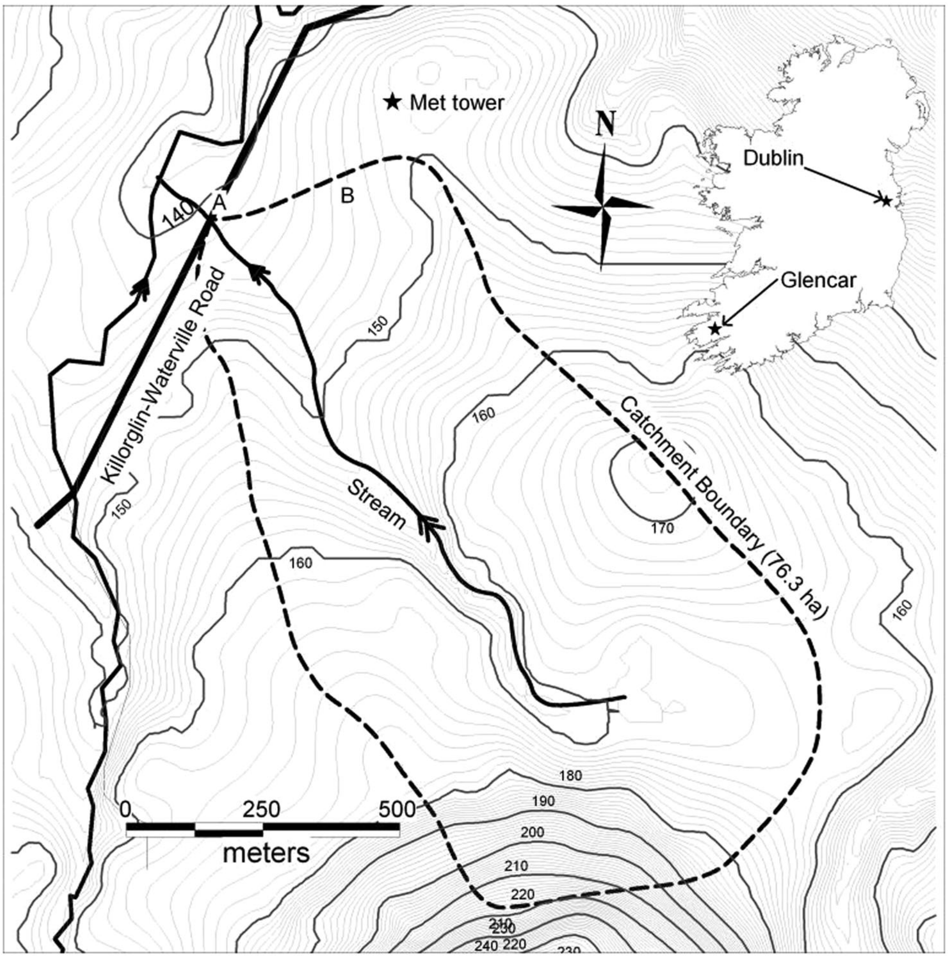


Figure 1. Peatland catchment and location map



DOI: 10.1002/hyp

an Obsermet OMC-200, Observator BV, The Netherlands) and a WT level recorder that consists of a pressure transducer (PCDR1830, Campbell Scientific, UK) placed inside a metal well pierced all along its height. Wind speed was recorded with a 2D sonic anemometer (WindSonic, Gill, UK). Air temperature and relative humidity were measured at 2-m height with a shielded probe (HMP45C, Vaisala, Finland), whereas atmospheric pressure was recorded with a barometer (PTB101B, Vaisala, Finland). An eddy covariance system for $CO_2$ fluxes was also located on the same tower. It consisted of a 3D sonic anemometer (Model 81000, R.M. Young Company, USA) and an open-path infrared gas analyzer for $H_2O$ and $CO_2$ concentrations (LI-7500, LI-COR, USA) mounted 3 m above the vegetation.

### *Climate*

Sottocornola and Kiely (2010) at the same site found that the range of annual rainfall (2002–2009) was 2236–3365 mm with an annual average of 2597 mm. The annual ET (estimated using eddy covariance methods) ranged from 369 to 424 mm with an annual average of 394 mm. From 2002 to 2009, there was an annual average of 208 wet days (>1 mm day$^{-1}$) (Koehler *et al*., 2009). The average annual air temperature was 10.5 °C.

The recorded flow at the stream outfall (see Figure 1) ranged between 0.015 and 10.0 l s$^{-1}$ ha$^{-1}$ (Koehler *et al*., 2009) with the 95 percentile flow exceeding 0.037 l s$^{-1}$ ha$^{-1}$. The flow was observed to be flashy with over 90% of the streamflow sourced from surface runoff (Lewis *et al*., 2011). This is due to a perennially high WT that was observed continuously over the 7 years, 2002–2009, to be within 17 cm of the land surface (with the 7-year mean WT at ~4 cm below the surface) at the eddy covariance/meteorological station. Although additional WT observation stations would be beneficial, the site is well known to the authors' through frequent site visits, and it is considered that the WT measurements are representative of the peatland. A manual WT observation station was established in 2009 near the stream and the WT was found to vary between 0 and 10 cm below the surface. Observations were taken approximately six–eight times a year particularly during dry periods. Lewis *et al*. (2011) investigated the spatial variation of bulk density and saturated hydraulic conductivity at the same site and found that at the surface (top 10 cm) saturated horizontal hydraulic conductivity was lowest at the bog margin near the stream (~10$^{-7}$ m s$^{-1}$) and increased at the bog interior (~10$^{-5}$ m s$^{-1}$). The converse was found for bulk density, which ranged from ~0.11 g cm$^{-3}$ at the bog margin to ~ 0.055 g cm$^{-3}$ near the bog interior.

### *Process-based hydrological model – GEOtop*

The process-based hydrological model GEOtop (Rigon *et al*., 2006) was used in this study. It is a distributed hydrological model (operating on a 8 m × 8 m grid) and simulates the complete hydrological balance in a continuous way during a whole year (at a temporal increment of 60 min). It uses geospatial data (e.g. topography, soil type, vertical and horizontal hydraulic conductivity, depth and the Van Genuchten parameters $\alpha$ and $n$ (van Genuchten, 1980)), vegetation cover (including crop height, Leaf Area Index (LAI) and root depth) and land cover. It provides spatially distributed output fields as well as routing water and sediment flows through stream and river networks.

GEOtop includes a rigorous treatment of the core hydrological processes (e.g. unsaturated and saturated flow and transport, surface energy balances and streamflow generation/routing). Unsaturated dynamics are treated with a 3D integration of Richards' equation, whereas surface runoff is routed via a kinematic wave. The space–time fields of radiation that drive the evaporative processes account for terrain effects, such as aspect, slope and shading. The energy processes in GEOtop have been extensively tested and validated (Bertoldi *et al*., 2006). Using GEOtop in an alpine catchment, Bertoldi *et al*. (2010) showed that the major factors controlling the land surface temperature in a humid climate were incoming solar radiation and land cover variability. Others have also taken the GEOtop model and added further modules to it including a snow module by Zanotti *et al*. (2004) and a landside probability function by Simoni *et al*. (2008).

The hourly meteorological data required (precipitation, atmospheric pressure, temperature, global shortwave radiation, relative humidity and, wind speed and direction) by GEOtop were available from the on site meteorological tower. A field measurement study by Lewis *et al*. (2011) at the same site found that the saturated horizontal hydraulic conductivity in the riparian zone within 10 m of the stream was ~10$^{-7}$ m s$^{-1}$, which was one to two orders of magnitude less conductive than the bog interior. The saturated horizontal conductivity was found to be approximately twice vertical hydraulic conductivity. To reflect this pattern in the soil matrix in GEOtop, the peat within 10 m of the stream was assigned the hydraulic parameters found by Lewis *et al*. (2011) in the riparian zone. A second zone was created between 10 and 20 m from the stream, and the peat in this zone was assigned a higher hydraulic conductivity value. An incremental process of increasing the hydraulic conductivity was utilized until at the bog interior the saturated hydraulic conductivity assigned was ~10$^{-5}$ m s$^{-1}$. Vegetation details (LAI, height and root depth) were adopted from Sottocornola *et al*. (2009) and Laine *et al*. (2007).

### *Modelling scenarios*

To reflect the practice of draining peatland prior to afforestation, an artificial drainage network was simulated for this GEOtop application. This consisted of a series of ditches placed 8 m apart and 350 mm deep. The ditches ran orthogonal to the contours and drained into the stream running through the centre of the bog. Initial trials of this new drainage network found, however, that there was little change in the WT. Peatland drains have been found to lower the WT adjacent to the drains specifically downslope



DOI: 10.1002/hyp

of drains as the drains intercept the surface runoff from upslope areas (Holden *et al.*, 2006). Because of model constraints, it was not possible to increase the drainage network density to achieve a realistic WT drawdown. It was therefore decided to increase the horizontal conductivity of the peatland to represent the changed travel time for water from the peat matrix to the drainage network that a peatland with a higher density of drains would have. However, it must also be noted that this increase in horizontal conductivity is also likely to reflect the increase in hydraulic conductivity caused by changes in soil structure associated with WT drawdown (Ramchunder *et al.*, 2007).

Two possible land use change scenarios were simulated in this study, changing the land use from natural peatland to a 10-year-old (Scenatio A) and a 15-year-old (Scenario B ) Sitka spruce forest. The LAI was adopted from Tobin *et al.* (2006) in a study on LAI in different ages of Sitka spruce forests in Ireland. Sitka spruce forests at approximately 15 years of age have the highest LAI and therefore deemed to have the largest impact on the rainfall runoff response, mainly from increased interception and transpiration. The changes to the model for Scenario A were made by increasing the LAI to 4.5, root depth to 40 cm and canopy height to 250 cm. For Scenario B, the LAI, root depth and canopy height were increased to 7.5, 55 and 800 cm, respectively. Along with the change in land use, both of these scenarios also included a new drainage network to reflect the practice of draining peatlands prior to afforestation.

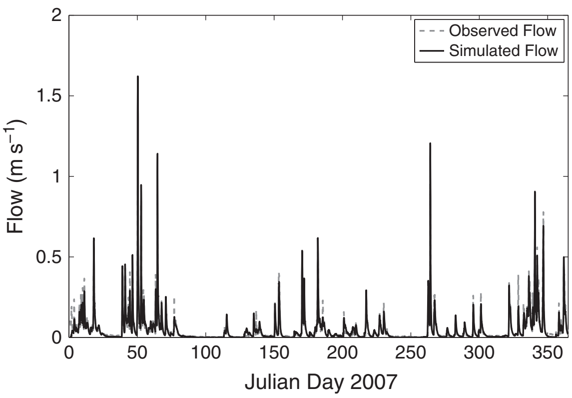


Figure 2. Observed and simulated flows for 2007 at hourly intervals

## RESULTS

The model was calibrated using observed data for 2007. Figure 2 shows the time series of observed and GEOtop modelled flows with in a Nash–Sutcliffe (Nash and Sutcliffe, 1970) efficiency of 0.87. The difference between observed and simulated flows is greatest in times of high flows where the simulated flow is larger than the observed. However, at times of high flow, the observed flows may be underestimated as flow spills overbank, and no streamflow measurements were recorded for overbank flow (because of safety reasons). The cumulative rainfall (2229 mm), observed streamflow (1925 mm) and simulated streamflow (2018 mm) are shown in Figure 3(a). The modelled ET of ~211 mm for 2007 is lower than both the observed value of 304 mm and the nearby eddy covariance estimate of ET of 388 mm for the hydrological year 2006/2007 reported by Sottocornola and Kiely (2010). Monthly totals of simulated flow compare well with observed values (Figure 3(b)) as do the instantaneous values of simulated and observed flows (Figure 3(c)) with the exception of the very highest flows. We believe this is due to the overbank flow for which our high observed flows are likely to be underestimated.

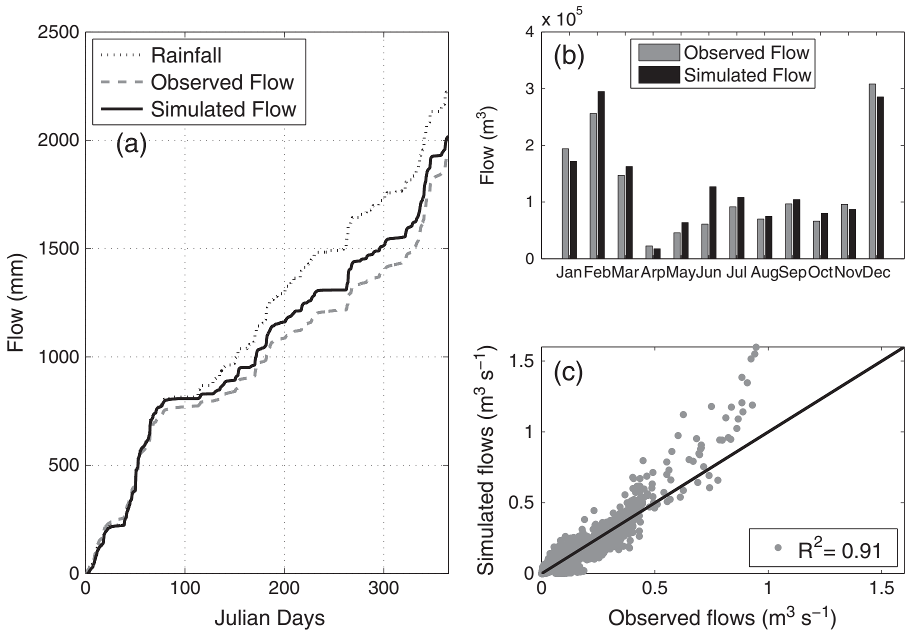


Figure 3. For 2007: (a) cumulative rainfall, observed flow and simulated flow; (b) monthly observed and simulated flows; (c) observed and simulated flows

The observed and simulated WT depths are shown in Figure 4. The model simulates WT over the full extent of the bog and will be somewhat different to the observed WT, which was from one WT sensor point. Examining Figure 4, for 2007, we note that the time series trends of both observed and simulated WTs agree, even though the absolute values are somewhat different. For the instantaneous WT (Figure 4), the range is larger for the simulated WT, but again not hugely different. The annual mean observed WT (Figure 4) was 3.87 cm below the surface, compared with the simulated WT of 4.85 cm. This WT difference is under 1 cm. From Figures 2–4, we suggest that GEOtop simulates well the hydrological process in the peatland for the calibration year.

Once the model was calibrated for 2007, it was then validated (no change to parameters) for 2008. Figures 5–7 and Table II show the results of the 2008 simulation. The Nash–Sutcliffe efficiency of 0.89 for 2008 showed a slight improvement on the 2007 value of 0.87, whereas the simulated flow was slightly greater than the observed flow (Figure 6). The simulated WT had an annual mean value of 2.9 cm below the surface, whereas the observed

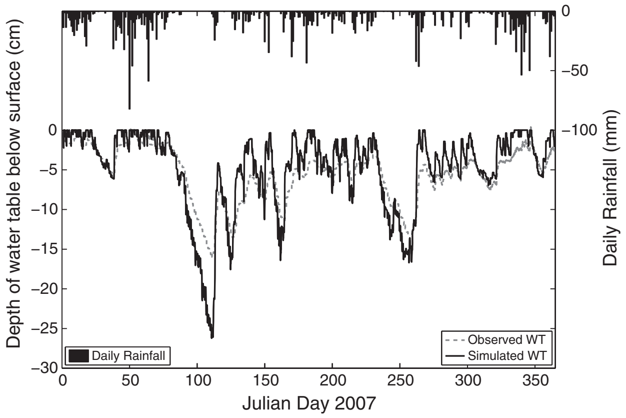


Figure 4. For 2007: daily rainfall (top); observed and simulated water table

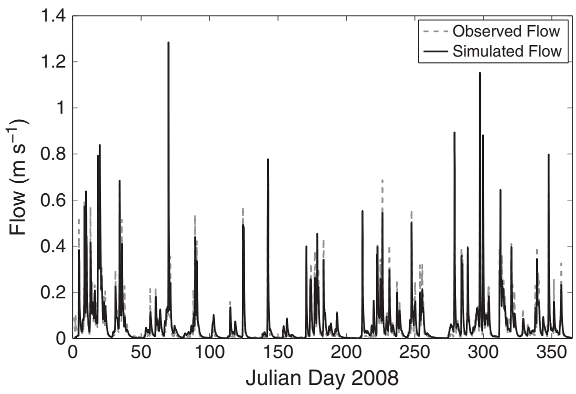


Figure 5. Observed and simulated flows for 2008 at hourly intervals

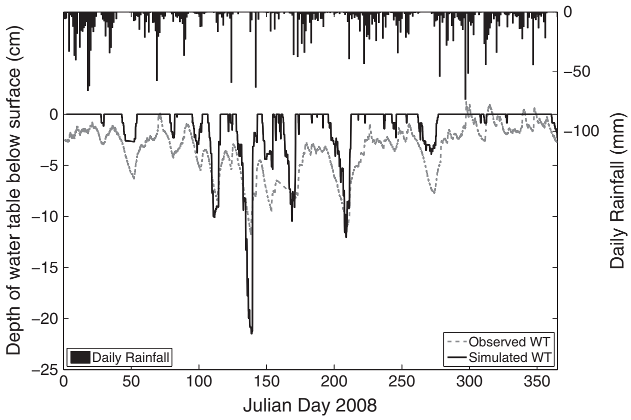


Figure 7. For 2008: daily rainfall (top); observed and simulated water table depth

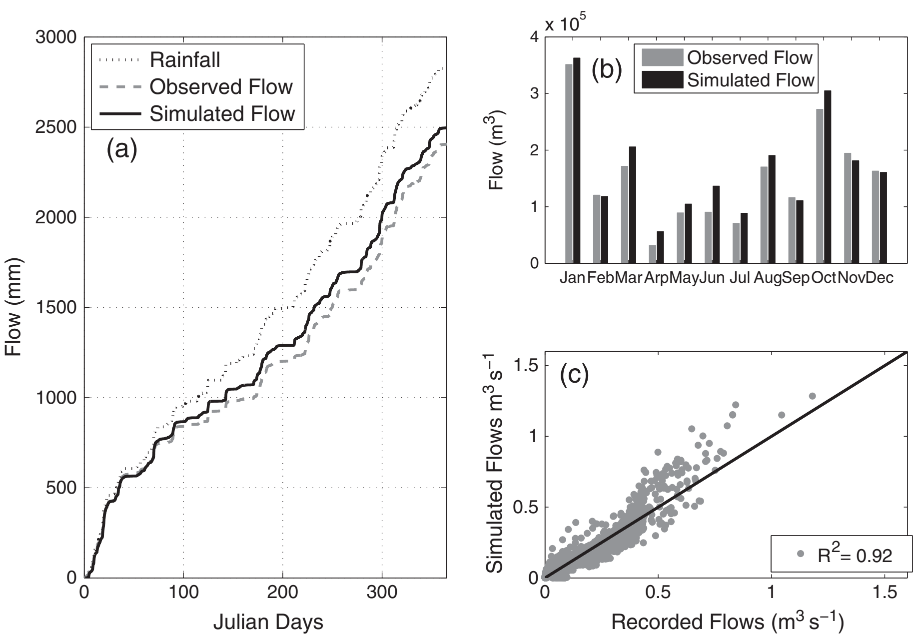


Figure 6. For 2008: (a) cumulative rainfall, observed flow and simulated flow; (b) monthly observed and simulated flows; (c) observed and simulated flows



DOI: 10.1002/hyp

Table II. Observed and modelled scenarios: rainfall, evapotranspiration and streamflow values

| Scenario | Year | Rainfall (mm) | Evapotranspiration (mm) | Streamflow (mm) | Streamflow/rainfall ratio |
|---|---|---|---|---|---|
| Observed | 2007 | 2229 | 304 | 1925 | 0.75 |
| Calibrated model | 2007 | 2229 | 211 | 2018 | 0.82 |
| Observed | 2008 | 2826 | 421 | 2405 | 0.85 |
| Validated model | 2008 | 2826 | 330 | 2496 | 0.88 |
| Scenario A | 2008 | 2826 | 501 | 2325 | 0.83 |
| Scenario B | 2008 | 2826 | 913 | 1913 | 0.67 |

WT had an annual mean depth of 3.5 cm below the surface for 2008. These figures show that GEOtop provides a similar level of accuracy for the validation year 2008 as it did for the calibration year 2007. From this, we suggest that the current configuration of GEOtop simulates well the hydrological processes in the Glencar blanket peatland and that we are able to proceed with a study of land use change scenarios.

The overall goal of this project is to study the change in hydrological response of peatland when land use is changed from its natural state to forestry. It is not possible to do this by simply changing the land use in the model, as in practice, peatlands are drained prior to planting (Holden *et al*., 2004). To reflect this, the drainage network in the model was modified, and a series of new network drains was inserted into the model. The model was then run again for the 2 years, 2007 and 2008, with land use change Scenarios A and B. Although the model was run for 2 years, the cumulative flow and ET values are shown in Figure 9 for 2008 only, after allowing the model to spin up for the first 3 months of 2007.

The changes in WT due to the drainage and land use change scenarios are shown in Figure 8. The simulated drained peatland showed a drop in WT, particularly in the summer months with the annual mean drained WT 15.0 cm below the surface and 11.5 cm below the observed WT. The annual mean observed WT depth for 2008 was 3.5 cm below the surface, whereas with mean simulated WT depths for scenarios A and B were 12.0 and 24.0 cm, respectively (see Figure 8).

The cumulative rainfall (2826 mm), observed flow (2405 mm) and simulated flows (2325 for Scenario A and 1913 mm for Scenario B) for 2008 are shown in Figure 9. From this, we estimate that ET from the peatland is ~420 mm in 2008, which is similar to the highest value (424 mm) of the eddy covariance estimated ET reported by Sottocornola and Kiely (2010) in the period 2002–2007. Scenario A showed very little change in ET from the undisturbed peatland, whereas the ET for Scenario B was 925 mm, an increase of 492 mm when compared with the observed ET in 2008. The total annual simulated streamflow for Scenarios A and B were reduced to 96% and 80%, respectively, of the observed flow. A comparison of the streamflow between the observed flow and Scenario B did not show that Scenario B was consistently reduced by 80%. It showed rather that Scenario B had at different times of the year, both higher (typically in winter) and lower streamflows (typically summer) than the observed

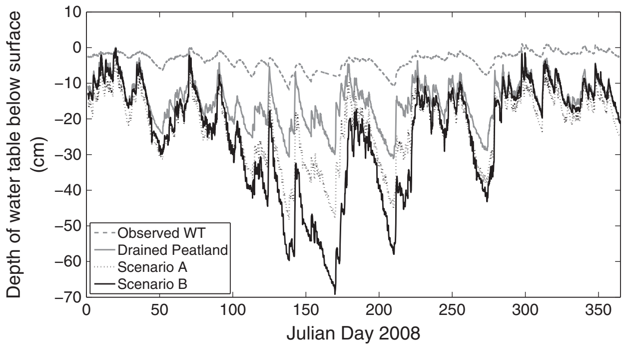


Figure 8. For 2008: water table for observed, drained peat, Scenario A and Scenario B

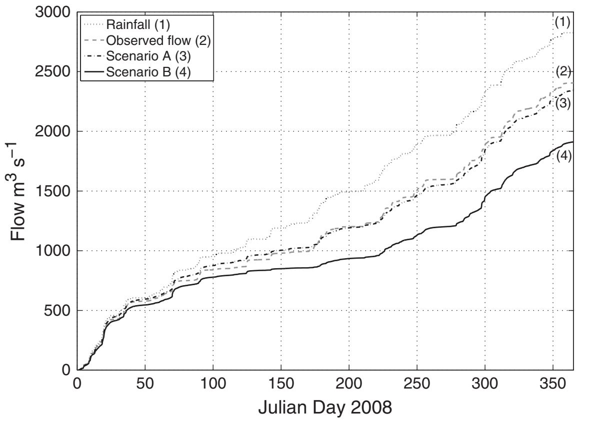


Figure 9. Cumulative rainfall, observed flow, simulated flow, Scenario A and Scenario B flows

streamflow. This is illustrated in Figure 10(a) and (b). Figure 10(a) shows the observed flow and the flow from Scenario B from Julian day 134 to day 140, 2007. April and May 2007 were unusually dry with April being one of the driest on record at two nearby Met Eireann (Irish weather service) synoptic weather stations, and below average rainfall was reported in May (http://www.met.ie/climate/monthly_summarys). This resulted in a large drop in WT. An analysis of the precipitation and streamflow on days 134–140 shows that the observed and simulated streamflows from Scenario B produced two very different rainfall runoff responses. The observed streamflow showed a large peak in flow, whereas the simulated Scenario B flow showed only a small response to precipitation. The Scenario B flow for Julian days 134–136 results in almost



DOI: 10.1002/hyp

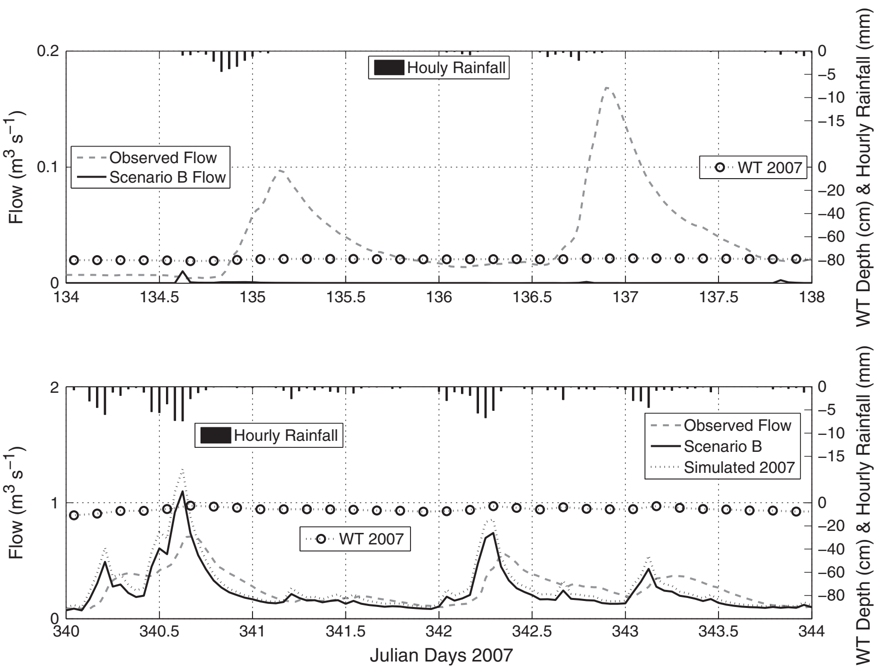


Figure 10. (a) For summer 2007: observed and modelled Scenario B flows; (b) for winter 2007: observed, simulated and Scenario B flows. The simulated winter (b) and summer (a) WTs are also shown

no flow in the stream. Figure 10(b) shows that the converse occurred between days 340 and 344 where the simulated flow from Scenario B was higher than the observed flow. As there is a slight discrepancy between the peak flows and simulated flows for reasons outlined earlier, the simulation of the undisturbed peatland is also shown in Figure 10(b).

## DISCUSSION

The comparisons of observed flows and WT depths with the corresponding simulated values from the GEOtop model in the calibration and validation years show that the current configuration of GEOtop is capable of reliably simulating the hydrological processes. Central to this configuration for the peatland is the spatial variation of hydraulic conductivity. Areas of low hydraulic conductivity at the margins near the stream are essential in maintaining the elevated WT in the centre of the bog. For the drainage scenarios, once these areas of lower hydraulic conductivity were modified by the insertion of a drainage network, the WTs level in the centre of the bog fell. Given that even a slight drop in WT impacts the vegetation distribution and composition (Sottocornola *et al.*, 2009), any disturbance of these relatively small areas of lower hydraulic conductivity will likely affect a much larger area of a bog.

Whereas the practice of drainage prior to afforestation of peatlands lowers the WT, its depth will also be affected by the increase in transpiration and canopy interception with the change of land use from natural peatland to Sitka spruce afforestation. From Figure 9 and Table II, we note that the simulated ET increased in the mature forest (Scenario B) to 492 mm greater than the pristine peatland. The ET rate of the younger forest (Scenario A) was similar to the undisturbed peatland. A study of ET by Sottocornola and Kiely (2010) at the same site found that the ET was not water limited and the observed ET ranged between 369 and 424 mm with an average of 394 mm of ET over a 5-year period. Sottocornola and Kiely (2010) concluded that one of the key limiting factors in ET was the lack of vascular plants, which if present would enhance transpiration. Although Figure 9 shows that there is a drop in the WT for Scenario A, particularly in the summer months, at this stage of development of a forest, the tree canopy would not provide full cover. As the WT is lower than in the undisturbed peatland, the ET rate from the original peatland vegetation, which has a large proportion of non-vascular plants, will have decreased. Thus, it would appear that the increase in ET under the Sitka spruce canopy is offset by the decrease in ET from the original peatland vegetation.

The estimated ET (913 mm) of Scenario B, of a more mature forest, was 412 mm higher than Scenario A. Such increases in ET as a result of changing peatland land use from grass, mosses and bare peat to Sitka spruce have been noted by others. Studies by others in areas such as the Scottish highlands that may be considered similar in soil type and climate to our Irish study site have found that Sitka spruce may intercept between 28% (596 mm) (Johnson, 1990) and 52% (1514 mm) (Heal *et al.*, 2004) of precipitation. Transpiration of Sitka spruce in Cumbria has been estimated at 12% of precipitation or 172 mm (Anderson *et al.*, 1990). We note that our estimates of ET from Scenario B at 32% of rainfall is in the range of values cited in the literature. Results from a study by the Institute of Hydrology (1991) into the effects of upland afforestation on water resources suggest that ET on a forested catchment receiving 2800 mm precipitation annually was approximately 1190 mm, which is similar to



DOI: 10.1002/hyp

the ET value of 925 mm in our Scenario B. Other studies on afforested peatlands such as the Marcell experimental forest in Minnesota and the Huhtisuo catchment in Finland found that ET represented a larger percentage of precipitation than values noted in this study. A study by Verry and Timmons (1982) found that ET from a mature Black Spruce forest represented up to 66% of the annual precipitation with Iritz *et al*. (1994) reporting ET values of 61% of precipitation in the Huhtisuo catchment in Finland. However, precipitation was much lower in both locations with the Huhtisuo catchment and Marcell forest annually receiving approximately 700 and 800 mm precipitation, respectively. The climate at both locations is described as continental with streamflow tending to cease for 2–4 months of each winter because of lower temperatures in Marcell (Kolka *et al*., 2001). The difference in climate is likely to have resulted in the difference in simulated and observed ET values in our study and that of those reported from the Huhtisuo catchment and Marcell forest. In our site, the average precipitation over a 5-year period was 2597 mm with an average ET of 394 mm representing approximately 15% of precipitation. The increased ET associated with afforestation in conjunction with the drainage network resulted in a WT draw down in dry periods (Figure 9). The WT in Scenarios A and B was on average 16.5 and 20.5 cm below the observed WT for the calendar year 2008. This is similar to the draw down noted by Bragg (2002) where the WT in a forested peatland was found to be 10.0–15.0 cm below that in the adjacent unforested peatland.

As the runoff from peatlands in their natural state (in Western Europe) is known to be flashy because of saturation excess overland flow, a lowering of the WT is expected to reduce the volume of runoff produced from saturation excess. This is noted in the hydrograph for a summer period in Figure 10(a), which shows the observed and the simulated flows from Scenario B, for Julian days 134–140. The rain event on day 135 was preceded by a dry period in April and May 2007; the end of which the WT was observed to be at its lowest level since records began in 2003. At the start of the precipitation event of day 135, the WT of Scenario B was 69.8 cm lower than the observed WT of the pristine peatland and 59.2 cm below the drained simulation. With this lower WT and reduced precipitation reaching the ground because of canopy interception, the streamflow from the simulated forest catchment is greatly reduced. However, the converse applies for the streamflow in winter as shown in Figure 10(b). Prior to day 340, there had been frequent rain events, which had resulted in a much higher WT both in the simulated and observed cases. A total of 53 mm fell on day 340, resulting in a higher simulated than observed flow. As the observed WT was 1.9 cm below the surface and Scenario B was just 2.5 cm below the surface, we consider that both simulations produced saturation excess overland flow. However, the forested simulation had a more extensive drainage network that was able to convey any surface runoff to the catchment outfall more rapidly resulting in a higher peak flows. Such a phenomenon has also been noted by others: with Ahti (1980) finding that increasing density of drainage ditches increased peak flows in a Finish peatland and model simulations by Iritz *et al*. (1994) noting that peak flows may be increased by forest drainage when the WT is close to the surface. The studies of Anderson *et al*. (2000) and (Ballard *et al*., 2011b) also drew similar conclusions.

This phenomenon of increasing the streamflow following afforestation of peatlands may have implications in larger catchments where afforestation may be falsely considered as a flood mitigation measure. Likewise, the reduction of flows from peatlands throughout the summer and in particular after dry periods may be of concern for water resource managers.

## CONCLUSION

With regard to applying the hydrological GEOtop model to an Atlantic blanket peatland, we found that GEOtop was suitable for the purposes of modelling the hydrological processes. Central to this was the input of the spatial variation of the saturated hydraulic conductivity. Peat with a lower hydraulic conductivity at the margins results in elevating the WT depth in the centre of the bog, which in turn results in saturation excess overland flow during precipitation events. It is also clear from the scenario modelling that afforestation and its associated drainage can change the hydrological response of this pristine peatland catchment. Whereas the ET rates from a young Sitka spruce catchment were similar to the existing pristine peatland catchment, a semi-mature Sitka Spruce forest resulted in an increase in ET of 492 mm through increased transpiration from the canopy and interception. This increase in ET was particularly noticeable in summer and resulted in an increase in depth of the WT and reduction in streamflow. However, in winter, following periods of heavy rainfall, the WT depth approached that of an unforested drained peatland. This shallow WT depth in combination with a drainage network results in an increase in peak flow in times of heavy rainfall. This suggests that there is limited or no benefit to flood attenuation from peatland afforestation during winter periods when the WT is high, whereas the converse applies to summer flows where the rainfall runoff was reduced in dry periods.

### ACKNOWLEDGEMENTS

This study was funded by the Irish Environmental Protection Agency under the Science Technology Research and Innovation for the Environment Programme 2007–2013 of Ireland (Soil H: Interactions of soil hydrology, land use and climate change and their impact on soil quality; 2007-S-SL-1-S1). We would like to thank Dr Alice Wemaere of the Environmental Protection Agency for her continuous support. We would also like to thank the SoilH steering committee for their support, advise and encouragement throughout this project: Prof. Mark Kibblewhite, Dr Arwyn Jones and Dr Otto Spaargaren. We particularly wish to thank our present and past colleagues in the HYDROMET group: Dr Paul Leahy, Mr Nelius Foley, Dr Rashid Rafique and Dr Michael Wellock. We thank Caitriona Douglas of NPWS and Coillte Teoranta for the permission to use the study site. We also very much appreciate the support of the developers of GEOtop in particular Prof. Riccardo Rigon and Dr Matteo Dall' Amico. We acknowledge in particular the earlier work of Dr Anna Laine, Dr Matteo Sottocornola and Dr Ann-Kristin Koehler and their work and publications from the same site.

## REFERENCES

Abbott MB, Bathurst JC, Cunge JA, Oconnell PE, Rasmussen J. 1986. An introduction to the European hydrological system—systeme hydrologique Europeen, she .2. Structure of a physically-based, distributed modeling system. *Journal of Hydrology* **87**(1–2): 61–77.

Ahti E. 1980. Ditch spacing experiments in estimating the effects of peatland drainage on summer runoff. *Proceedings of the Helsinki Symposium* Helsinki.

Anderson AR, Pyatt DG. 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.

Anderson AR, Pyatt DG, Stannard JP. 1990. The effects of clearfelling a Sitka Spruce Stand on the water-balance of a peaty gley soil at Kershope Forest, Cumbria. *Forestry* **63**(1): 51–71.

Anderson AR, Day R, Pyatt DG. 2000. Physical and hydrological impacts of blanket bog afforestation at Bad a' Cheo, Caithness: the first 5 years. *Forestry* **73**(5): 467–478.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR. 1998. Large area hydrologic modeling and assessment: Part I. model development. *American water resources Association* **34**(1): 73–89.

Baird AJ, Eades PA, Surridge BWJ. 2008. The hydraulic structure of a raised bog and its implications for ecohydrological modelling of bog development. *Ecohydrology* **1**(4): 289–298. DOI: 10.1002/Eco.33.

Ballard CE, McIntyre HS, Wheater HS, Holden J, Wallage ZE. 2011a. Hydrological modelling of drained blanket peatland. *Journal of Hydrology* **407**: 81–83. http: //dx.doi.org/10.1016/j.jhydrol.2011.07.005

Ballard CE, Mclntyre N, Wheater HS. 2011b. Effects of peatland drainage management on peak flows. *Hydrology and Earth System Sciences* **8**: 6533–6563. DOI: 10.5194/hessd-8-6533-2011.

Bay R. 1969. Runoff from small peatland watersheds. *Journal of Hydrology* **9**: 90–102.

Bertoldi G, Rigon R, Over TM. 2006. Impact of watershed geomorphic characteristics on the energy and water budgets. *Journal of Hydrometeorology* **7**(3): 389–403.

Bertoldi G, Notarnicola C, Leitinger G, Endrizzi S, Zebisch M, Della Chiesa S, Tappeiner U. 2010. Topographical and ecohydrological controls on land surface temperature in an alpine catchment. *Ecohydrology* **3**(2): 189–204. DOI: 10.1002/Eco.129.

Beven K, Kirkby MJ. 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* **23**: 419–437.

Black K, Gallagher G, O' Brien P, Redmond J, Barrett F, Twomey M. 2008. *Dispelling myths: the ture extent of recent peatland afforestation in Ireland*. Coford: Dublin.

Bragg OM. 2002. Hydrology of peat-forming wetlands in Scotland. *Science of the Total Environment* **294**(1–3): 111–129. Pii S0048-9697 (02)00059-1.

Burke B. 1975. Effect of drainage on the hydrology of blanket-bog. *Irish journal of agricultural research* **14**: 145–62.

Byrne KA, Farrell EP. 2005. The effect of afforestation on soil carbon dioxide emissions in blanket peatland in Ireland. *Forestry* **78**(3): 217–227. DOI: 10.1093/forestry/cpi020.

Conway VM, Millar A. 1969. The hydrology of some small peat-covered catchments in the northern Pennines. *Journal of the Institute of Water Engineers* **14**: 415–24.

Dept. of Agriculture. 1996. Growing for the future—a strategic plan for the Development of the Forestry Sector in Ireland, Dublin.

Dunn SM, Mackay R. 1996. Modelling the hydrological impacts of open ditch drainage. *Journal of Hydrology* **179**(1–4): 37–66.

Eaton J, McGoff N, Byrne K, Leahy P, Kiely G. 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Climatic Change* **91**(3–4): 317–334. DOI: 10.1007/s10584-008-9412-2.

Frolking S, Roulet NT. 2007. Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. *Global Change Biology* **13**(5): 1079–1088. DOI: 10.1111/j.1365-2486.2007.01339.x

van Genuchten MT. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44**(5): 892–898.

Hargreaves KJ, Milne R, Cannell MGR. 2003. Carbon balance of afforested peatland in Scotland. *Forestry* **76**(3): 299–317.

Heal KV, Stidson RT, Dickey CA, Cape JN, Heal MR. 2004. New data for water losses from mature Sitka spruce plantations in temperate upland catchments. *Hydrological Sciences Journal* **49**(3): 477–493.

Hoag RS, Price JS. 1995. A field-scale, natural gradient solute transport experiment in peat at a Newfoundland blanket bog. *Journal of Hydrology* **172**(1–4): 171–184.

Hogan JM, van der Kamp G, Barbour SL, Schmidt R. 2006. Field methods for measuring hydraulic properties of peat deposits. *Hydrological Processes* **20**(17): 3635–3649. DOI: 10.1002/Hyp.6379.

Holden J. 2005. Peatland hydrology and carbon release: why small-scale process matters. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* **363**(1837): 2891–2913. DOI: 10.1098/rsta.2005.1671.

Holden J, Burt TP. 2002. Infiltration, runoff and sediment production in blanket peat catchments: implications of field rainfall simulation experiments. *Hydrological Processes* **16**(13): 2537–2557. DOI: 10.1002/Hyp.1014.

Holden J, Burt TP. 2003. Hydraulic conductivity in upland blanket peat: measurement and variability. *Hydrological Processes* **17**(6): 1227–1237. DOI: 10.1002/Hyp.1182.

Holden J, Chapman PJ, Labadz JC. 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography* **28**(1): 95–123.

Holden J, Evans MG, Burt TP, Horton M. 2006. Impact of land drainage on peatland hydrology. *Journal of Environmental Quality* **35**(5): 1764–1778.

Holden J, Wallage ZE, Lane SN, McDonald AT. 2011. Water table dynamics in undisturbed, drained and restored blanket peat. *Journal of Hydrology* **402**(1–2): 103–114. DOI: 10.1016/j.jhydrol.2011.03.010.

Horgan T, Keane M, McCarthy R, Lally M, Thompson D. 2004. *A Guide to Forest Tree Species Selection and Silviculture in Ireland*. Coford: Dublin.

Hudson JA, Gilman K, Calder IR. 1997. Land use and water issues in the uplands with reference to the Plynlimon study. *Hydrology and Earth System Sciences* **1**(3): 239–397.

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

Iritz L, Johansson B, Lundin L. 1994. Impacts of forest drainage on floods. *Hydrological Sciences Journal* **39**(6): 637–661.

Johnson RC. 1990. The interception, throughfall and stemflow in a forest in Highland Scotland and the comparison with other upland forests in the UK. *Journal of Hydrology* **118**(1–4): 281–287.

Koehler AK, Murphy K, Kiely G, Sottocornola M. 2009. Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South Western Ireland. *Biogeochemistry* **95**: 231–242. DOI: 10.1007/s10533-009-9333-9.

Koehler AK, Sottocornola, M, Kiely, G. 2011. How strong is the current carbon sequestration of an Atlantic blanket bog? *Global Change Biology* **17**(1): 309–319. DOI: 10.1111/j.1365-2486.2010.02180.x.

Kolka RK, Griagal DF, Nater EA, Verry ES. 2001. Hydrologic cycling of mercury and organic carbon in a forested upland-bog watershed. *Soil Science Society* **65**: 897–905.

Lafleur PM, Hember RA, Admiral SW, Roulet NT. 2005. Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada. *Hydrological Processes* **19**(18): 3533–3550.

Laine A, Byrne KA, Kiely G, Tuittila ES. 2007. Patterns in vegetation and CO2 dynamics along a water level gradient in a lowland blanket bog. *Ecosystems* **10**(6): 890–905. DOI: 10.1007/s10021-007-9067-2.

Lane SN, Brookes CJ, Kirkby AJ, Holden J. 2004. A network-indexbased version of TOPMODEL for use with high-resolution digital topographic data. *Hydrological Processes* **18**(1): 191–201.

Lapen DR, Price JS, Gilbert R. 2005. Modelling two-dimensional steady-state groundwater flow and flow sensitivity to boundary conditions in blanket peat complexes. *Hydrological Processes* **19**(2): 371–386. DOI: 10.1002/Hyp.1507

Lees JC. 1972. Soil aeration and Sitka Spruce seedling growth in peat. *Journal of Ecology* **60**(2): 343–349.

Letts MG, Roulet N, Comer NT. 2000. Parameterization of peatland hydraulic properties for the Canadian land surface scheme. *Canadian Meterological and Oceanographic Society* **38**: 141–160.

Lewis C, Albertson J, Xu X, Kiely G. 2011. Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. *Hydrological Processes* **26**: 1527–1537. DOI: 10.1002/hyp.8252.

Limpens J, Berendse F, Blodau C, Canadell JG, Freeman C, Holden J, Roulet N, Rydin H, Schaepman-Strub G. 2008. Peatlands and the carbon cycle: from local processes to global implications—a synthesis. *Biogeosciences* **5**(5): 1475–1491.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models part I—a discussion of principles. *Journal of Hydrology* **10**(3): 282–290.

NFI. 2007. National Forest Inventory—Republic of Ireland—Results, Johnstown Castle Estate, Co Wexford, Ireland.

Nilsson M, Sagerfors J, Buffam I, Laudon H, Eriksson T, Grelle A, Klemedtsson L, Weslien P, Lindroth A. 2008. Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire—a significant sink after accounting for all C-fluxes. *Global Change Biology* **14**(10): 2317–2332. DOI: 10.1111/j.1365-2486.2008.01654.x

Oechel WC, Vourlitis GL, Hastings SJ, Zulueta RC, Hinzman L, Kane D. 2000. Acclimation of ecosystem CO2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature* **406**(6799): 978–981.

Pilcher JR, Mac an tSaoir S. 1995. *Wood, Trees Forests in Ireland*. Royal Irish Academy: Dublin.

Prevost M, Belleau P, Plamondon AP. 1997. Substrate conditions in a treed peatland: responses to drainage. *Ecoscience* **4**(4): 543–554.

Price JS, Branfireun BA, Waddington JM, Devito KJ. 2005. Advances in Canadian wetland hydrology, 1999–2003. *Hydrological Processes* **19**(1): 201–214. DOI: 10.1002/Hyp.5774.

Ramchunder SJ, Brown LE, Holden J. 2007. Environmental effects of drainage, drain-blocking and prescribed vegetation burning in UK upland peatlands. *Progress in Physical Geography* **2009**(33): 49. DOI: 10.1177/0309133309105245.

Reggiani P, Sivapalan M, Hassanizadeh SM. 2000. Conservation equations governing hillslope responses: exploring the physical basis of water balance. *Water Resources Research* **36**(7): 1845–1863.

Rigon R, Bertoldi G, Over TM. 2006. GEOtop: a distributed hydrological model with coupled water and energy budgets. *Journal of Hydrometeorology* **7**(3): 371–388.

Robinson M. 1986. Changes in catchment runoff following drainage and afforestation. *Journal of Hydrology* **86**(1–2): 71–84.

Simoni S, Zanotti F, Bertoldi G, Rigon R. 2008. Modelling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS. *Hydrological Processes* **22**(4): 532–545. DOI: 10.1002/Hyp.6886.

Sottocornola M, Kiely G. 2010. Energy fluxes and evaporation mechanisms in an Atlantic blanket bog in southwestern Ireland. *Water Resources Research* **46**. DOI: 10.1029/2010WR009078.

Sottocornola M, Laine A, Kiely G, Byrne KA, Tuittila ES. 2009. Vegetation and environmental variation in an Atlantic blanket bog in southwestern Ireland. *Plant Ecology* **203**(1): 69–81. DOI: 10.1007/s11258-008-9510-2.

Strack M, Waddington JM, Rochefort L, Tuittila ES. 2006. Response of vegetation and net ecosystem carbon dioxide exchange at different peatland microforms following water table drawdown. *Journal of Geophysical Research-Biogeosciences* **111**(G2). DOI: 10.1029/2005jg000145.

Tobin B, Black K, Osborne B, Reidy B, Bolger T, Nieuwenhuis M. 2006. Assessment of allometric algorithms for estimating leaf biomass, leaf area index and litter fall in different-aged Sitka spruce forests. *Forestry* **79**(4): 453–465. DOI: 10.1093/forestry/cpl030.

Verry ES, Timmons DR. 1982. Waterborne nutrient flow through an upland-peatland watershed in Minnesota. *Ecology* **65**(5): 1456–1467.

Waldron S, Flowers H, Arlaud C, Bryant C, McFarlane S. 2009. The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance, a stoichiometric perspective. *Biogeosciences* **6**(3): 363–374.

Zanotti F, Endrizzi S, Bertoldi G, Rigon R. 2004. The GEOTOP snow module. *Hydrological Processes* **18**(18): 3667–3679. DOI: 10.1002/Hyp.5794.