Modelling soil water fluxes in a Norway spruce {*Picea abies* (L.) Karst.} stand at Ballyhooly, Co Cork

Julian Aherne[1], Thomas Cummins[1] and Edward P. Farrell[1]

Abstract

Solute fluxes within the soil can contribute greatly to the understanding of biogeochemical processes. They are typically estimated from measured concentrations and simulated soil water fluxes. Models used to calculate soil water fluxes generally require water retention characteristics, hydraulic conductivity characteristics and root distribution as inputs.

Using measured precipitation and throughfall volume in combination with modelled soil water fluxes, estimated using the FORHYD model, the six-year (1989–1994) mean annual hydrological balance for a Norway spruce stand at Ballyhooly, Co Cork, has been estimated. Precipitation was 1141 mm yr^{-1} while evaporation from tree surfaces was 497 mm yr^{-1}. The vertical soil-water flux, estimated by simulation, was 322 mm yr^{-1} at 1 m depth.

Keywords: hydrological balance, soil water fluxes, FORHYD model, forest ecosystems.

Introduction

The Forest Ecosystem Research Group (FERG), at University College Dublin, operates four forest monitoring plots in Ireland with the aim of quantifying the effects of atmospheric deposition on forest ecosystems (Farrell *et al.* 1993). An important part of the research involves estimating water and element budgets within the ecosystem. Element transport is typically estimated from measured concentrations and simulated soil water fluxes. The hydrological study, which is presented here, describes the six-year mean annual hydrological balance for a forest ecosystem at Ballyhooly, Co Cork.

The Ballyhooly intensive forest monitoring plot is located in a mixed intensive farming area in the south of Ireland (8°25' W, 52°08' N). The altitude is 70 m, annual precipitation averages 1141 mm and the mean annual temperature is 9.9° C. The monitoring plot is located in a plantation of Norway spruce {*Picea abies* (L.) Karst.} established on a former oak woodland site, supporting a relatively rich woodland flora. The spruce was planted in 1939, with periodic thinning between 1950–1985 and was clearfelled in 1995. The dominant soil type is orthic podzol (Spodosol; Typic Haplorthod), developed from periglacial colluvium, which overlies Devonian sandstone till. It is deep and relatively free-draining, stones are common and fine roots occur throughout. A detailed site description is given in Farrell *et al.* (1996)

Methods

Precipitation was measured weekly at a treeless site near the forest plot using permanently open 10 cm diameter funnel collectors (three collectors). Throughfall was collected weekly in similar collectors located below the tree canopy but above the herb layer (nine

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[1] Forest Ecosystem Research Group, Department of Environmental Resource Management, Faculty of Agriculture, University College Dublin, Belfield, Dublin 4.
Corresponding author: julian.aherne@ucd.ie

collectors). Stemflow was collected in helical, silicon rubber gutters attached to tree stems (eight collectors). Canopy interception was calculated as the difference between precipitation and throughfall plus stemflow. Soil-water fluxes were estimated using a hydrological model developed for forest soils (Tiktak and Bouten 1992). Soil moisture tension, used for model calibration and validation, was measured weekly using Thies Clima type tubes with an unglazed ceramic cup sealed to a frost-resistant transparent hollow tube, with the upper end sealed by a rubber septum in a screw cap. Tensiometers were installed at two depths, 25 cm (ten tensiometers) and 75 cm below the organic horizon (16 tensiometers). Measurement methods are further described in Farrell *et al.* (1996).

The FORHYD model

Soil water fluxes were estimated using the computer simulation package FORHYD (FORest HYDrology), developed by the Laboratory of Physical Geography and Soil Science, University of Amsterdam (Tiktak and Bouten 1992). FORHYD contains several modules simulating the hydrological processes in forested ecosystems. SWIF (Soil Water In Forests) the soil water module, describes root-water uptake and vertical water flow in the unsaturated soil zone (m week^{-1}) as well as lateral drainage in the saturated zone. Essentially the model calculates the finite difference solution of the Richards equation (Richards 1931):

$$C(h)\cdot\frac{\delta h}{\delta t}=\frac{\delta\left[K(h)\left(\frac{\delta h}{\delta z+1}\right)\right]}{\delta z}-S(h)-D(h)$$

where:
C is differential water capacity (m^{-1}),
t is time (estimated weekly for the simulation scenario presented here),
z is height (m),
h is soil-water tension (m),
K(h) is unsaturated conductivity (m week^{-1}),
S is a sink term accounting for root water uptake and
D is a sink term accounting for net lateral drainage (m week^{-1}).

The energy available (W m^{-2}) for forest floor evaporation and root-water uptake is calculated as the Makkink reference evapotranspiration (de Bruin 1987) based simply on air temperature (K) and global solar radiation (W m^{-2}). The available energy is partitioned between potential transpiration and soil evaporation, using a canopy gap fraction (Von Röhle and Huber 1985). A crop factor is used to calculate the actual root water uptake from the potential transpiration.

Several of the system parameters that are used in the uptake and drainage functions were not, or cannot be, measured directly. They are either obtained from literature or need calibration. Details of the model, including the equations and underlying assumptions, are given in Tiktak *et al.* (1990).

Measurements and simulations

The physical soil properties required as inputs for the model were: (a) water retention characteristics—obtained using a sand/kaolinite box and pressure plates at higher tensions for the three depths: 0–30 cm, 31–60 cm and 61–100 cm, (b) hydraulic conductivity characteristics - calculated as described in van Genuchten (1980), and (c) distribution density of roots <2 mm, determined from a study of root numbers by depth (Jones 1990). The soil properties used in the model are shown in Figure 1.

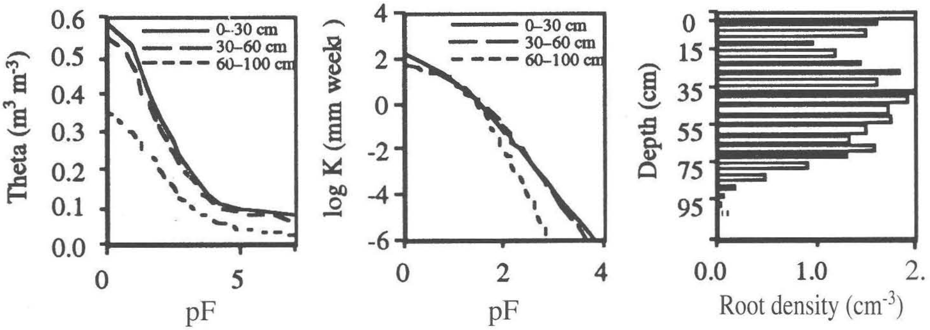

Figure 1. *Model inputs: (a) water content, theta, as a function of soil tension (after Hall 1990), (b) hydraulic conductivity as a function of soil moisture tension (after Hall 1990) and (c) average root distribution, 150 cm from the trees, as a function of depth (after Jones 1990).*

Global solar radiation, used in the calculation of Makkink evapotranspiration, was obtained using an Ångström-type relationship solved for Ireland as described by Connaughton (1967).

The model was validated by comparing simulated with measured soil water tensions. There was a close correlation ($r = 0.731$) between the two. This gave some reassurance that the model was accurate, especially as tensiometers are known to be sensitive to minor changes in water uptake and rainfall, which would not be predicted from the model. A plot (Figure 2) of measured (average of ten tensiometers, sampled weekly) and simulated soil water tensions for 1989–1994 at 25 cm depth shows the closeness of the correlation.

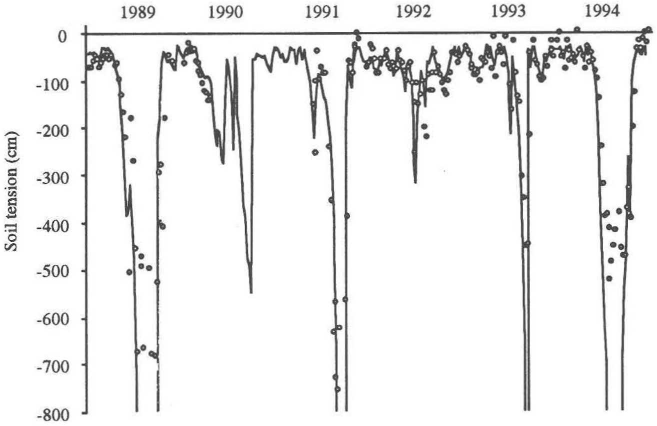

Figure 2. *Measured (•) and simulated (–) soil water tensions at 25 cm depth, 1989–1994.*

Results

The six-year mean annual water budget for the measured and modelled water fluxes are presented in Table 1. Precipitation at Ballyhooly (1141 mm yr^{-1}) was close to the mean for the whole of Ireland (Rohan 1975). The amount of evaporation from the tree surfaces, 497 mm yr^{-1}, is typical for coniferous plantations in this climate. Stemflow volumes were insignificant at Ballyhooly. Tree transpiration, via soil-water uptake, removed a further 291 mm yr^{-1}. The vertical soil-water flux, estimated by simulation, was 570 mm yr^{-1} between the organic and mineral soil horizon (humus water: 0 cm below mineral soil); 472 mm yr^{-1} at 25 cm depth (soil-water shallow); 331 mm yr^{-1} at 75 cm depth (soil-water deep); and 322 mm yr^{-1} at 100 cm depth.

Table 1. *Six-year annual mean water budget at Ballyhooly, 1989–1994.*

Water flux layer	*Volume mm*	*Calculation method*
Precipitation	1141	Measured
Throughfall	632	Measured
Stemflow	12	Measured
Interception	497	By difference
Humus water (0 cm depth)[1]	570	FORHYD
Soil water shallow (25 cm depth)[1]	472	FORHYD
Soil water deep (75 cm depth)[1]	331	FORHYD
Transpiration	291	FORHYD

[1] Depths correspond to solute concentration measurement depths, see Farrell *et al.* (1996) for details.

The water balance is shown graphically in Figure 3.

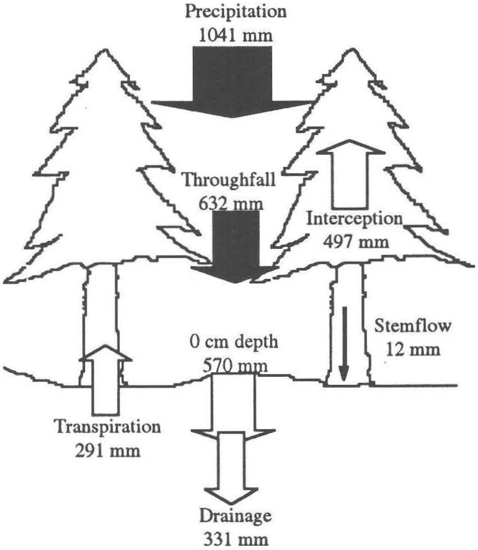

Figure 3. *Six-year mean annual measured (shaded arrows) and simulated (white arrows) water fluxes, at Ballyhooly 1989–1994.*

The water flux estimates, in combination with solute concentrations, can be used to compute solute fluxes {in cases where the solute concentrations over the time intervals (C_i) are assigned to the recharges (q_i) estimated for the same time periods}. Such a computation has been carried out on the Ballyhooly data which has allowed the forest biogeochemical cycles to be described (Farrell *et al.* 1996, 1997).

Limitations

There are a number of limitations to the accurate application of the hydrological balance to Ballyhooly. Open-funnel collectors are designed for chemical analysis of rain water and do not match standard rain gauge design. Long-term comparison suggests an underestimation of 10–15% by the smaller funnels used in this study. Therefore, the water flux entering the soil was probably underestimated. Large, dead root channels in the forest soil and other macropores may allow significant bypass flow, which was not assessed, nor was it taken into account by FORHYD. This may be especially important during heavy rainfall. A further limitation concerns lateral soil-water flow, which was evident occasionally at Ballyhooly. FORHYD does not take this into account in the unsaturated zone. Several of the model parameters and inputs were based on literature or preliminary measurements and may not adequately describe the soil properties. This may cause inaccurate distributions of simulated water through the simulated soil profile.

Conclusions

A thorough knowledge of the hydrological behaviour of ecosystems can greatly contribute to the understanding of biogeochemical processes. Using water fluxes together with measured ion concentrations, solute fluxes can be estimated for forested ecosystems. This allows biogeochemical cycling and turnover of elements to be quantified. Using measured water fluxes and simulated soil-water fluxes the hydrological budget for a Norway spruce stand at Ballyhooly has been described. Using these water fluxes in combination with measured solute concentrations, solute fluxes through the forest ecosystem have been described (Farrell *et al.*, 1996)

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