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Groundwater recharge and evapotranspiration for two natural ecosystems covered with oak and heather

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Abstract

The evapotranspiration and groundwater recharge from two natural areas with high (oak) and low (heath) vegetation were estimated by calibrating a semi-physical numerical soil water and heat model to fit 8 and 7 years of TDR-measurements of water content, respectively. The measurements were made between the surface and 7 m depth. For the oak stand, the estimated annual recharge for the years 1992–1999 is 390 mm, the evaporation from soil and interception is 205 mm, and the transpiration is 285 mm. For the heath area estimation was carried out for the years 1993–1999. However, the heath was struck by a heavy beetle attack in 1994, which strongly affected the vegetation and thus the water balance for the following 3 years. For years not affected, the estimated recharge is 733 mm (about 50% larger than for the oak stand for the same years), the evaporation is 316 mm, and the transpiration is 128 mm. The estimated recharge values compare fairly well to estimates obtained from bromide tracer experiments. However, the recharge estimates obtained from the tracer experiments are very uncertain. The uncertainty is mainly due to spatial heterogeneity making the three replicate samples taken here for each time and depth insufficient.

The analyses of TDR-measurements and tracer data showed that water front movement depends on the antecedent soil water content. Some layers are bypassed, especially at low water contents, and at high soil water contents preferential flow was observed at the heath site.

Keywords: Evapotranspiration; Recharge; Water balance; Tracer; TDR

1. Introduction

In European countries with intensive farming, increasing interest has been paid to protection of pristine groundwater resources by afforestation and conservation of natural ecosystems. In this context knowledge of the water balance of natural and semi-natural ecosystems on poor sandy soils is crucial.

While precipitation is probably relatively unaffected by moderate changes in landuse, the interaction between evapotranspiration and interception on

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the one hand and recharge on the other may be more sensitive to the type of vegetation cover. Thus, studies of coniferous plantations in Scotland (Calder and Newson, 1979) have shown considerable reduction of recharge due to afforestation, although recharge below coniferous trees may be smaller than below deciduous because of their longer foliage season. Also, Wallace et al. (1982) found that the transpiration from forest was slightly higher compared to grass and heather whereas the interception loss was considerably higher in the forest than from the low vegetation. For grass and heather Wallace et al. (1982) found that the evapotranspiration was similar although there were small differences in the contribution from interception loss and transpiration.

Both evapotranspiration and recharge are difficult to measure directly and may instead be estimated by numerical models that are calibrated on indirect experimental data such as soil moisture. Tracer experiments can also be used to study the water balance and to estimate recharge. The chloride mass balance (e.g. McCord et al., 1997; Rosen et al., 1999; Wood, 1999) is a common method to predict water fluxes through or below especially natural ecosystems (Beier, 1998; Ladekarl, 2001; Mossin and Ladekarl, 2004). However, the method is sensitive to measuring depth (McCord et al., 1997), temporal delay between input and output in the unsaturated zone, and in forests also to throughfall (Beier, 1998). Although chloride is already present and natural to the environment more accurate tracer techniques may be preferred. Such another tracer technique is, e.g., to use the velocity of the centre of mass of an applied tracer and the average water content to estimate the recharge rate (Moss and Edmunds, 1989; Buchter et al., 1997; McCord et. al., 1997).

The smaller recharge below forests as compared to low vegetation reduces seepage velocities and thus increases the average residence time in the unsaturated zone (Allen and Chapman, 2001). However, in more heterogeneous soils some of the water may travel relatively fast in preferential pathways as fingers (Hillel and Baker, 1988; Kung, 1990). This effect may be more pronounced in dry soils (Sililo and Tellam, 2000).

The main objectives of this study are (1) to estimate and compare recharge and evapotranspiration for two different natural ecosystems with tall (oak) and low vegetation (heath), respectively, exposed to similar climate (temperate humid climate) and fairly similar soil conditions, (2) to apply and compare different estimation methods and (3) to analyse the soil water dynamics below the root zones of the two vegetation types. The analyses are based on long records of measurements taken to 7 m depth which is shown to give unique information on the influence of climate and vegetation on the water balances.

2. Field sites

2.1. Oak stand

The oak stand, Hald Ege, is located in Central Jutland, Denmark (Fig. 1). The oak trees are approximately 150 years old and the 25 ha forest area has probably never been deforested in post-glacial time (Tybirk and Strandberg, 1996). The trees are 15-20 m high, and the stand density is about 375 trees/ha (Henriksen et al., 1995). The oak wood is a mixed stand of pedunculate (*Quercus robur*) and sessile oak (*Quercus petraea*) and their hybrids.

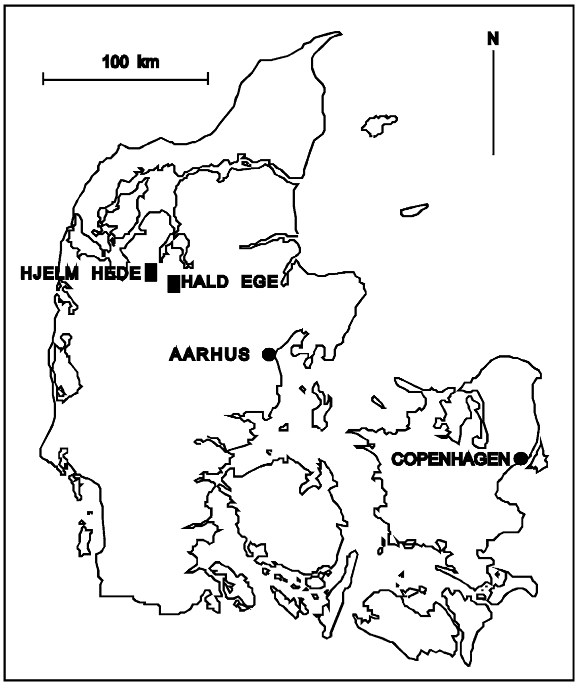

Fig. 1. Location of the two field areas, the oak stand at Hald Ege and the heath site at Hjelm Hede.

The effective root depth is approximately 2 m although roots have been observed at greater depth (Ladekarl, 1998). Leaf Area Index (LAI) was measured once a month in 1998 and occasionally in the other years with a LAI-2000 Plant Canopy Analyser (LI-COR, Lincoln, Nebraska, USA). In 1998 the maximum LAI was about 4 m^2/m^2 in the oak stand.

The soil type ranges from an acid brown forest soil to a spodosol (Typic Udorthens to Typic Fragiorthod; Olsen, 1992). The sediment from the percolation zone below the oak stand is well-sorted sand (87–99%) dominated by the medium sand particle size fraction (Fig. 2a). In general the clay content is very low, between 0.7 and 4% in the root zone and less than

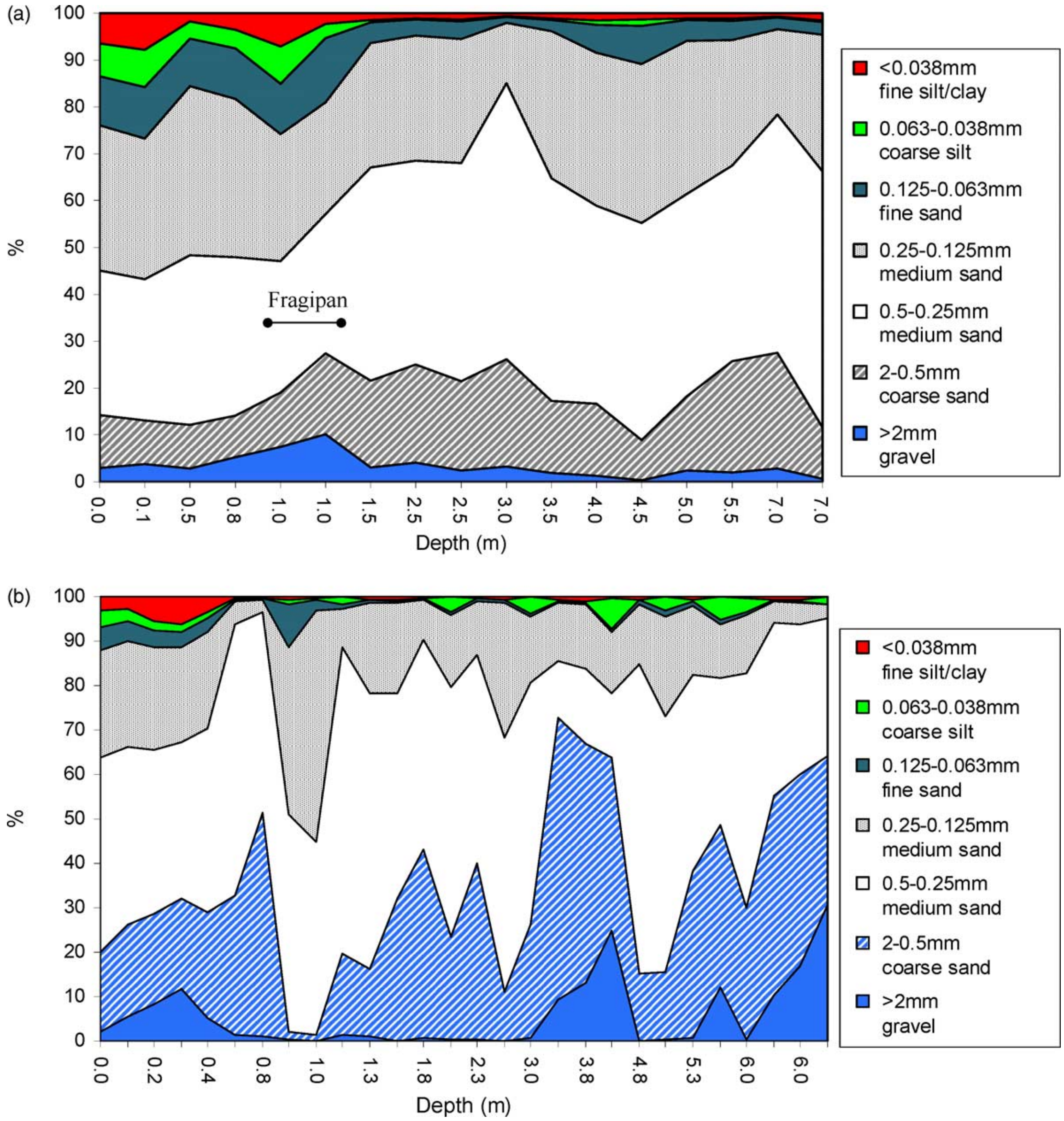

Fig. 2. The textures of the unsaturated zones of (a) the oak stand and (b) the heath area. The position of the fragipan in the oak stand is indicated by a horizontal line.

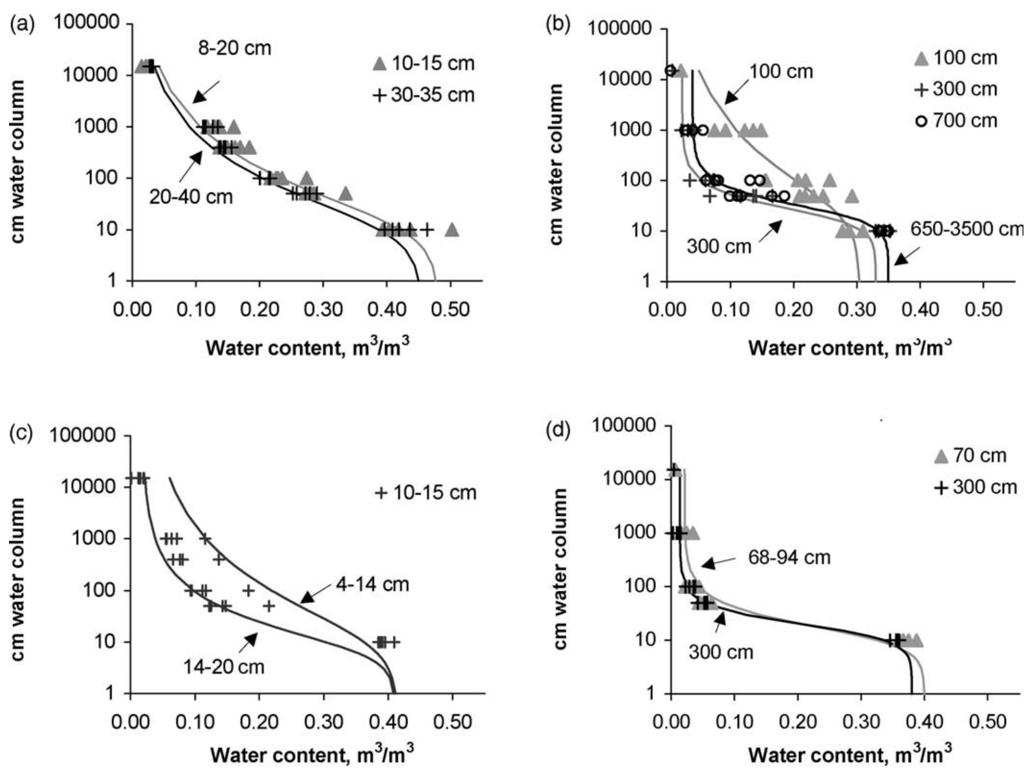

Fig. 3. Retention curves for selected depths in the oak stand (a) 10–15, 30–35 cm, (b) 100, 300 and 700 cm, and at the heath area (c) 10–15 cm, (d) 70 and 300 cm. Lines are retention curves for the specified depths in the COUP-model.

0.4% below the root zone. At a depth of about 1 m in the forest there is a 40 cm thick, hard and compact fragipan with a higher content of fine sand and clay as well as gravel compared to the sediment beneath. The bulk density is 1.67 g/cm^3 at 1 metre's depth, but decreases to 1.43 g/cm^3 at 7 metre's depth.

Five replicate samples for retention (Fig. 3) and density estimation were taken at 0.1, 0.3, 1, 3 and 7 m in the oak stand by cylinders of 100 cm^3. The saturated hydraulic conductivity (K_S) was measured on the retention samples in the laboratory using a constant gradient set-up (Table 1).

The groundwater table is estimated from groundwater potential maps to lie at 35 m below the surface.

2.2. Heath site

The heath land, Hjelm Hede, is also located in Central Jutland, Denmark (Fig. 1), on a glacial outwash plain formed during the Weichelian glaciation. Pollen diagrams show that heath land has existed in the area for more than 3000 years (Odgaard, 1994). The size of the area is approximately 4000 hectares and the vegetation consists of about 60 cm high heather (*Calluna vulgaris*), wavy hairgrass (*Dechampsia flexuosa*) and black berries (*Empetrum nigrum*). The root zone is estimated to 60 cm from root countings (Riis-Nielsen, 1997). In 1998 LAI did not exceed 2.5 m^2/m^2 at the heath site. The between-year variation in leaf area was estimated from measurements of LAI in 1998 using a Plant Canopy Analyzer LAI-2000 (LI-COR, Lincoln, Nebraska, USA) and by the reflectance ratio (Monteith and Unsworth, 1990) based on measurements of the reflected (r) and incident (i) radiation with two two-channel 650 nm (NIR), and 800 nm (R) ligth sensors (SKYE Instruments, Ltd, Powys, Wales, UK):

$$\text{Reflectance ratio} = (\text{NIR}_r/\text{NIR}_i)/(R_r/R_i)$$

The reflected and incident radiation was measured occasionally in 1995 and 1996 and continuously from 1997. In periods lacking measurements estimations

Table 1
Calibrated COUP-model parameter values used for the field sites

COUP-model parameters	Oak stand		Heath site	
Interception constant, I_C	0.6 mm		0.5 mm	
Max LAI	4 m^2/m^2		2.5 m^2/m^2	
Root depth	1.9 m		0.6 m	
Organic layer thickness	0.05 m		0.016 m	
Reference height	21 m		2 m	
Temp air mean	7.9 °C		7.9 °C	
Tension before reduction in root water uptake, cm water column	410 cm		200 cm	
Roughness length	0.5–0.7 m		0.02–0.022 m	
Displacement height	12 m		0.15–0.2 m	
Albedo	16–19 (Raunier, 1976)		13 (Wallace et al., 1982)	
Aerodynamic resistance, r_a				
Canopy conductance, maximal of fully open stomata	5–50 s/m (model est.)		18–100 s/m (model est.) 0.0183 (m/s) (Jackson et al., 1999)	
Surface resistance, r_s	–			
Initial values	30–400 s/m (Persson and Lindroth, 1994)			
Final values	14–105 s/m		52–1000 s/m (model est. Lohammar eq)	
Saturated hydraulic conductivity, K_S	Measured values	Calibrated values	Measured values	Calibrated values
0.7 m	–	–	4.7×10^4–5.7×10^4	8.0×10^4
1 m	4.0×10^1–1.8×10^4	3.3×10^4	–	–
3 m	7.0×10^3–2.3×10^4	1.6×10^4	3.7×10^4–5.0×10^4	1.0×10^3
7 m	3.7×10^2–1.9×10^4	1.7×10^3	–	–

from a water balance model were used, see also Ladekarl et al. (2001) for more details. The heath site was struck by a heather beetle attack in late 1994 and all the Calluna heather died the following year. In 1998 the heather was in good growth again. Details of how the attack affected the soil water dynamics and the water balance were described by Ladekarl et al. (2001).

The soil is podsolic and the sediments mainly consist of medium to coarse sand (Fig. 2b). The sand content is between 68 and 99%, and the texture of the sediment varies from one depth to another with layers rich in gravel and coarse sand, especially the horizons at 0.3, 4.0 and 6.2 m. The bulk density is on average 1.54 g/cm^3 from 0.7 to 3 m depth. Five replicate samples for retention (Fig. 3), saturated hydraulic conductivity (Table 1), and density estimation were taken at 0.1, 0.7 and 3 m.

The groundwater table is 21 m below the surface according to the groundwater potential maps.

Although the sediments at the two field sites exhibit some differences they are both dominated by the sand fractions and as such provide comparable growing conditions for the two vegetation types considered in the study.

3. Monitoring at field sites

3.1. Climatic measurements

Precipitation was measured automatically by a tipping bucket (0.25 mm) at each field site and converted to daily values. Additional daily measurements were made available by the Danish Meteorological Institute (DMI) from a site 2–3 km outside the areas. Data were corrected for aerodynamic effects and wetting loss (Allerup et al., 1998). From late 1998 half hourly values of downwelling global solar radiation (LI-200SZ Pyranometer, ED Service-center, Denmark), net-radiation (NR-LITE, ED Service-center, Denmark), wind speed (Risoe cup anemometer, ED Service-center, Denmark), relative humidity (Vaisala HMP35D, ED Service-center, Denmark) and temperature (Vaisala PT-100 4 Wire Sensor, ED Service-center, Denmark) were recorded above the forest using a 24 m tall mast. Data were aggregated to daily values. In order to simulate the water balance of the oak stand from 1992 to 1998 the measurements from the mast were compared to measurements made at a nearby meteorological station (Foulum). Wind speed and relative humidity differed at the two sites and a linear relation for daily values was found for measurements above the oak stand and at 10 m height at Foulum. For wind speed the regression line is: $y=1.491x-0.25$, $R^2=0.78$. For relative humidity the regression line is: $y=0.6605x+29.505$, $R^2=0.7$. Global radiation and temperature were alike for the two locations. After transformation, data from Foulum were applied to the oak site for the period 1992–1998.

At the heath site global radiation, wind speed and temperature were recorded from 1993 using a 5 m tall mast. Relative humidity was measured from 1998 and correlated to measurements at Foulum (regression line: $y=1.1467x-9.228$, $R^2=0.82$). Throughfall was estimated from three collector troughs (Hansen and Nielsen, 1998) both in the forest and at the heath area. In the oak stand the development in LAI was the same each year in the model. At the heath area the development in LAI differed each year according to measurements and model predictions given in Ladekarl et al. (2001).

The distance between the two experimental plots is only about 30 km and the mean annual precipitation at both sites is about 875 mm (DMI database, 1960–1990). The mean monthly temperature ranges from −0.2 °C in January to 15.4 °C in July at both areas. The year 1996 was unusually dry with only 578 mm of precipitation while 1998 was unusually wet with 1029 mm in the oak stand and slightly more at the heath area. Surface runoff was not observed at any of the sites.

3.2. Measurements of the water content in the root zone

At both field sites the volumetric water content (θ) in the root zone was measured by Time Domain Reflectometry (TDR) with a Tektronix 1502 B metallic cable tester (Tektronix, 1991). The probes consist of two parallel 6 mm thick stainless steel rods with a span of 50 mm between the rods. Most of the probes were inserted vertically from the surface to 20, 50 and 100 cm depth, respectively.

In the oak stand a total of 59 probes were installed in the root zone in 1992 of which eight sets (24 probes) were placed within an area of 10 m^2. Additionally, three vertical probes were installed from 100 to 200 cm depth and eight sets of horizontal probes at 10, 20, 50 and 100 cm below surface (32 in total).

At the heath site a total of 24 vertical probes were installed in the root zone. In 1993 four replicate probes were installed at each depth, and from 1997 additionally four, totalling eight replicate probes at each depth from 1997 to 1999.

Measurements took place at least once a month from 1992 (oak stand) and 1993 (heath area) until 1999 and θ was calculated by the formula given by Topp et al. (1980). Detailed descriptions of the measurements in the root zones were given by Ladekarl (1998) and Ladekarl et al. (2001).

3.3. Measurements of soil water in the percolation zone

In the percolation zone, θ was measured in an access well at each site using 1 m long TDR-probes inserted horizontally at regular intervals between 1 and 7 m depth in the forest and 1 and 6 m depth at the heath (Fig. 4). The wells were placed about 30 m from the root zone study areas and lined with concrete rings (Hansen et al., 1999). The TDR-probes were pushed additionally 15 cm into the soil to reduce effects of water flow disturbance from the well. One probe was inserted at each depth except at 2.5 m and in the bottom of the wells (6 and 7 m for the heath and oak sites, respectively) where two probes were inserted for comparison. Additionally, in the oak stand a 2 m long probe was installed vertically 5 m from the well. θ was measured automatically every second hour from October 1996 in the oak stand and from October 1998 at the heath site. The TDR-traces produced by the automatic system were checked to assure that the probes were inserted correctly. Manual measurements performed before the automatic system was applied showed a similar variation as the automatic readings.

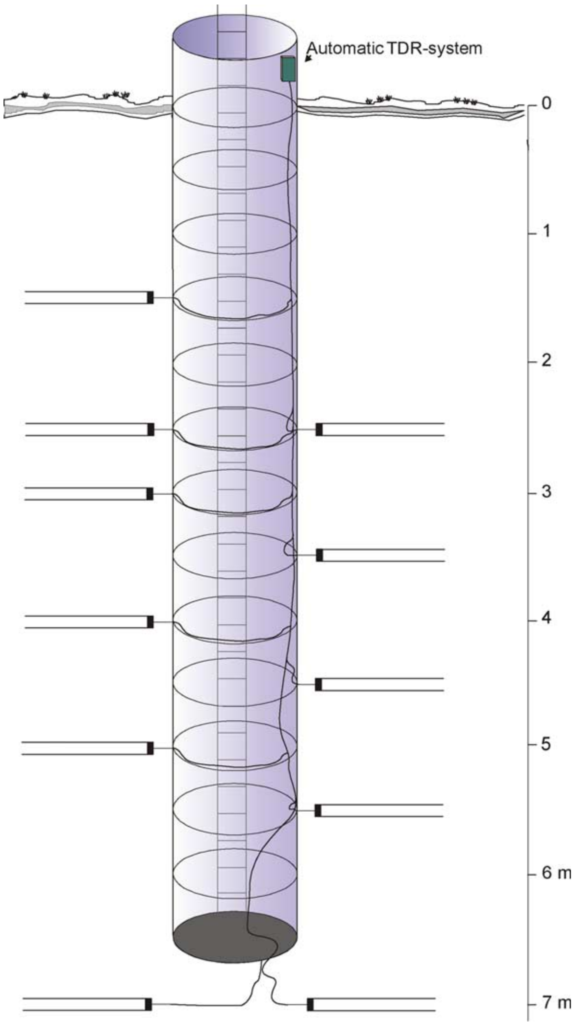

Fig. 4. The 7 m deep well in the oak stand equipped with TDR.

A general description of the automatic measurement system is given by Thomsen (1994).

3.4. Bromide tracer experiments

Bromide was chosen for the tracer experiments since it is close to being an ideal tracer in soil (Sposito, 1989; Flury and Papritz, 1993; Hosang, 1996). Additionally the natural bromide concentrations in soil and rain water are very low. The experiments were designed so that the Br-concentration was $\ll 1$ mg/l in the water reaching the saturated zone below the experimental areas. The general water quality criterion is 1 mg Br^-/l (Flury and Papritz, 1993).

On 27 September 1996 NaBr was applied uniformly over an area of 80 m^2 in the oak stand. In order not to affect the TDR measurements this was done about 30 m from both the well and the root zone study area. A total of 2.318 kg was dissolved in 40 l of water. This corresponds to an application of 22.5 g Br^-/m^2. The water added, 0.5 mm, was not regarded to be of any importance to the water balance. Both 1995 and 1996 were unusually dry and before the tracer application in 1996 the rainfall for that year was only 257 mm. On the day of application it started raining and 97 mm of rain fell during the next month so that the tracer leached under natural rainfall conditions.

At the heath area 35 g Br^-/m^2 was applied to an area of 40 m^2 on the 14th of October 1998, about 50 m from the well and the root zone study area. The year 1998 was unusually wet and, as for the oak stand, the tracer leached under natural rainfall conditions. The concentration of the tracer applied at the heath area was slightly higher than in the oak stand since it was expected that dilution would be more pronounced at the heath area due to lower evapotranspiration.

The temporal change in the vertical distribution of bromide was recorded by analysing water samples extracted from soil samples from boreholes made in the tracer experiment plot (Table 2). The cored upper samples were taken as 20 cm long cores (4.81 cm outer diameter) while a small drill rig with a 90 mm auger was used to take the deeper samples (Table 2). The outer few millimetres of the augered sediment samples were removed in order to avoid contamination. The auger was lowered half a metre or one metre at a time in the oak stand and one or two metres at a time at the heath site. Samples were taken from the lower half metre of the auger. On the first two occasions we did not find it necessary to take samples with the auger. Due to refinement of the coring technique from one occasion to the other it was possible to core ever deeper. On the first occasion the samples were taken at least 0.5 m from the edge of the applied area. Later samplings were taken closer to the centre. On all occasions at least three samplings were taken. All samples were well-sealed in plastic bags in the field and stored at 4 °C until Br^- was extracted.

Table 2
Sampling frequency, sample depth, and precipitation after bromide application

	Days after application	Maximum depth of soil coring (m)				Maximum depth of augering (m)			Precipitation after application (mm)
Oak stand									
Occasion 1	30	0.70	0.50	0.60					113
Occasion 2	32	0.58	0.85	0.70	0.95				121
Occasion 3	81	1.10	1.10	1.10		4.00	4.00	4.00	342
Occasion 4	545	4.00	4.00	4.00		12.00	12.00	12.00	1426
Heath area									
Occasion 1	26	4.00	4.00	4.00		14.00	14.00	12.00	216
Occasion 2	151	4.00	4.00	4.00		18.00	18.00	16.00	580

In the laboratory the samples were weighed and a high speed centrifuge (2000 rpm) was used to extract the soil water. The extracted water was 45 μm filtered and subsequently analysed for bromide using an ion sensitive electrode (Metrohm 6 Ωhm 0502·100). The detection limit was 0.8 mg Br^-/l. After centrifugation all samples were oven-dried at 40 °C for at least 48 h to determine their water contents. It was tested that no further water was extracted from the sandy soil at higher temperatures.

4. Methodologies

4.1. Numerical model

The COUP-model (former SOIL-model, Jansson, 1998) was used for estimation of the water balance components at both sites. The COUP-model is a standard numerical 1D soil water flow model based on Richards' equation for unsaturated flow. Details about the model can also be found on http://www.lwr.kth.se/english/OurSoftWare/Index.htm. The model divides evapotranspiration into transpiration and interception evaporation from plant canopy and soil evaporation beneath the plant canopy. Potential transpiration (Et,p) is defined as the canopy transpiration rate when not constrained by soil water deficits or low soil temperatures. Daily values are calculated from the Penman–Monteith equation (Monteith, 1965), allowing for specification of surface resistances estimated from leaf area index and stomatal conductance (gc) using the Lohammar equation (Lindroth, 1985). Reduction of potential to actual transpiration is performed separately for each depth where the normalised root density, $r(z)$ is above zero. The model allows the root system to reallocate root extraction from layers deficient in water to layers with an excess of water. Interception evaporation is also based on the Penman–Monteith equation using a low value for the surface resistance. The interception of water on the canopy is determined by a simple water balance of an interception storage of specified maximum capacity. Evaporation from soil is also estimated from the Penman–Monteith equation based on estimates of available radiation energy and aerodynamic and surface resistances applicable at the soil surface. More details on model setup focusing on evapotranspiration estimation is found in Jansson et al. (1999).

The model is driven by daily meteorological data for precipitation, air temperature, downwelling global solar radiation, relative humidity and wind speed. The plant properties to be specified are: development of vertical root distribution, surface resistance and seasonal variation in leaf area index. For each soil horizon considered in the model the water retention and unsaturated hydraulic conductivity functions need to be specified.

A variable numerical discretization of the flow domain was applied using 5 cm near the soil surface and then gradually increasing to 2 m towards the lower boundary. The upper boundary condition was a flux boundary in the form of net precipitation and the lower boundary was a zero pressure boundary at the water table. The model adopts a variable time step to minimise the water balance error.

4.2. Estimation of the mean pore water velocity and recharge by the bromide tracer experiment

The CXTFIT2-code (Toride et al., 1995) was used to estimate the mean pore water velocity (v_z) and the dispersion coefficient (D_c) by fitting to the bromide tracer data. For each day where samples were taken four sets of values for v_z and D_c were estimated: one set of values by fitting to the data of each of the three replicates, and one set by simultaneous fitting to the data of all replicates. The input of bromide was specified as a pulse injection and the analytical model was used in the flux concentration mode. Groundwater recharge, q, was estimated as the product of v_z and the mean water content, $\bar{\theta}$, of the soil samples to the depth of the bromide front.

5. Results and discussion

5.1. Soil water dynamics

5.1.1. In the root zone

In the root zones at both sites soil water has a cyclic variation where drying starts in March/April and wetting starts in August. In Fig. 5a and b the relative extractable water (REW) is shown for 0–200 cm (oak) and 0–100 cm (heath), respectively. The REW is defined as (Granier et al., 1999):

$$\mathrm{REW} = (\theta - \theta_m)/(\theta_f - \theta_m)$$

where θ_m is minimum soil water content (%), and θ_f is soil water content at field capacity (%). At both sites the θ_m is estimated at 2% from TDR-measurements and retention data. θ_f is estimated at 18% at each site from 0 to 200 cm (oak) and 0 to 100 cm (heath). In Fig. 5a each measured value is the average of eight replicate measurements and in Fig. 5b measurements are average values of four replicate measurements from 1993 to summer 1997 and eight replicate measurements from summer 1997 to 1999.

In relatively dry years such as 1993 the heath vegetation seems to be more water stressed than the oak since the REW at the heath falls significantly below 0.4 (Fig. 5b), a threshold below which transpiration is gradually reduced due to stomatal closure (Granier et al., 1999). Also, at the heath site the fluctuations in REW are more rapid than at the oak stand, which is typically a result of the thinner soil depth (Granier et al., 1999). Finally, compared to the oak stand an earlier autumn increase in REW is noticed at the heath from 1995 to 1997. Most likely this is caused by the heather beetle attack in 1994 that reduced the vegetation cover and thus its soil water uptake for the following 3 years. Further details on variations in soil water content in the oak stand and at the heath are found in Ladekarl (1998) and Ladekarl et al. (2001), respectively.

5.1.2. In the percolation zone

After re-wetting of the oak stand root zone in late autumn/early winter the wetting front can be followed to 7 m depth. However, the front velocity, which is generally sensitive to variations in the initial water content (Philip, 1957; Miller and Klute, 1967), varies from year to year (Fig. 6a). In late 1996 and early 1997, after two dry seasons, the wetting front reached 7 m after about 4 months whereas in 1998, when soil water content was relatively high, the same advance took only 2 months. Also in the dry year 1996, at 2.5 m the replicate with the higher initial water content showed a rise in water content slightly before the rise was seen in the other replicate with the lower water content. Thus front velocities in the range 6–12 cm/day were observed at this site.

The front advance is also slowed by alternating layers of fine and coarse materials (Miller and Klute (1967). For a fine layer overlying a coarse layer, for instance, the pressure head builds up in the fine layer until it is large enough for water to enter the large pores (Hillel, 1998). This phenomenon possibly occurred at 7 m depth (Fig. 6a) where a steep rise in water content was observed both in early 1997 and 1998 in one of the replicates whereas the other replicate hardly showed any change in water content. A soil sample taken during installation of the first replicate showed that it contained more fine material than the second replicate.

Preferential flow may also be observed when water enters a coarse sub-layer. In this case the wetting front pauses until the suction falls sufficiently to allow entry of water typically as finger flow (Hillel and Baker, 1988). Kung (1990) showed that in sloping layers water may be transported laterally on top of the coarse layers (capillary barrier effect). Preferential flow will be faster than the mean pore water travel velocity

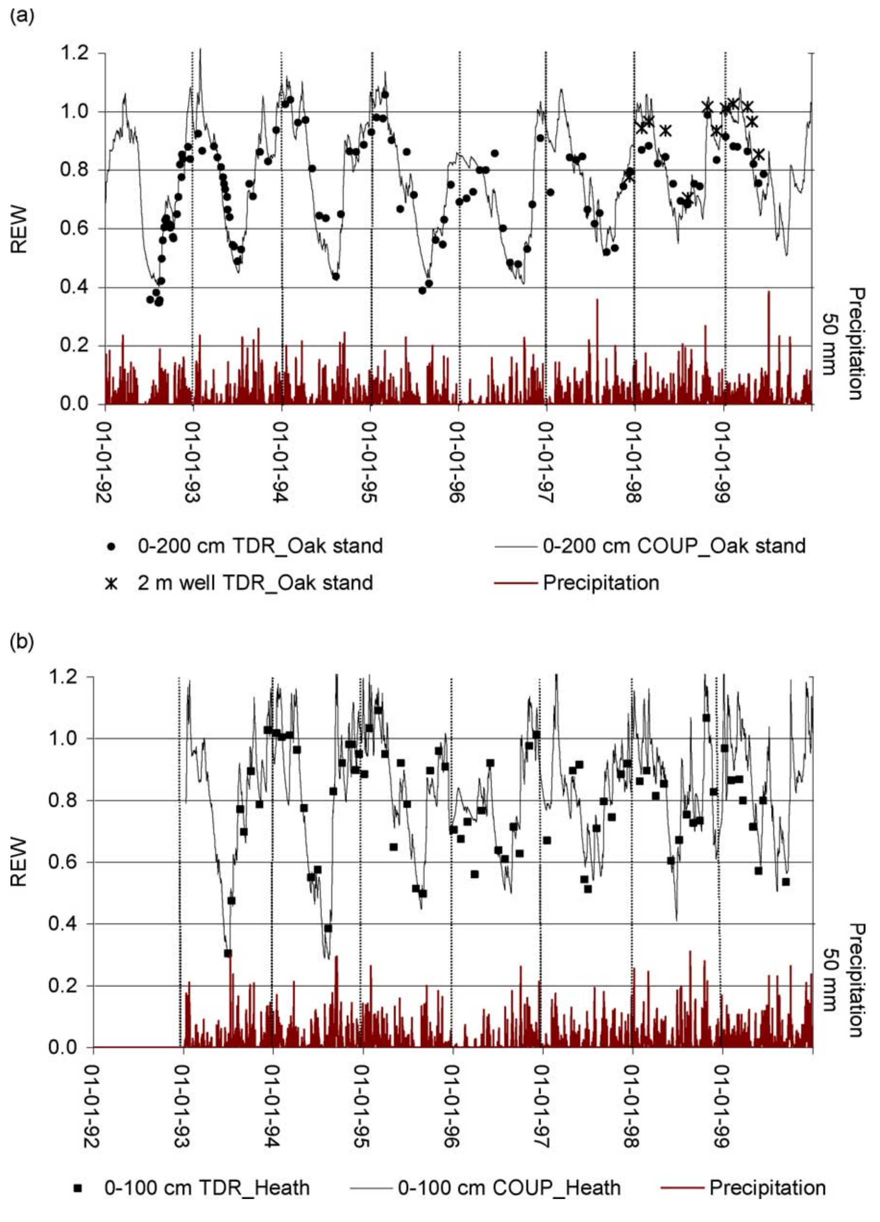

Fig. 5. Measured and COUP-model simulated Relative Extractable Water (a) 0–200 cm in the oak stand and (b) 0–100 cm at the heath site. The 2 m well symbols correspond to manual measurements made 5 m from the well.

and perhaps also faster than the front velocity. In the oak stand preferential flow was indirectly observed in coarse sub-layers at 3.5 and 5.0 m (Fig. 6a) which maintained a nearly constant, low water content during the monitoring period. The overlying horizons contained slightly finer material (Fig. 2) and the constant water content thus indicates that the water may have passed the coarse horizons in preferential flowpaths away from the probes. High relative variations in water content were also observed in the root zone, especially during wetting (Ladekarl, 1998), indicating that preferential flow was also present there. Likewise, indications of preferential flow were observed in the soil water chemistry in the oak stand

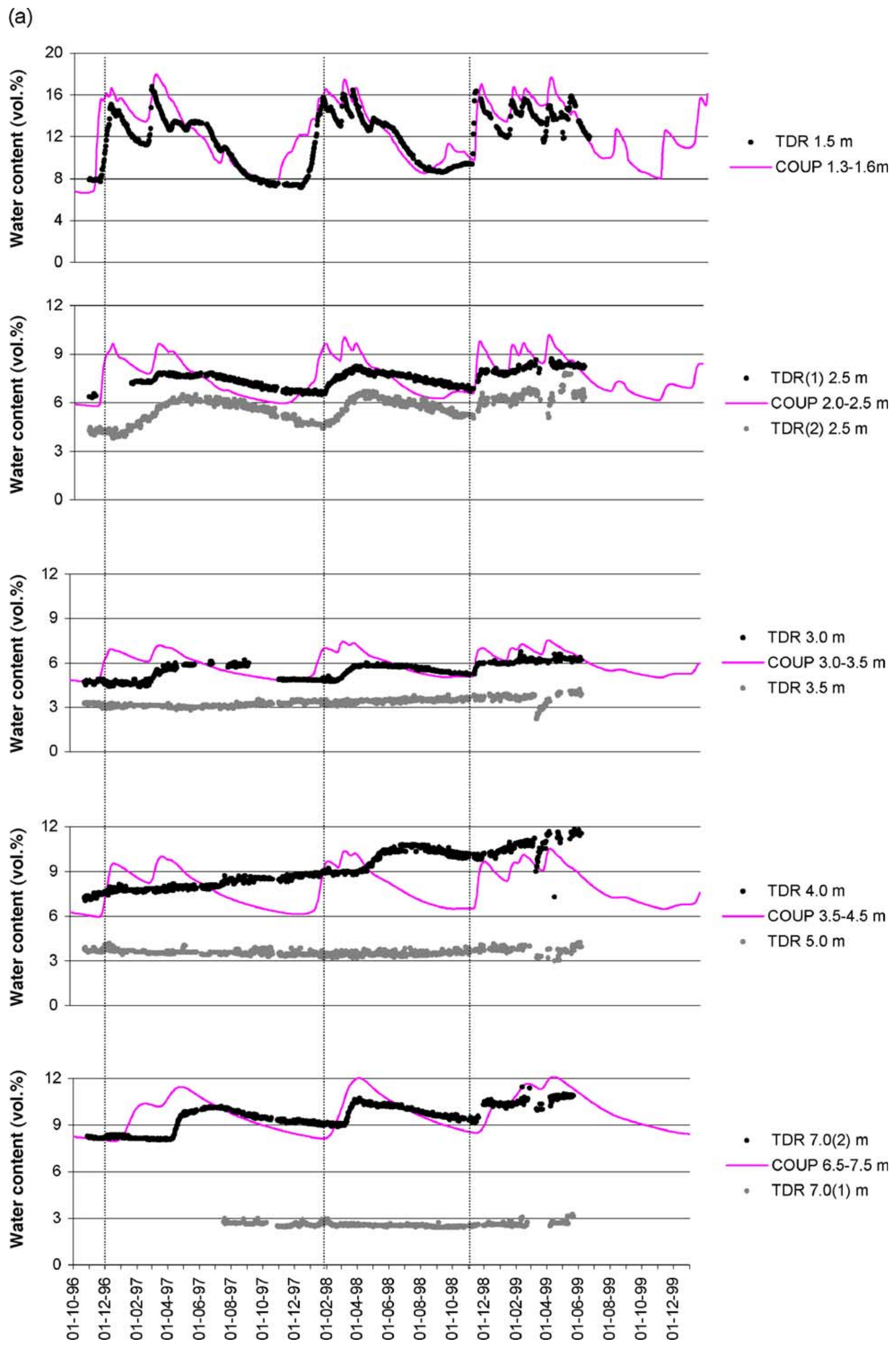

Fig. 6. Comparison of measured and COUP-model simulated water content in the well in the oak stand (a) and at the heath site (b). The vertical lines indicate the time at which the water front reaches the uppermost probe.

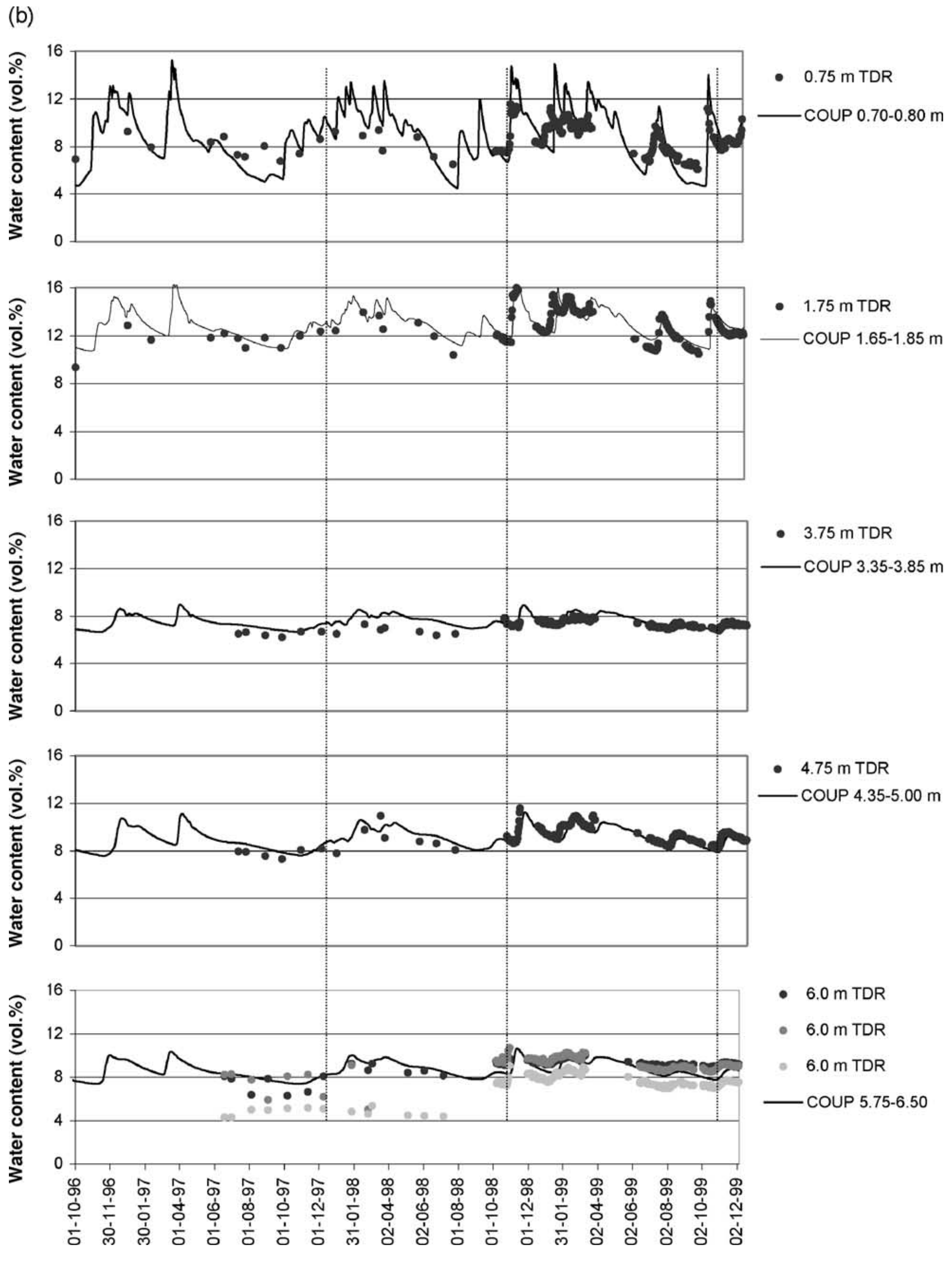

Fig. 6 (*continued*)

by Hansen et al. (1999) since the spatial variation in dissolved carbon content was substantial below the root zone.

At increasing initial water content, the differences in water content below and above the front diminish and preferential flow will be less pronounced (Sililo and Tellam, 2000). Also, since the hydraulic conductivity is high in wet soils, the conductivity of preferential flow channels is approached and differences between the two flow types diminish (van Genuchten and Sudicky, 1999). Below the oak stand at 4 m depth there was an overall increase in θ from about 7 to 12 vol % over the three year period. At the lower water content in 1996 and 1997 the water front was absent, but in 1998 when the water content had risen a water front was observed for the first time in that layer possibly because the water content had increased. Thus in 1997, the layer may have been bypassed in contrast to 1998 when the soil was wetted. Compared to the layer at 7 m depth the layer at 4 m was filled about a month later indicating that bypass flow may still have been effective in 1998 in the latter layer.

A study on the wetting front velocity by Young et al. (1999) showed that mean local front velocities varied significantly due to differences in soil texture and strong layering. However, with depth the general front velocity became more uniform. This is contrary to the oak stand at Hald Ege where it is not possible to detect a common front velocity based on the replicate measurements of water content either at 2.5 or 7 m. This may be due to a relatively shallow measuring depth.

In contrast to the oak stand the water fronts at the heath area moved very fast and were observed in all layers and replicate measurements of the water content at 6 m depth were fairly similar (Fig. 6b). This might indicate less heterogeneity in the percolation zone at this site. Both 1998 and 1999 were very wet and the soil moisture rapidly responded to precipitation events. In October 1998, for instance, rain was unusually heavy and the wetting front which was observed at 0.75 m in mid-October reached 2.25 m 3 days later while 6 m was reached after 11 days, i.e. a front velocity of 47 cm per day. Even during the summer of 1999 the soil wetted up after rain and water fronts travelled below the 6 m monitoring well within 2 months.

5.2. Calibration and validation of the COUP-models

At both field sites vertical TDR-measurements in the root zones and horizontal measurements in the percolation zone were used to calibrate the COUP-model. The bromide tracer data were used for validation of the model. Additionally, in the oak stand, the horizontal TDR-measurements in the root zone were used for validation of the model. Selected model parameters including initial and final calibrated values are shown in Table 1.

5.2.1. Vegetation properties

Net-radiation was not used as an input variable in the COUP-model since it varies greatly with vegetation cover and was not recorded above the forest until late 1998. However, a comparison of estimated and measured net-radiation from 1998 and 1999 showed that the net radiation was fairly well estimated (regression line $y = 1.18$, $r^2 = 0.90$) based on measured downwelling global solar radiation and an estimated albedo (between 16 and 19%, Raunier, 1976).

In the oak stand, simulated throughfall was slightly overpredicted and differed from measured values on individual sampling occasions (regression line $y = 1.14$, $R^2 = 0.35$; $p = 0.13$, students t-test). However, an attempt to increase interception loss resulted in occasionally very low water contents, and additionally, an interception constant of 0.6 as finally used is relatively high (Rasmussen and Rasmussen, 1984; Halldin et al., 1984/85). In Halldin et al. (1984/85) the summer interception capacity was 2.29 mm in a 120 year old oak stand with LAI of about four suggesting that I_c should not exceed the value of 0.6 used here (Table 1).

At the heath area, the throughfall samplers often suffered from overflow but in the relatively dry years of 1995 and 1996, when overflow was low, the throughfall predicted by the COUP-model compared well to measured values (regression line $y = 1.06$, $r^2 = 0.69$; $p = 0.25$, students t-test) indicating that the leaf area was reasonably estimated. The better correlation between measured and modelled throughfall at the heath site may be due to the variable LAI. In the oak stand, the same development in LAI is used for all years. At the heath site, the leaf area was not measured during and after the beetle attack in 1994, so estimated values (Ladekarl et al., 2001) have been used. It was found that during 1996, which was the year most strongly affected by the attack, leaf area was only about 10% of the normal leaf area.

In the oak stand preliminary values of seasonal surface resistances (Persson, 1997) were used while the final range of values are listed in Table 1. The variation in resistances were alike each year. In order to reduce root water uptake in spring, the resistance of

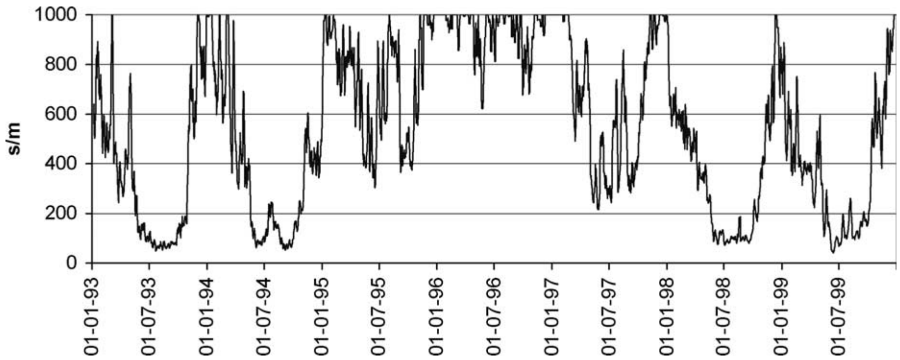

Fig. 7. Surface resistance of the vegetation at the heath site estimated by the Lohammar equation.

the trees had to decrease later than the peak in leaf area indicating that the old leaves were less prone to closure at low soil water content. A seasonal decrease in canopy resistance was also observed by Calder (1982) and Nizinski et al. (1989).

At the heath site the minimum surface resistance was predicted from the LAI using the Lohammar equation. Note that the low LAI during wintertime and in the period 1995–1997 gives rise to very high resistances, Fig. 7.

In order to simplify calibration of the model, root densities were assumed to decrease linearly with depth over the length of the root zone at both sites. Due to the flexible root water uptake of the permanent vegetation the error compared, for example, to an exponential decrease, is assumed to be small.

5.2.2. Soil properties

Soil water retention curves were initially estimated by least squares fitting of the van Genuchten (1980) model to experimental retention data from each layer. During the COUP model calibration slight adjustments were made to the residual water content, the saturated water content, and the α and n shape factors of the van Genuchten model. Final retention curves for selected measured horizons are shown in Fig. 3. Curves from neighbouring horizons were used for horizons without retention measurements. Also, the curve estimated from the retention data at the bottom of each well was assumed to represent the entire profile from the bottom of the well to the groundwater table.

The measured K_S values varied by up to three orders of magnitude between replicates (Table 1) and therefore arithmetic mean values were used initially. Unsaturated hydraulic conductivities were modelled by the Mualem-van Genuchten model (van Genuchten, 1980) using parametric values obtained by fitting the measured retention data. Calibrated saturated conductivities are shown in Table 1 and are compared with measured values. In the oak stand, the calibrated K_S-values in the root zone varied between 8.0×10^2 mm/day in the upper most horizon (not shown) and 3.3×10^4 mm/day at about 1 m depth. These are reasonable values for sandy soils (Jacobsen, 1989). The saturated hydraulic conductivity was used as a calibration parameter since the water content in layers below the root zone is very sensitive to this parameter. Between 3 and 7 m the final K_S values varied from 1.6×10^3 to 9×10^4 mm/day (not shown) with the higher values in relatively coarse layers. At the heath site the saturated hydraulic conductivities varied from 5×10^2 to 7×10^3 mm/day in the root zone and from 1×10^3 to 5×10^5 below the root zone. The discrepancies between measured and predicted K_S were probably due to spatial variation in soil texture and structure but also due to the relatively small sample size.

5.2.3. Soil moisture in the root zone

A comparison of COUP-modelled REW and the corresponding measurements made by vertical TDR probes from the surface to 200 cm depth (oak) and to 100 cm (heath) generally compare well both in dry and wet years (Fig. 5a and b). However, the simulations obtained for the oak stand are less accurate during spring when the simulated water content is too low, and during winters when it is too high. In spring, possible variations in LAI from year to year may lead to discrepancies between actual and simulated evapotranspiration since the same seasonal development in LAI is used in simulations for all years in the oak stand.

At the heath site, a slight underprediction of the water content is seen in 1996, and a slight over-prediction is seen in 1997. This probably leads to overprediction of the actual evapotranspiration in 1996 and the opposite in 1997.

In the oak stand, the soil moisture data from the horizontal TDR probes at 10, 20, 50 and 100 cm were used to validate the model, since these data were not used for calibration. The model fits measured values very well at both 10 and 20 cm depth (Fig. 8). At 50 and 100 cm the model respectively slightly under-predicts and overpredicts the water content. A comparison of the model predictions for the 0–2 m layer and the water content measured with the 2 m

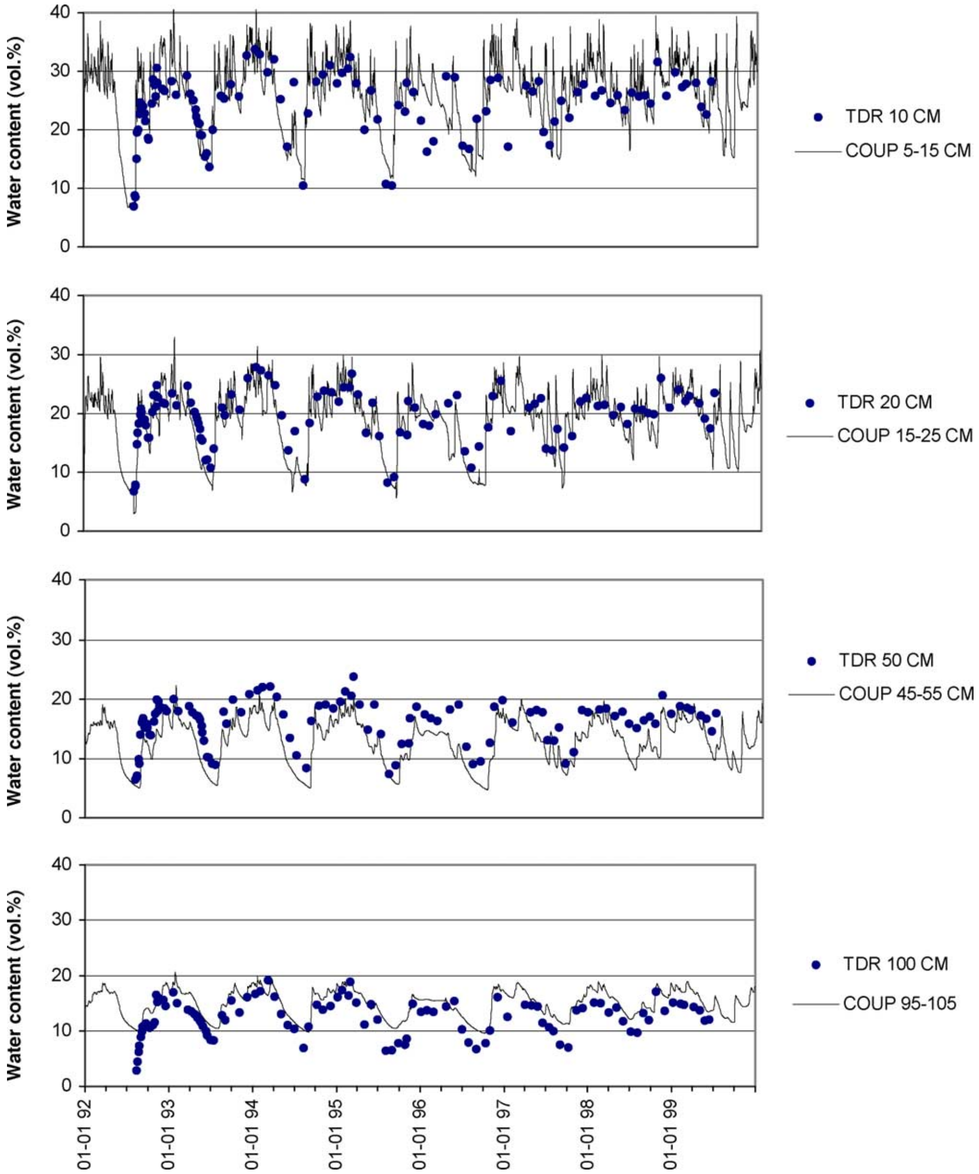

Fig. 8. Verification of the COUP-model with horizontal TDR-probe measurements ($n = 8$) from the oak stand.

vertical probe next to the well in the oak stand (Fig. 5a) shows that the model simulates the measurements very well. At times the model prediction fits the measurement near the well better than it fits the vertical measurements used for calibration. This confirms that the variation in water content in the root zone near the well is similar to the variation at the root zone study site (with the many TDR-probes) 30 m away.

5.2.4. Soil moisture in the percolation zone

The horizontal TDR measurements from the wells were used to calibrate the COUP-model below the root zone at both sites. The modelled water content in the oak stand at 1.5 m is reasonably similar to the horizontal measurements from the well (Fig. 6a), even though the upper 2 m of the model domain was calibrated to fit data from the root zone 30 m away from the well. However, the simulated water content at 2.5 and 3 m fluctuated more than the measurements with the infiltrating water predicted to reach the probe-levels earlier than was measured. At 7 m the modelled water content fits the measured water content of one of the replicates fairly well, but between 3 and 7 m the simulated water content differs significantly from the measured contents. The considerable differences in soil water content observed within short distances could probably only be simulated if the model allowed most of the water to bypass the dry layers. Water uptake from below 2.0 m is unlikely since the REW is greater than 0.4 in the upper 2 m, indicating that the amount of extractable water to this depth is sufficient for transpiration.

At the heath area, the modelled water content (Fig. 6b) fits the measurements fairly well at all depths. The peaks in measured water content during infiltration events are usually well reproduced by the model except at 0.75 m where the water content is slightly overpredicted during wetting.

5.2.5. Bromide tracer

The bromide tracer data were used to further validate the COUP-model at each site. Even though the model only takes advective transport into account, it reproduces the measured bromide concentrations reasonably well below the oak stand, at least for the first two sets of samples (Fig. 9a and b). For the third and fourth set of samples (Fig. 9c and d) the peaks of the model simulations are a little deeper than indicated by the measurements, showing that the specified hydraulic conductivity below the root zone may be too high. This is also indicated by Fig. 6a where the modelled water content rises earlier than the measurements at several depths in the well. However, the shape of the simulated concentration curve is fairly similar to the measured values.

At the heath site, the COUP-model reproduces the measured bromide concentrations reasonably well for the first sampling occasion, 26 days after application of the bromide (Fig. 10a). The variation in bromide concentration between replicates is relatively large but the COUP-model simulation falls within the measurements. On the second occasion (Fig. 10b), 151 days after application, the COUP-model predicts a faster bromide movement than indicated by the measurements. On both occasions some of the bromide had travelled considerably faster than the centre of mass which, in combination with the relatively high variation in bromide concentration, may indicate preferential flow.

The fair agreement between measured and simulated bromide concentrations at both sites strongly indicates that the contribution from dispersion is of little significance when seasonal variation of flow and spatial variation of soil properties are taken into account.

Generally, the good agreement between the model simulated water contents and those measured by both the horizontal and vertical TDR-probes in the root zone and in some cases also in the well, and the fair fit to the measured bromide concentrations shows that the water balance is fairly well simulated by the COUP-model.

5.3. The COUP model estimated water balances

The simulated water balance components are shown for the oak stand and the heath area in Tables 3a and b, respectively. The largest variations from year to year are seen for annual recharge. In the oak stand this varies from 197 mm in the dry year 1996 to 536 mm in 1993, and at the heath area from 428 mm in 1996 to 821 mm in 1994. The recharge was on average 390 mm/yr in the oak stand (about 45% of precipitation), and 635 mm/yr at the heath site (about 68% of precipitation).

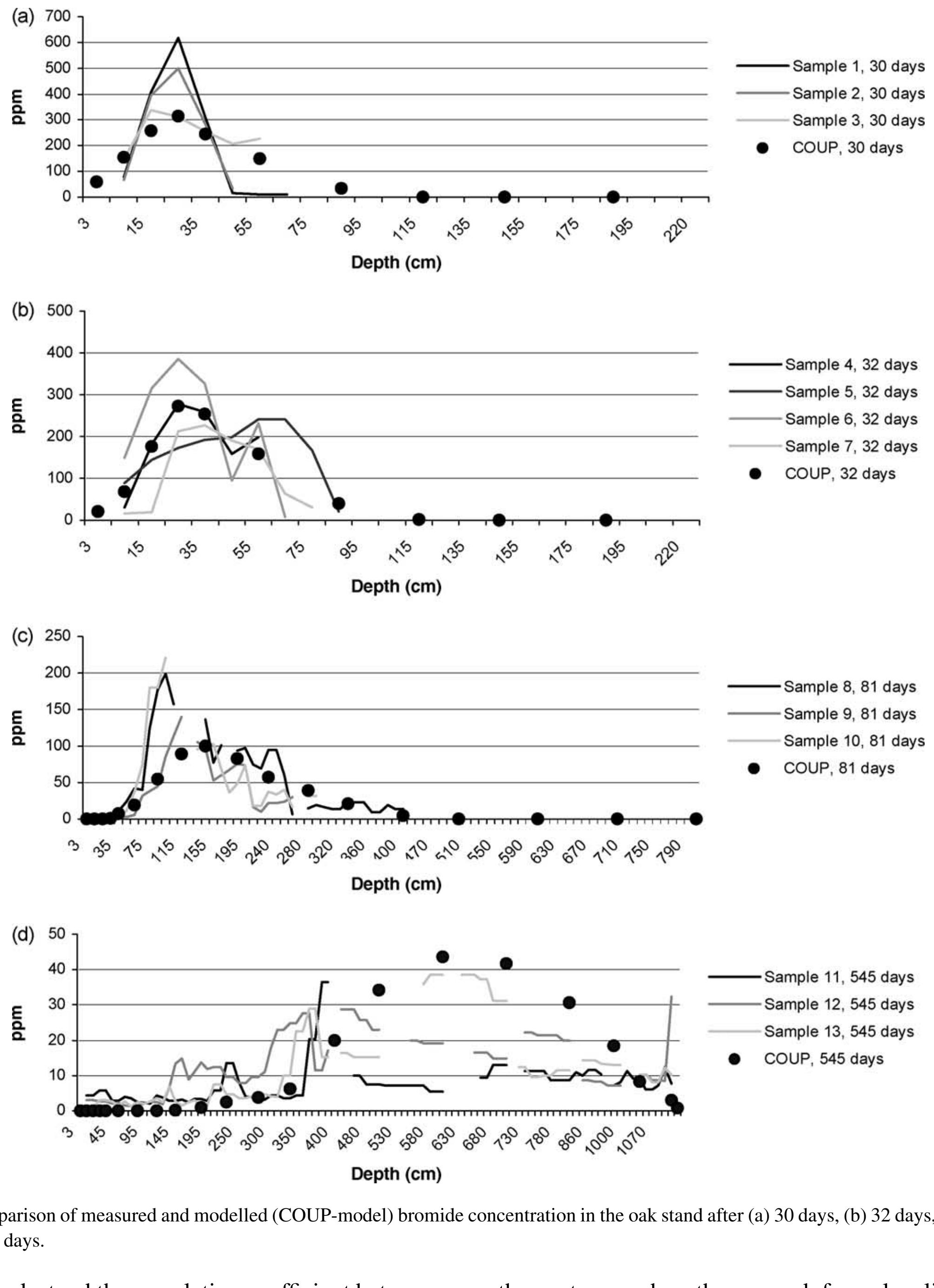

Fig. 9. Comparison of measured and modelled (COUP-model) bromide concentration in the oak stand after (a) 30 days, (b) 32 days, (c) 81 days, and (d) 545 days.

In the oak stand the correlation coefficient between measured and modelled throughfall was rather low. In most years only three collecting bottles were used in the forest which introduces considerable uncertainty in the measured throughfall because a large part of the water reaches the ground from localised drip-points (Durocher, 1990). However, studies with more collectors (unpublished results by Lea Taggaard, 1997) indicates that the model overpredicts the throughfall. More accurate prediction of interception

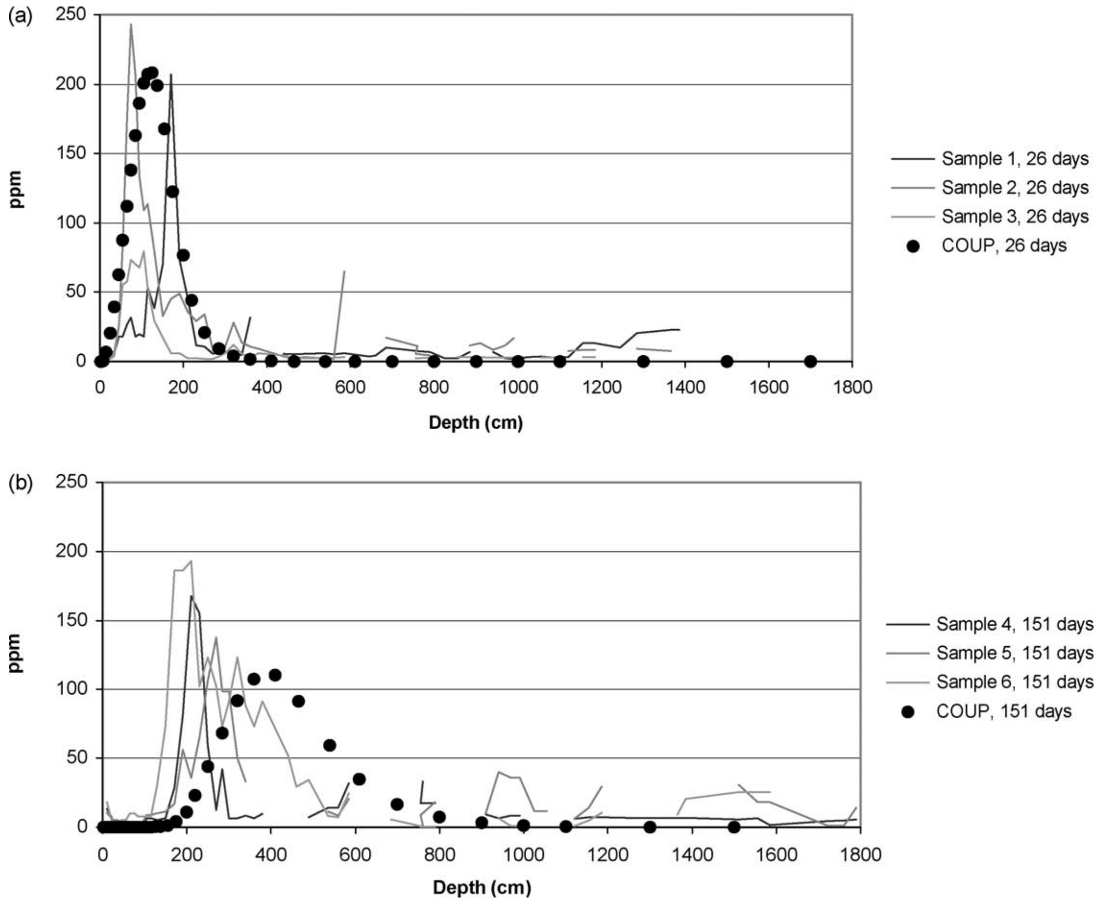

Fig. 10. Comparison of measured bromide concentration at the heath site and the COUP-model estimation after (a) 26 days and (b) 151 days.

Table 3a
Estimated yearly water balance components for the oak site using the COUP-model (mm). *P* is precipitation, $E(t,p)$ potential transpiration, Et transpiration, Es evaporation from soil, Ea actual evapotranspiration, *I* interception loss and *D* is recharge at 2 m depth. $D = P - \text{Ea}$, with $\text{EA} = I + \text{Es} + \text{Et}$

Year	*P*	$E(t,p)$	Ea	Et	Es	*I*	*D*
1992	888	382	440	261	71	108	448
1993	959	269	423	224	71	128	536
1994	1004	354	472	264	71	137	533
1995	770	335	456	262	75	119	314
1996	578	386	381	230	65	86	197
1997	835	398	585	365	90	130	251
1998	1029	345	569	322	85	162	460
1999	974	364	594	351	82	161	381
Sum	7037	2833	3919	2279	609	1030	3118
Avg	880	354	490	285	76	129	390
Average 1993–1994, 1998–1999	992	333	515	290	77	147	478

Table 3b
Estimated water balance components for the heath site with the COUP-model (mm). D is recharge at 1 m depth

Year	P	$E(t,p)$	Ea	Et	Es	I	D
1993	905	187	303	110	91	101	602
1994	1131	209	311	124	74	112	821
1995	814	23	214	15	150	48	600
1996	588	9	160	6	126	28	428
1997	797	73	310	52	179	79	487
1998	1136	196	383	132	107	144	753
1999	1134	208	378	144	109	125	756
Average 1993–1994, 1998–1999	1077	200	344	128	95	121	733
Average 1993–1999	930	129	294	83	119	91	635

loss and throughfall would probably require more specialised models as e.g. Gash et al. (1995).

At the heath site the simulated actual evapotranspiration (Table 3b) was unusually low in both 1995 and 1996, the two years most affected by the beetle attack. The beetle attack lead to low transpiration during the three years, 1995–1997, as also indicated by the high surface resistances seen in Fig. 7. In 1997, the third year after the beetle attack, the evaporation from soil was high and therefore the actual evapotranspiration was similar to that of the years not affected by the attack (1993, 1994, 1998, and 1999).

When the atmospheric evaporation potential is high the stomata of trees may close in order to minimise water uptake despite that soil water is available (Bréda et al., 1992; Granier and Bréda, 1996). Therefore in dry years, like 1996, the surface resistance used in the COUP-model is able to describe stomata closure and thereby reduce transpiration. In 1996 transpiration was only 60% of potential transpiration estimated from the Penman–Monteith equation (Table 3a) although the REW in the root zone was above the critical threshold of 0.4. Also, the oak trees in Hald Ege may have responded to water stress in the spring of 1996 by reducing the leaf area (Dickson and Tomlinson, 1996) even though sessile oak is known to be drought tolerant because of deep rooting, and to maintain efficient xylem sap transport and significant stomatal conductance during severe drought (Bréda et al., 1992). The soil water content was relatively low in the winter 1995 and spring 1996 (Fig. 5a) and the leaves of the oaks were visually smaller in 1996 than during the former years as a response to the dry winter and spring. Yet, observations during the following years gave no indication of permanent damage to the stand. In, e.g. 1997–1999 Et/Et,p was above 90%.

At the heath site Et/Et,p was between 59 and 71% in all years indicating that periodically, when REW was below 0.4 during 1993 and 1994, stomatal control was effective.

5.4. Groundwater recharge predicted from the bromide tracer experiment

As discussed previously, preferential flow (and maybe lateral flow) may occur in the fluvio-glacial deposits and therefore some tracer might have leached deeper than the augering depth so that the bromide recovery would be smaller than the amount actually applied at the sites.

In the oak stand the recovery of bromide from the samples taken after 1.5 years (three replicates) varies between 51 and 95% (Table 4a), which is satisfactory and at least as good as found in other investigations (e.g. Springer et al, 1996; Nachabe et al., 1999). However, for the earlier occasions recoveries of $>100\%$ were found. The discrepancy might be caused by the micro topography of the forest floor. Even though the tracer was applied evenly over the surface, the water may have collected in local low depressions of the forest floor giving rise to preferential flow. Additionally, old stubs, branches etc. hindered a totally random sampling of soil, and both the infiltration and sampling may unintentionally

Table 4a
Oak stand. Mass recovery of bromide (22.5 g/m^2 applied), mean pore-water velocity, and statistics

Sample	Days after application	Recovered (mg/cm^2)	%	Pore water velocity, Equi.CDE cm/day
1	30	2.87	128	0.86
2	30	2.65	118	0.83
3	30	2.71	120	0.83
1-3	30	2.74		0.83
4	32	2.2	98	1.00
5	32	2.97	132	1.26
6	32	2.8	124	0.79
7	32	2.3	102	1.36
4-7	32	2.57		1.06
8	81	4.26	189	1.52
9	81	1.69	75	1.61
10	81	2.47	110	1.28
8–10	81	2.81		1.45
11	545	1.14	51	1.11
12	545	2.14	95	0.95
13	545	1.90	84	1.03
11–13	545	1.73		1.02
Avg of 1–13		2.47	110	1.11

have been concentrated in flat or even low areas of the forest floor.

At the heath site the recovery of bromide tracer was on average 27% higher than the applied mass (Table 4b). For the individual replicate samples the discrepancy between recovered and applied mass varied from 65 to 218%. However, augered samples were only taken every metre or, for the last two bore-holes, every second metre (in the oak stand sampling was done every half metre or every metre). The fairly low resolution of the sampling increases the uncertainty of interpolation at this site.

Table 4b
Heath area. Mass recovery of bromide (35 g/m^2 applied), mean pore-water velocity, and statistics

Sample	Days after application	Recovered (mg/cm^2)	%	Pore water velocity, Equi.CDE cm/day
1	26	2.96	88	6.91
2	26	4.12	123	3.03
3	26	2.18	65	3.21
1–3	26	3.09		3.79
4	151	3.83	114	1.41
5	151	5.09	152	1.71
6	151	7.30	218	1.46
4–6		5.41		1.53
Avg of 1–6		4.25	127	

The CXTFIT2-model was used to estimate the average pore water velocity for each bromide sampling and the results are listed in Tables 4a and b. For each sampling occasion the groundwater recharge was estimated as the product of the average velocity and the corresponding average water content between the surface and the front of the bromide. Table 5 lists the recharge estimated from the bromide experiment together with the corresponding recharge simulated by the COUP-model (i.e. simulated recharge from the day of application to the day of sampling).

For the oak stand it is noticeable that the model-predicted recharge for the first and second periods only differ by 4 mm, whereas the corresponding recharge values estimated from the bromide experiment differ by 25 mm and are up to 100% larger than model-predicted recharge. The reason may be that the soil water content varies greatly in the root zone during wetting, so using an average water content for the entire profile may lead to an overestimation of recharge by the tracer test method. The same applies to the last occasion (sampling after 545 days) where the tracer test estimate of recharge is 70% larger than predicted by the COUP-model. At this time the bromide has reached a depth of about 5.5 m and at this

Table 5
Estimated groundwater recharge by the bromide tracer compared to recharge predicted by the COUP-model (mm). Days after injection in brackets

	Bromide	COUP
Hald Ege, oak stand		
960927-961029 (32)	51	42
960927-961031 (34)	76	38
960927-961218 (81)	163	166
960927-980325 (545)	793	465
Hjelm Hede, heath site		
981014-990324 (151)	411	448

depth the recharge predicted by the COUP-model is not influenced by recent rainfall infiltrating the root zone. In contrast the method used to estimate recharge from the bromide tracer test takes into account the high water content in the root zone and therefore overpredicts the recharge (Table 5). For the preceding period (bromide sampling after 81 days) the root zone was wetted to about field capacity with the result that the infiltration was approximately at steady state. In this case the recharge values obtained by the two methods are comparable.

At the heath site the average pore water velocity varied between 3 and 7 cm/d (more than 100%) when calculated from data sampled in each of the three boreholes 26 days after injection. The average value is 3.8 cm/d. The data obtained 151 days after injection gave an estimated average velocity of 1.53 cm/d and the variation between velocities calculated from data from individual bore-holes was fairly small (Table 4b). Only data from the last sampling occasion was used to estimate the groundwater recharge because of the large variation between replicate measurements on the first sampling occasion. The estimate of 411 mm obtained from the bromide concentration data compares well with the recharge predicted by the numerical model (448 mm), the difference being about 10% (Table 5).

At the heath site, some of the bromide travelled much faster than the centre of mass (Fig. 10). A small increase in the concentration was seen at 14 m after only 26 days, which corresponds to a velocity of 54 cm/day. Compared to the estimated water front velocity (47 cm/day) the tracer movement was apparently a little faster. This may be an indication of preferential flow.

Despite the possibility that a constant pore water velocity may not be reached and the year 1998 was rather wet, it should be noted that the ratio between the pore water velocities at the two sites (1.32) is almost the same as the ratio between the average recharge rates (1.38).

6. Conclusions

The recharge from an oak stand and a heath area was estimated for the periods 1992–1999 and 1993–1999, respectively. The periods include average, extremely dry, and wet years. The recharge was estimated by calibrating the COUP-model to fit both vertical TDR-measurements of water content in the root zone and horizontal TDR-measurements of water content below the root zone to a depth of 7 and 6 m. The COUP-model simulations were compared with horizontal TDR-measurements of water content in the root zone and recharge estimated from bromide tracer experiments; these data were not used in the model calibration. The comparison validates the results simulated by the COUP-model for both the oak stand and the heath area. For recharge estimation the thoroughly calibrated and validated water balance model produces more reliable results than the bromide tracer experiments.

The water balance of the heath area for 1995–1997 was significantly affected by a heather beetle attack that occurred in late 1994. Neglecting 1995, 1996 and 1997, the estimated average recharge from the heath area (733 mm/yr) was 255 mm larger than from the oak stand (478 mm/yr). The difference was partly due to the 83 mm/yr higher precipitation at the heath area and partly due to a lower transpiration and interception loss (188 mm/yr) from the heath. The estimated transpiration from the heath was 128 mm/yr as compared to 290 mm/yr from the oak stand, and the interception loss from the two sites was 121 and 147 mm/yr, respectively. The smaller transpiration from the heath resulted from the smaller leaf area of the heath vegetation (maximal 2.5 as compared to 4) and the thinner root zone (60 cm as compared to 200 cm). Soil evaporation was slightly lower in the oak stand than at the heath site, 77 and 95 mm/yr, respectively. The COUP-model simulations for the two sites confirm that both the interception loss and the transpiration from the oak forest exceed those of the low heath vegetation.

For both sites the recharge estimated from the bromide tracer test were comparable to the estimates obtained by the COUP-model as long as the solute centre of mass was within the root zone or when the infiltration was steady. However, at all times there was a significant variation in the bromide concentration between replicate samplings indicating that an accurate estimate of recharge may not be obtainable from only three replicate measurements, as was used in this study.

At the heath site the texture primarily was medium to coarse sand scarce in finer components and generally predicted soil moisture in the root- and percolation zones fit the observations well. This indicates that soil moisture is reliably observed with the methods used in the study. At the forest site the variation between predictions and observations is low in the root zone, but varies greatly in the percolation zone. The likely explanation is the presence of considerable heterogeneity in the percolation zone, rather than deficiencies in instruments or method. Alternating layers with fine and less fine texture observed during installation together with the observed differences in soil moisture between neighbouring probes support the hypothesis that, at this site, preferential flow is an important element in recharge through the percolation zone.

Average pore water velocities were estimated from the bromide experiments. The large precipitation surplus at the heath area lead to a relatively high mean pore-water velocity of 1.5 cm/day estimated after 5 months. In the oak stand the mean pore-water velocity was estimated at 1.11 cm/day. The velocity of the water front movement at the heath area was as high as 50 cm/day due to wet soils, whereas the velocity at the oak stand was only between 6 and 12 cm/day depending on the initial soil water content before front arrival. Both soil moisture measurements and tracer tests indicate preferential flow. For instance, at the heath area bromide was found at 14 metres as early as 26 days after application.

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