Eur J Forest Res (2004) 123: 93–104
DOI 10.1007/s10342-004-0033-7

ORIGINAL PAPER

G. Jost · H. Schume · H. Hager

Factors controlling soil water-recharge in a mixed European beech (*Fagus sylvatica* L.)–Norway spruce [*Picea abies* (L.) Karst.] stand

Received: 26 February 2004 / Accepted: 21 June 2004 / Published online: 31 July 2004

Abstract The spatial dynamics of soil water-recharge in a forest stand is the product of a number of interacting processes. This study focuses on the role of tree species and antecedent soil water content upon horizontal and vertical patterns of soil water recharge in heavy clay soils of a mixed European beech–Norway spruce stand and of a pure Norway spruce stand after rewetting periods with different rain quantities and intensities. Volumetric water content (VWC) was measured at 194 locations across 0.5-ha plots in each stand using time-domain reflectometry (TDR) with fixed 30- and 60-cm vertical waveguides. This was repeated 28 times (as close as possible) before and after rewetting periods during the vegetation seasons in 2000 and 2001. In addition, the locations of all trees within the plots were recorded. Geostatistics was used to describe the spatial correlation between VWC measurements and to interpolate soil water recharge in space. Spatial patterns of soil water recharge were then evaluated according to antecedent soil water-content and tree species distribution. Open-field precipitation of 30 mm (maximum intensity 10 mm h^{-1}) on extremely dry initial soil conditions resulted in higher subsoil (30–60 cm soil depth) recharge and erratic recharge patterns. This was presumably due to preferential flow in opening shrinkage cracks of the heavy clay soil. A comparable quantity and intensity of rainfall under moderately dry antecedent soil water conditions resulted in almost exclusively topsoil (0–30 cm soil depth) water recharge and patterns of recharge that were clearly related to tree species distribution. The higher recharge around beech trees can be attributed to the lower interception rates there. Spatial patterns of soil water recharge reflect patterns of antecedent soil water conditions.

G. Jost (✉) · H. Schume · H. Hager
Institute of Forest Ecology, BOKU—University of Natural Resources and Applied Life Sciences, Peter Jordan Straße 82, 1190 Vienna, Austria
E-mail: georg.jost@boku.ac.at
Tel.: +43-1-476544142
Fax: +43-1-4797896

Keywords Forest hydrology · Soil water-content · Geostatistics · Spatial variability · Variogram · Precipitation

Abbreviations VWC: Volumetric water-content · TDR: Time-domain reflectometry · SWS: Soil water storage · ET_{pot}: Potential evapotranspiration · OK: Ordinary kriging · $Intens_{max}$: Maximum rain intensity · P_0: Open-field precipitation · P_S: Stand precipitation · Int: Intercepted rain evaporation

Introduction

Precipitation in the form of rain and snow is the major input variable into the water balance of terrestrial forest ecosystems. The partitioning of precipitation into evapotranspiration, runoff and soil water recharge is closely related to vegetation cover. Compared with other terrestrial land use types, forests are characterized by higher rates of evapotranspiration and lower rates of runoff (e.g. Bosch and Hewlett 1982; Hornbeck et al. 1993; Stednick 1996). However, amounts and rates of evapotranspiration and runoff vary with the physiological characteristics of trees (e.g. leaf-area index, leaf colour, root system or stomata response to environmental stress) and thus vary in space and time with the species composition of a forest.

For example, Chang (2002) gives average daily transpiration rates for forest tree species in the USA ranging from 1.2–7.2 mm day^{-1}. In addition to different transpiration rates, rooting depth is a modifying factor with respect to water-extraction patterns in space and time. In their study of a drying period in a mixed European beech–Norway spruce stand, Schume et al. (2003) showed that species-dependent characteristics are the main source of temporal changes in the spatial patterns of soil water content during drying. They identified very dry soil conditions near the permanent wilting point as a lower boundary, down to which species alter the spatial patterns of soil water content via different transpiration and water-extraction behaviours.

An understanding of spatial and temporal variation of soil moisture is essential for studying other hydrological, biological or chemical soil processes, such as water movement, microbial activity and biogeochemical cycling (Bruckner et al. 1999; Ridolfi et al. 2003). Representing spatial variability in estimates of hydrological or ecological models (spatially distributed modeling) requires spatially distributed input variables (Grayson et al. 2002). Thus, for accurate measuring or modelling of spatial heterogeneity, the dominant controls on spatial patterns of hydrological variables need to be identified.

This paper focuses on the spatial variation of soil water-recharge at the scale of a forest stand. In this context, crown architecture and canopy interception, which vary largely between tree species (Peck and Mayer 1996; Huber and Iroumé 2001) are important factors that influence the spatial variation of soil water-recharge. Once precipitation has passed the canopy, antecedent soil moisture status directly affects the ability of the soil to store water and thus to buffer runoff (Ruprecht and Stoneman 1993; Nichols and Verry 2001). In addition to this quantitative effect, antecedent soil moisture may also influence the horizontal and vertical distribution of soil water-recharge and, consequently, the spatial distribution of soil moisture. For example, in dry clayey soils, shrinkage cracks open up and rapidly conduct a major proportion of the total water from precipitation into deeper soil regions, bypassing the soil matrix (Dekker and Ritsema 2000; Ritsema and Dekker 2000) and thereby reducing water availability in the rooting zone.

In order to study the soil rewetting patterns under different forest cover, spatially distributed TDR (time-domain reflectometry) measurements were carried out in a pure Norway spruce stand and in a mixed European beech–Norway spruce stand prior to and after rewetting periods during the growing seasons of 2000 and 2001. The measurements were taken in a grid layout and covered an area of approximately 5,000 m^2 per stand. Rewetting periods with different antecedent soil water content, but comparable total rain quantities and intensities were chosen to demonstrate the influence of species-specific interception and antecedent soil water content on spatial variation of soil water recharge.

Materials and methods

Site and stand description

The study site is located at an elevation of 480 m above mean sea level on an 18% inclined north-facing slope (mid-slope position) near Kreisbach, Lower Austria. The mean annual precipitation of 850 mm is usually sufficient for both spruce and beech, unless summer drought occurs, as in the year 2000. The mean annual air temperature is 8.4 °C. The natural plant association is an *Asperulo odoratae–Fagetum*. A stagnic Cambisol soil developed over flysch bedrock with a low permeability horizon beginning at about 50–60 cm soil depth. For comparability of the effect of tree species on soil water-storage (SWS), a study site with little variation in soil properties, such as thickness of mineral soil layers, texture class and soil structure, was selected. The bulk densities vary from 1.17 g cm^{-3} at 10 cm to 1.52 g cm^{-3} at 100 cm depth, with corresponding pore volumes ranging from 54% in the topsoil to 41% in the subsoil. The rock content increases over depth from about 4–15 vol%. The soil is heavily textured, with a clay content ranging from 36–70%.

The research plots were established in a spruce stand, and in a mixed transition zone from a pure beech stand to this spruce stand. All stands had reached a dominant height of 27 m within 60 years and consisted of only one tree layer. Canopy closures were around 90%. In the mixed plot, the mixing ratio of beech and spruce was roughly 4 to 1 on a stem-number basis; in terms of timber volume, this ratio decreases to 2 to 1. In the neighbouring beech and spruce stand, the respective dominating species reached a proportion of more than 80%, making them ‘pure’ by convention (Helms 1998).

Data sampling

The volumetric water-content of the soil (VWC) was measured manually at 194 locations across 0.5-ha plots in the spruce stand and in the mixed transition zone using a Trase1 TDR-system (Soilmoisture Equipment Corp., Goleta, CA, USA). Vertically oriented TDR wave guides were permanently installed over a soil depth of 0–30 and 0–60 cm. Metallic waveguides act as (parallel installed) transmission lines for the electro-magnetic pulse of energy generated by the TDR-system (for details, see Topp et al. 1980). In order to relate VWC to rainfall and interception, VWC (vol%) was converted to soil water storage [SWS (mm)]. The measurements were taken along a coarse 7×7 m approximate regular grid (100 points) and two 1.6×1.6 m grids (49 points each) nested within the coarse grid. The sample design is shown in Fig. 1. Waveguides installation had to be adapted to tree species locations so that the actual sample design slightly diverges from a square grid. Twenty-eight measuring cycles were performed during the growing seasons of 2000 and 2001 in roughly biweekly intervals. The sample strategy was to cover dry periods as well as possible, i.e. to measure at the beginning, during and near to the end of drying cycles and to capture rainfall by measuring before and after precipitation. Measurements were taken at least 2 days after the last rain, so that the rapid movement of water within the soil had ceased (Sumner 2000).

To test the influence of tree species, the locations and growth characteristics (height, diameter at breast height) of all trees within the plots were recorded

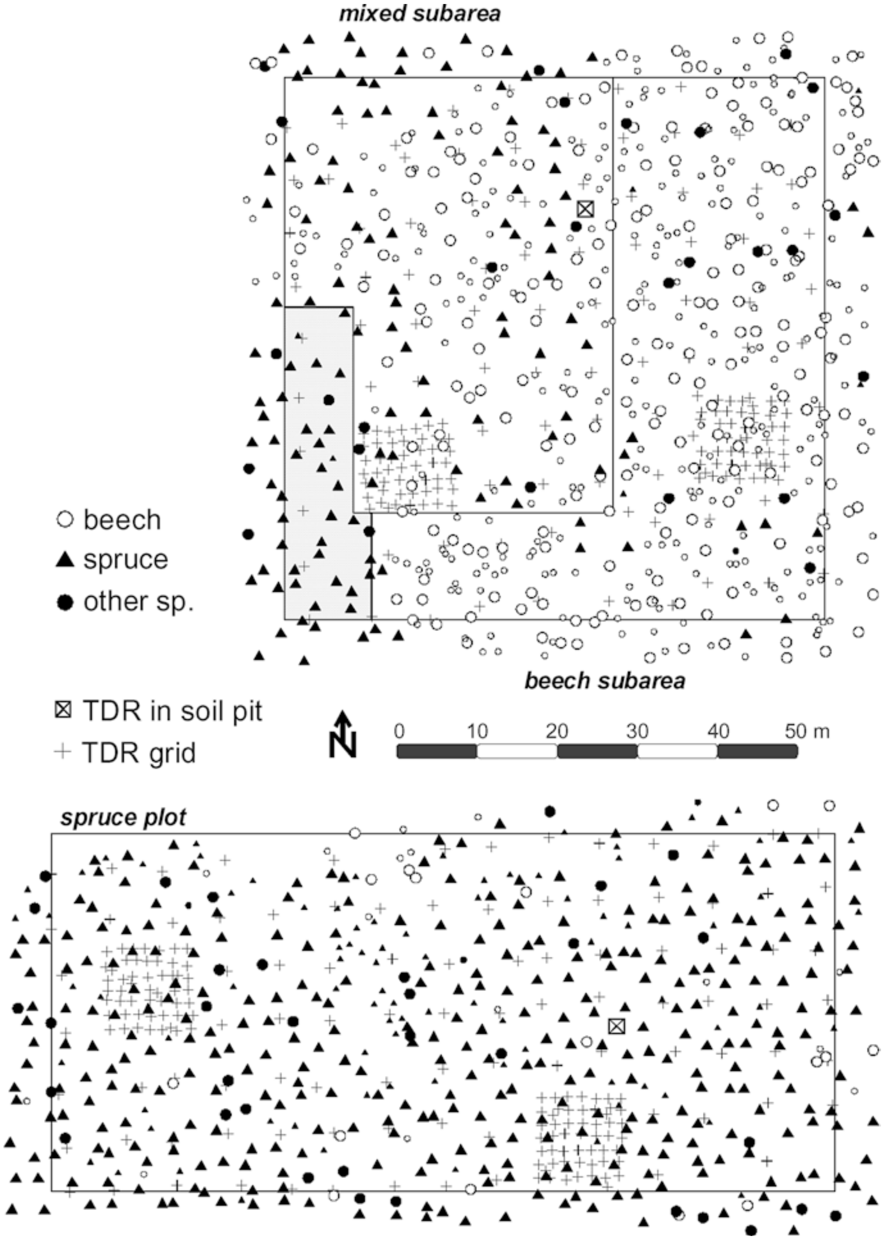


Fig. 1 Sampling locations and tree positions in the research plots. *Small symbols* refer to trees with DBH (diameter at breast height) less than 20 cm

(Fig. 1). Open-field precipitation (P_0) was measured on a meadow approximately 100 m outside the forest. Additionally, canopy throughfall measurements were carried out in both stands. Stem-flow along beech was recorded in the mixed stand. Global radiation, air temperature, wind speed and atmospheric humidity were continuously measured 5 m above canopy (15-min averages were recorded). Potential evapotranspiration (ET_{pot}) was calculated using a modified Penman approach (Smith 1988).

Data analysis

The traditional variogram (e.g. Goovaerts 1997) was used to analyse spatial correlation of SWS. Only very slight and temporal, unstable, anisotropy appeared from experimental semivariograms. Therefore, and for reasons of comparability, semivariograms were computed omnidirectionally. Nested models consisting of a nugget and an exponential function were fitted interactively in Surfer 7 software for contouring and 3D surface mapping (Golden Software, Inc., Golden, Colorado, USA). Global ordinary kriging (OK) was used to interpolate the SWS for the 30- and 60-cm measurements in space (Goovaerts 1997; Deutsch and Journel 1997). Interpolations of topsoil water-storage (SWS_{30}) were directly computed from the 30-cm measurements. Subsoil water storage ($SWS_{30–60}$) was computed from differences between 60- and 30-cm interpolations. Spatial variations in soil water-storage (ΔSW) in the topsoil and subsoil were derived by subtracting the SWS interpolations after rewetting from the SWS interpolations before rewetting. Descriptive statistics were computed from coarse grid

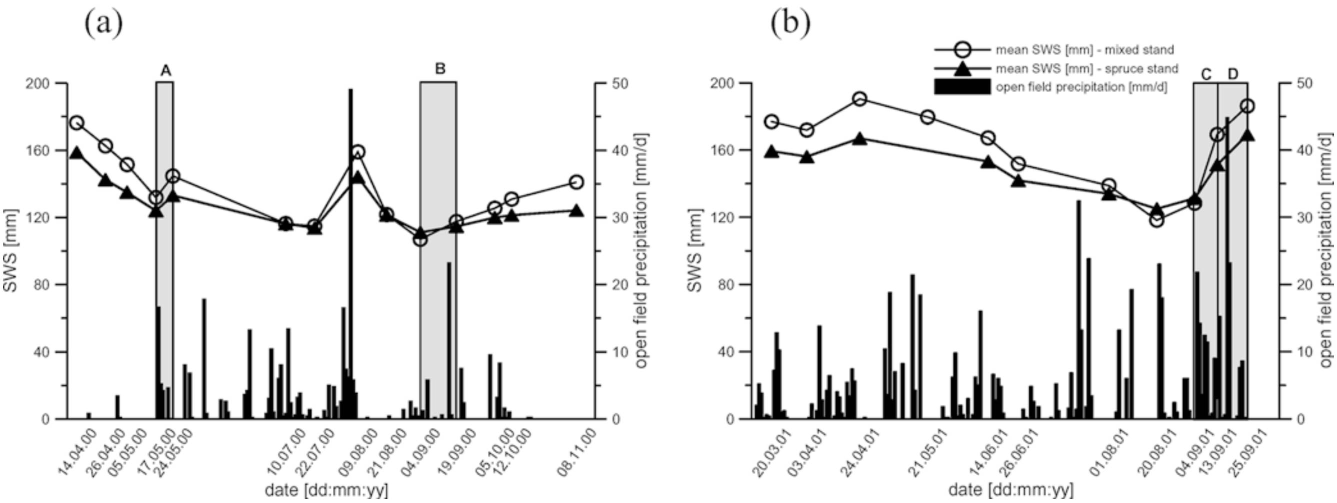


Fig. 2 Daily open-field precipitation and mean soil water storage (SWS) in the top 60 cm of the soil in the mixed and in the spruce stand during the growing seasons of 2000 (**a**) and 2001 (**b**). *Grey-shaded bars* indicate the considered rewetting periods *A*, *B*, *C* and *D*

measurements only, which turned out to be largely uncorrelated in space (see variograms in Fig. 3). To better illustrate the influence of the tree species upon soil water-recharge in top- and subsoil, we split the mixed plot into two subareas, resulting in 46 and 48 coarse grid points in an evenly mixed and a beech-dominated subarea, respectively (Fig. 1). The six measuring points under spruce in the south-west of the plot were omitted. Soil water recharge in both subareas was then compared with the soil water recharge in the pure spruce stand.

Results

Period characterization

Figure 2 gives an overview of the daily stand precipitation, together with the temporal progression of mean soil water storage in the top 60 cm (SWS_{60}), for the growing seasons of 2000 and 2001. Soil water storage in early spring was close to field capacity in both years, which is common after the dormant season (Schume et al. 2003).

With respect to precipitation, the two seasons were very different. Year 2000 was exceptionally dry (Fig. 2a). The only time when VWC was close to field capacity in this growing season was after a rainy week in early August ($P_0 = 91.3$ mm). Several moderate rewetting periods (around 30 mm P_0) occurred at various antecedent soil water-conditions, leading to differences in soil water recharge quantities as well as in spatial rewetting patterns. Two of these rewetting periods, one in May 2000 with initially moderately dry soil (period A), and the second one in September 2000 with very dry antecedent soil conditions (period B), will serve as examples to demonstrate the influence of antecedent soil water-content on spatial patterns of soil water recharge.

The growing season in 2001 was characterised by abundant precipitation, resulting in high SWS for most of the time, except for a drying period in August (Fig. 2b). After this drying period, 73.6 mm of open-field precipitation between 4 and 12 September significantly increased the SWS to almost field capacity (period C). Another high quantity of precipitation (100.8 mm) in the following 12 days caused a comparatively small increase of SWS (period D). Spatial patterns of soil water-recharge around field capacity in September 2001 will be analysed for these two subsequent rewetting periods.

Table 1 summarises potential evapotranspiration (ET_{pot}), maximum rain intensity ($Intens_{max}$), open-field (P_0) as well as stand precipitation (P_S) and intercepted rain evaporation (Int) in the four considered rewetting periods for both mixed and spruce stands. Interception losses were generally higher in the spruce stand, causing lower fluctuations of SWS under spruce (Schume et al. 2004).

Table 1 Potential evapotranspiration (ET_{pot}), maximum rain intensity ($Intens_{max}$), open-field (P_0) and stand precipitation (P_S) together with intercepted rain evaporation (Int) by stands for the four selected rewetting periods

							Mixed stand		Spruce stand	
Period	Start date	End date	Days	ET_{pot} (mm)	P_0 (mm)	$Intens_{max}$ (mm h^{-1})	P_S (mm)	Int (mm)	P_S (mm)	Int (mm)
A	17.05.00	23.05.00	7	21.2	30.6	14.2	24.1	6.5	17.7	12.9
B	04.09.00	18.09.00	15	33.7	31.8	10.6	26.3	5.5	22.9	8.9
C	04.09.01	12.09.01	9	9.8	73.6	5.4	61.8	11.8	47.2	26.4
D	13.09.01	24.09.01	12	15.1	100.8	6.4	92.0	8.8	73.8	27.0

Table 2 Antecedent top- and subsoil water-content (vol%) including standard deviation for rewetting periods A–D in the spruce stand and in the mixed and beech subareas of the mixed stand

Period	Start date	Spruce stand ($n=100$)		Mixed subarea ($n=46$)		Beech subarea ($n=48$)	
		Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
A	17.05.00	20.9 ± 3.0	23.0 ± 4.5	22.5 ± 2.6	24.0 ± 4.6	23.7 ± 2.4	24.4 ± 3.7
B	04.09.00	18.0 ± 2.9	23.0 ± 4.5	18.0 ± 2.5	20.9 ± 4.7	17.8 ± 2.6	20.1 ± 4.5
C	04.09.01	23.2 ± 4.6	24.8 ± 4.9	23.7 ± 2.2	22.1 ± 4.3	23.8 ± 2.8	21.6 ± 4.4
D	13.09.01	28.0 ± 5.2	27.4 ± 5.4	31.0 ± 3.8	28.8 ± 6.0	32.7 ± 3.7	28.9 ± 5,7

Periods A and B are comparable with respect to rain quantity and maximum intensity (Table 1). Soil water-depletion was negligible in both periods, although period B lasted almost twice as long as period A, because soil drought and progressing leaf senescence in September kept the actual evapotranspiration rates very low. The final measurement of both periods was taken a few days after the last rainfall (Fig. 4).

The two consecutive periods C and D are both characterised by very high precipitation rates and low evapotranspiration losses (Table 1).

Table 2 comprises the volumetric water-contents of top- and subsoil in the spruce plot as well as in the mixed and beech subarea of the mixed plot at the beginning of the discussed periods A–D. The higher standard deviation in the subsoil largely reflects the error resulting from the computation of differences between 30- and 60-cm waveguides. The topsoil water content at the beginning of period A ranged from 20.9% under spruce to 23.7% under beech. Subsoil VWC under spruce (23.0%) was only slightly lower compared with beech (24.4%). Most of the time, VWC was highest under beech and lowest under spruce, in both the topsoil and subsoil. On 4 September 2000, the start of period B, soil water content was at the lowest recorded value. The topsoil water status in the spruce stand and both subareas of the mixed stand was similar. In contrast with soil wate conditions in period A, subsoil water content was higher under spruce and lower under beech. Similar to period A, VWC prior to rewetting period C can be described as 'moderately dry', with marginal differences of topsoil VWC under beech, spruce and mixture. A total of 73.6 mm of open-field precipitation in rewetting period C resulted in a VWC close to field capacity under beech (initial values of rewetting period D, Table 2).

A compilation of soil water recharge by stands, soil horizons and periods is given in Table 3. The sometimes high standard deviation cannot solely be attributed to variation in space. A considerable amount of the standard deviation might result from taking the difference between SWS prior to and after the considered precipitation period (particularly in the subsoil, where differences from 30- and 60-cm measurements are computed earlier). This variation is part of the nugget in the variogram and is thus smoothed out in the kriging procedure. Significance tests were not performed, since the samples within our subplots cannot be treated as real replicates. Means and standard deviations of SWS and ΔSW were used only for explanation of the observed spatial variation. Apart from period D, soil water recharge was generally highest under beech and lowest under spruce. Independent of species composition, the moderate rainfall of period A (Table 1) at intermediate antecedent VWC led to only marginal subsoil water recharge. Almost the entire recharge took place in the topsoil. On the other hand, a similar amount of precipitation on very dry topsoil in September (period B) resulted in higher subsoil recharge and a minor increase in SWS in the topsoil. The low rewetting rates under spruce (0.4 mm topsoil and 2.8 mm subsoil) are particularly interesting. The total recharge in period B approached that of period A only under beech.

Starting out from a soil water content of roughly 23% in all stands, the increase in topsoil water-storage caused by the first heavy rewetting period (period C) was 92% higher under beech than under spruce. For the subsoil, the difference between the pure stands was almost a factor of 3 (180% higher under beech). At the end of period C, topsoil VWC under beech was close to field capacity allowing only 4.4 mm of topsoil water recharge in period D, although the total amount of precipitation in period D was higher than in period C. Owing to the lower antecedent soil water content, the topsoil under spruce and the beech–spruce mixture could still absorb more water during this period. Total recharge was highest under spruce and lowest under beech at this time.

Overall, the topsoil in the mixed subarea responded to precipitation like an intermediate between the pure stands, while subsoil recharge was very similar to that of the beech stand.

Table 3 Topsoil and subsoil water-recharge (in mm) including standard deviation and total water-recharge by stands and periods

Period	Spruce stand ($n=100$)			Mixed subarea ($n=46$)			Beech subarea ($n=48$)		
	Topsoil	Subsoil	Total	Topsoil	Subsoil	Total	Topsoil	Subsoil	Total
A	7.8 ± 4.2	1.2 ± 4.4	9.0	11.9 ± 4.4	0.9 ± 5.8	12.7	13.6 ± 4.7	1.0 ± 6.1	14.6
B	0.4 ± 4.5	2.8 ± 6.0	3.2	2.2 ± 3.8	7.0 ± 7.9	9.2	5.4 ± 4.8	6.9 ± 9.5	12.3
C	13.3 ± 5.8	7.1 ± 8.5	20.4	20.9 ± 7.1	18.4 ± 13.4	39.3	25.5 ± 7.7	19.9 ± 15.3	45.4
D	8.7 ± 6.6	7.8 ± 10.2	16.5	6.4 ± 6.6	10.0 ± 10.5	16.4	4.4 ± 7.5	9.9 ± 11.5	14.3

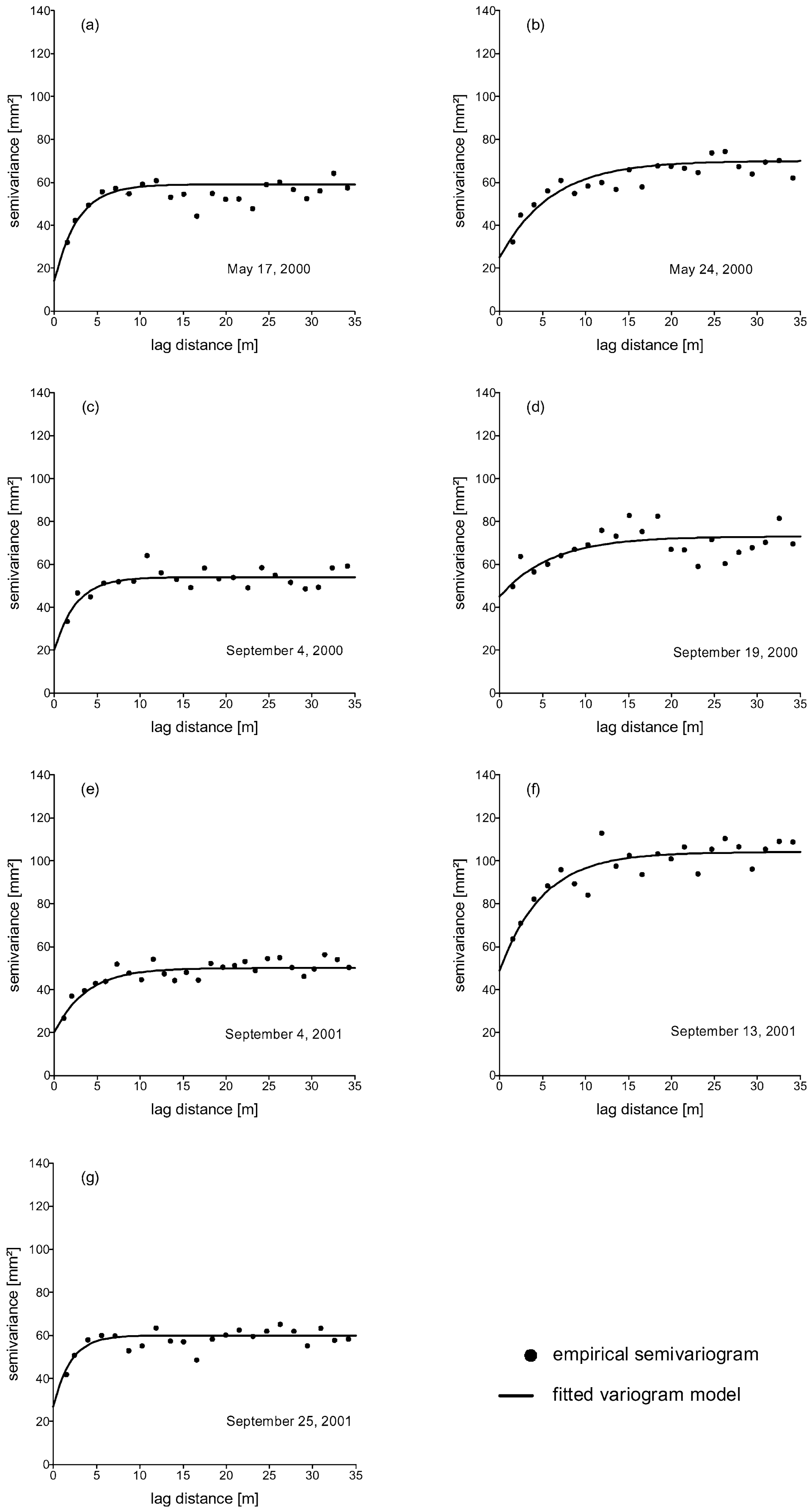


Fig. 3 Empirical semivariograms and fitted exponential variogram models characterizing the spatial variation of topsoil SWS at the beginning and at the end of period A (**a**, **b**), period B (**c**, **d**) and at the three consecutive dates (**e**–**g**) delineating periods C and D

Spatial patterns of soil water-recharge

The entire mixed plot was chosen to illustrate the effect of antecedent soil water content, rain quantity and tree species on the spatial variability of soil water-recharge. Kriging interpolation plots of soil water-recharge serve to compare rewetting patterns to tree species distribution. We computed semivariograms at the beginning and the end of the selected periods to analyse the temporal change of spatial variation of SWS. Nested semivariogram models consisting of an exponential structure and a nugget variance turned out to describe sufficiently the empirical semivariograms (Fig. 3). The nugget variance (e.g. the'nugget') is representative of 'unsampled variability' and random measurement error, i.e. small-scale variability. Global ordinary kriging was used to interpolate SWS and ΔSW in space.

During rewetting period A, the range of spatial autocorrelation increased from 8 to 18 m, and the sill from around 60 to 70 mm^2. Little change can be seen in the nugget (initially and at the end of period A around 20 mm^2). Persistent drought during August 2000 decreased the range and the sill of the variogram on 4 September 2000. The nugget was the same at 20 mm^2. This nugget increased significantly to 43 mm^2, until the end of period B, which brought 31.8 mm of precipitation. After rainfall, the semivariogram range and sill increased, similarly to period A.

Rewetting period C started with a comparable spatial structure to the former two periods. The high amount of precipitation in period C increased the sill to the highest observed value of 100 mm^2 and doubled the nugget variation. Subsequent precipitation resulted in a decrease of sill, range and nugget variation in the semivariogram. The spatial autocorrelation on 25 September 2001, the wettest measuring date, was very similar to the spatial autocorrelation on 4 September 2000, which was the driest measuring date.

Figure 4 compares spatial patterns of topsoil and subsoil water recharge starting out from moderately dry (period A) and very dry (period B) topsoil conditions. As mentioned earlier, the 30.6 mm of open-field precipitation in period A mainly led to water recharge in the topsoil and only marginal recharge in the subsoil. A tendency towards water-redistribution into the subsoil can be observed at initially drier patches in the topsoil, which seem to be associated with the occurrence of spruce. The decrease in SWS in the subsoil (chequered signature in the plot of period A, Fig. 4, lower left) most likely reflects the measurement and the interpolation error associated with computing differences between the two measuring depths (0–30 and 0–60 cm) and/or root water uptake by deeper rooting beech. Spatial rewetting patterns in the topsoil can be clearly related to tree species distribution: the increase in SWS under beech was significantly higher than under spruce.

An inverse recharge behaviour of the soil emerged when antecedent topsoil conditions were very dry. In period B, 31.8 mm of P_0 caused higher subsoil than topsoil water recharge. The evaporative demand between 4 and 16 September, the day when the major part of precipitation fell, was low (Fig. 4, above), so that the soil water distribution pattern right before precipitation should not have been too different from the presented pattern of 4 September 2000 (Fig. 4c). The spatial recharge patterns in top- as well as in subsoil appear to be largely random in period B referenced by a small range and a high nugget-to-sill ratio (Fig. 3c).

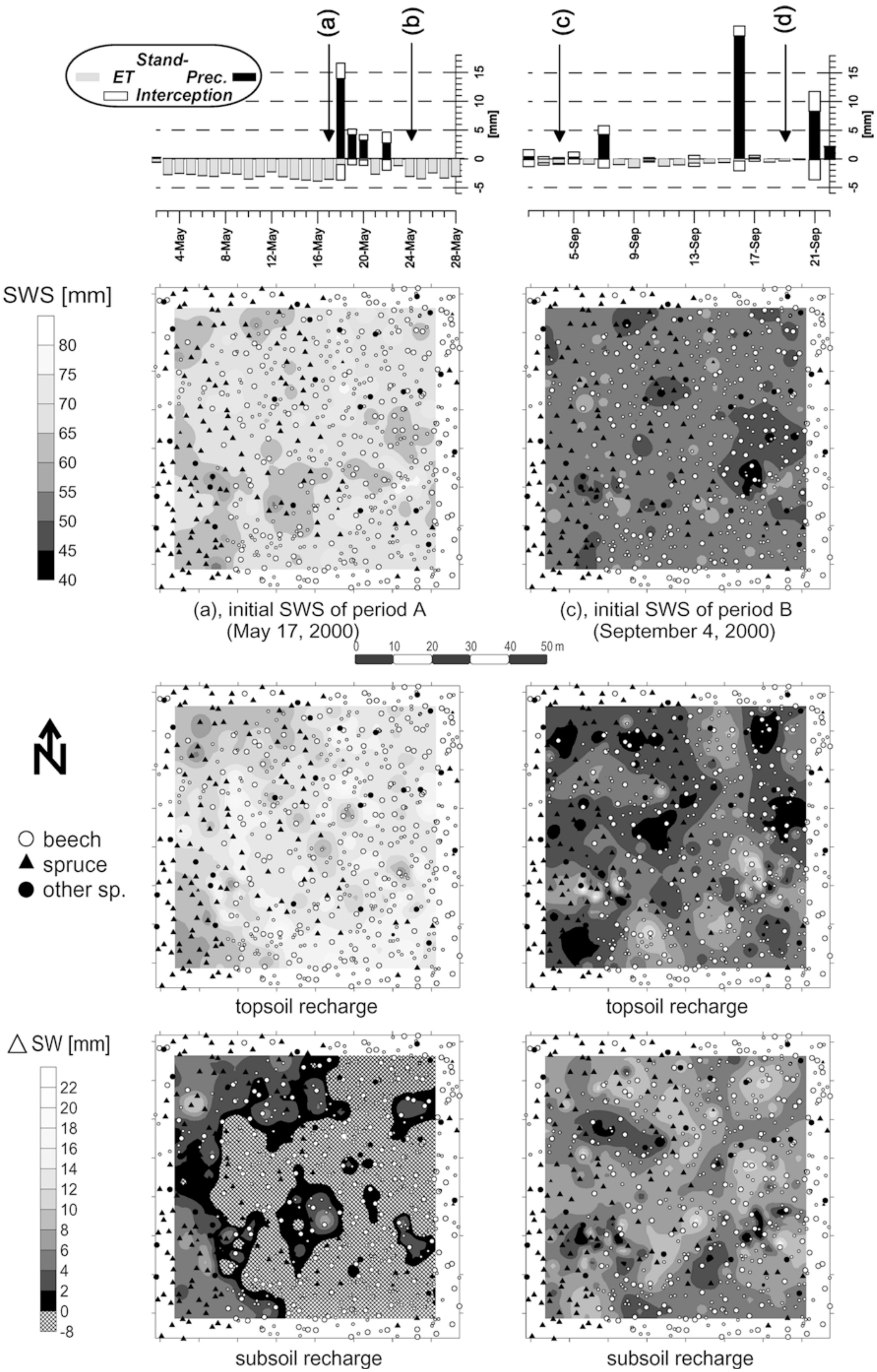
Spatial patterns of topsoil water recharge after the heavy rain period C (Fig. 5) exhibit the same species dependency already described for a lower rain quantity on similarly depleted soil (period A). More pronounced topsoil recharge under beech and lower recharge under spruce were observed, while the interpolation plot of period D appears just the inverse of that of period C. However, the recharge patterns of both plots reflect the initial soil water distribution: patches with a higher soil water recharge in the topsoil correspond to patches with a lower SWS prior to precipitation and vice versa. Eventually, on 25 September 2001, SWS was uniformly high throughout the whole plot (Fig. 5, date g).

Subsoil recharge, on the other hand, seems to be controlled less by initial soil moisture status but more by topsoil recharge patterns (Figs. 5, 6): zones with higher recharge in the topsoil match zones with lower recharge in the subsoil and vice versa. In contrast to period A, which was comparable in terms of antecedent soil water content and topsoil recharge patterns, the high amount of rain in period C caused considerable subsoil recharge, although the distribution was erratic.

Discussion

In comparison to the mixed stand, the fluctuations of SWS in the top 60 cm of the soil were less pronounced under spruce. Except for very dry situations, SWS_{60} in the mixed stand was higher during both the dry growing season 2000 and the wet season 2001. These relations reflect architectural, as well as physiological, properties of the contrasting species. On the one hand, spruce is more economical in its consumptive water use (Hietz et al. 2000) and, on the other hand, the spruce canopy allows substantially less stand precipitation, as is known from the literature (e.g. Benecke 1984; Augusto et al. 2002).

Besides above-ground architecture, which significantly influences the amount of precipitation actually reaching the forest soil, below-ground architecture is a decisive factor regarding water-extraction patterns. In the mixed stand at Kreisbach, Schmid (2002) found 80% of beech fine roots between 20 and 60 cm soil depth, while rooting of spruce was restricted to the uppermost 30 cm. In the spruce stand, 35% of the fine root mass was located between 30 and 60 cm depth. No fine roots of spruce occurred below 60 cm. Having access to a larger available soil volume, beech was able to maintain higher transpiration rates, even under high evaporative demand and/or persisting drought (Hietz et al. 2000). As


(a)
(b)
(c)
(d)
Stand-
ET
Prec.
Interception
[mm]
4-May
8-May
12-May
16-May
20-May
24-May
28-May
5-Sep
9-Sep
13-Sep
17-Sep
21-Sep
SWS [mm]
(a), initial SWS of period A
(May 17, 2000)
(c), initial SWS of period B
(September 4, 2000)
0 10 20 30 40 50 m
N
beech
spruce
other sp.
topsoil recharge
topsoil recharge
△SW [mm]
subsoil recharge
subsoil recharge

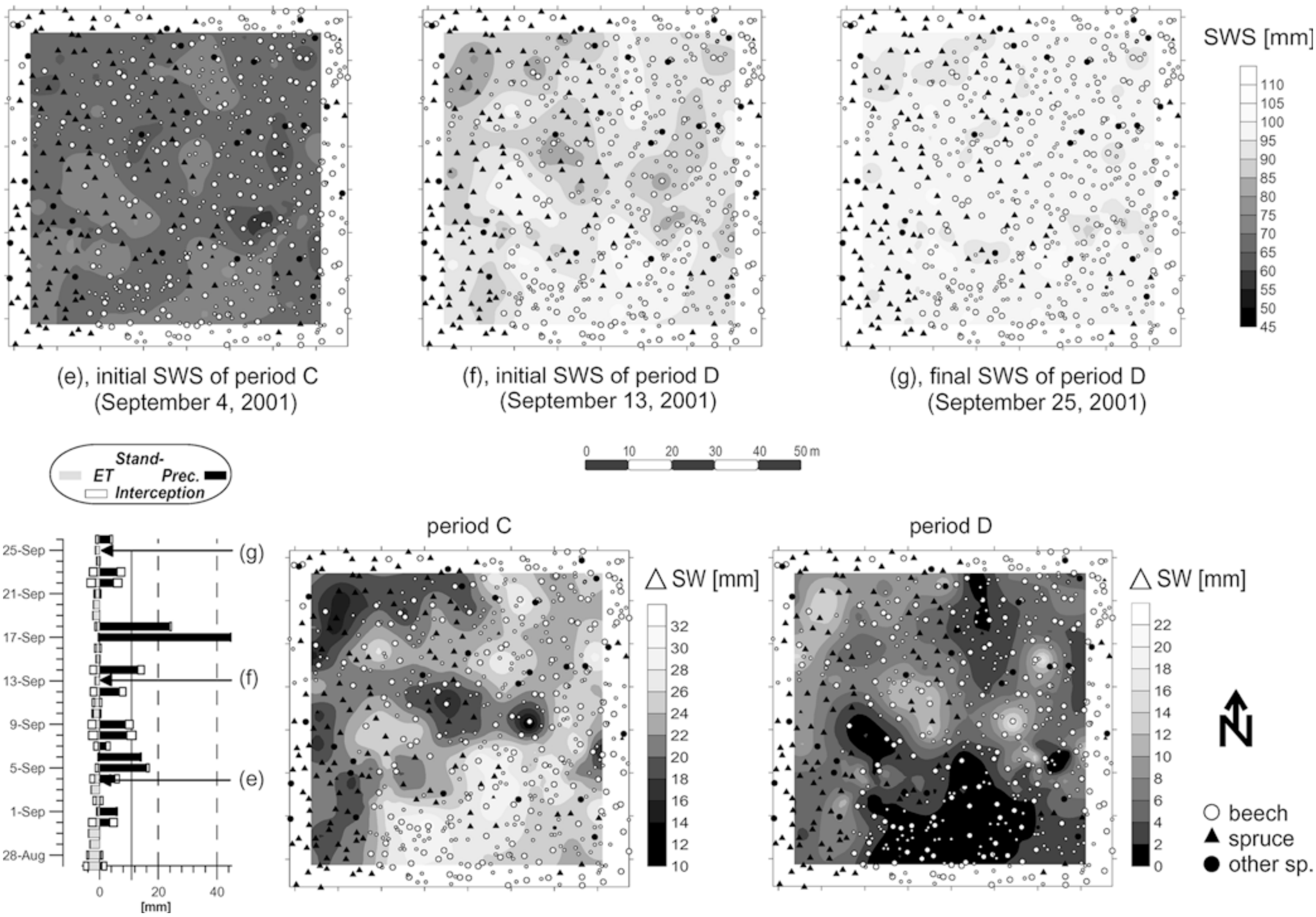


Fig. 5 Interpolations of topsoil SWS at three consecutive dates during a rainy period in autumn 2001 (**e–g**). *Below* Interpolation plots show the changes of topsoil water-storage (ΔSW) between the measuring dates *e*, *f* and *f*, *g*, respectively. *Left* Precipitation, interception and evapotranspiration in the considered period

a consequence, water depletion of soil layers below 30 cm depth was more intense in stands containing beech (Schume et al. 2004).

Our results suggest that soil water-recharge is, to a large extent, dependent on soil water content prior to precipitation, apart from precipitation characteristics. Low (not shown here) to medium rain quantities on moderately dry soil resulted in topsoil recharge only (period A). Under these circumstances, magnitude and spatial patterns of soil water recharge in the mixed stand directly reflect differences in canopy interception. The dryer the soil, the more recharge seems to occur in the subsoil (period B). At the same time, spatial recharge patterns become more erratic and the small-scale variation, reflected by the nugget in the semivariogram, increases.

◄

Fig. 4 Changes of soil water storage (ΔSW) in the top- and in the subsoil caused by precipitation on moderately dry (17 May 2000) and very dry (4 September 2000) soil. *Above* Precipitation, interception and potential evapotranspiration in the considered periods

One reason for this spotty pattern can be found in preferential flow. The occurrence of preferential flow is usually favoured by high initial soil water content (Germann 1986; Zehe and Flühler 2001). In the heavy clay soils at Kreisbach, a variable macropore system develops when the soil starts to shrink under dry conditions. This additional and very effective macorpore system conducts precipitation water quickly into deeper soil regions (Dekker and Ritsema 2000). In their study of vertical recharge patterns, Dekker and Ritsema (2000) found a considerable variation of soil moisture and irregular wetting patterns associated with precipitation on initially dry soil. Similar patterns were found by Villholth et al. (1998) in fine textured soils in Denmark. Hence, under very dry soil conditions, such as in period B, the preferential flow proportion of the total flow rate is possibly higher than under moderately dry soil conditions (period A), with closed shrinkage cracks, and thus leads to domination of matrix flow. Since preferential flow responds faster and over much larger vertical as well as horizontal distances than matrix flow, shrinkage cracks also offer an explanation for the weaker dependency of soil water-recharge patterns on tree species distribution.

Nevertheless, the three forest types differed in recharge quantities. Total recharge under beech exceeded that under spruce by 60–280% (Table 3), which cannot be explained solely by higher stand precipita-

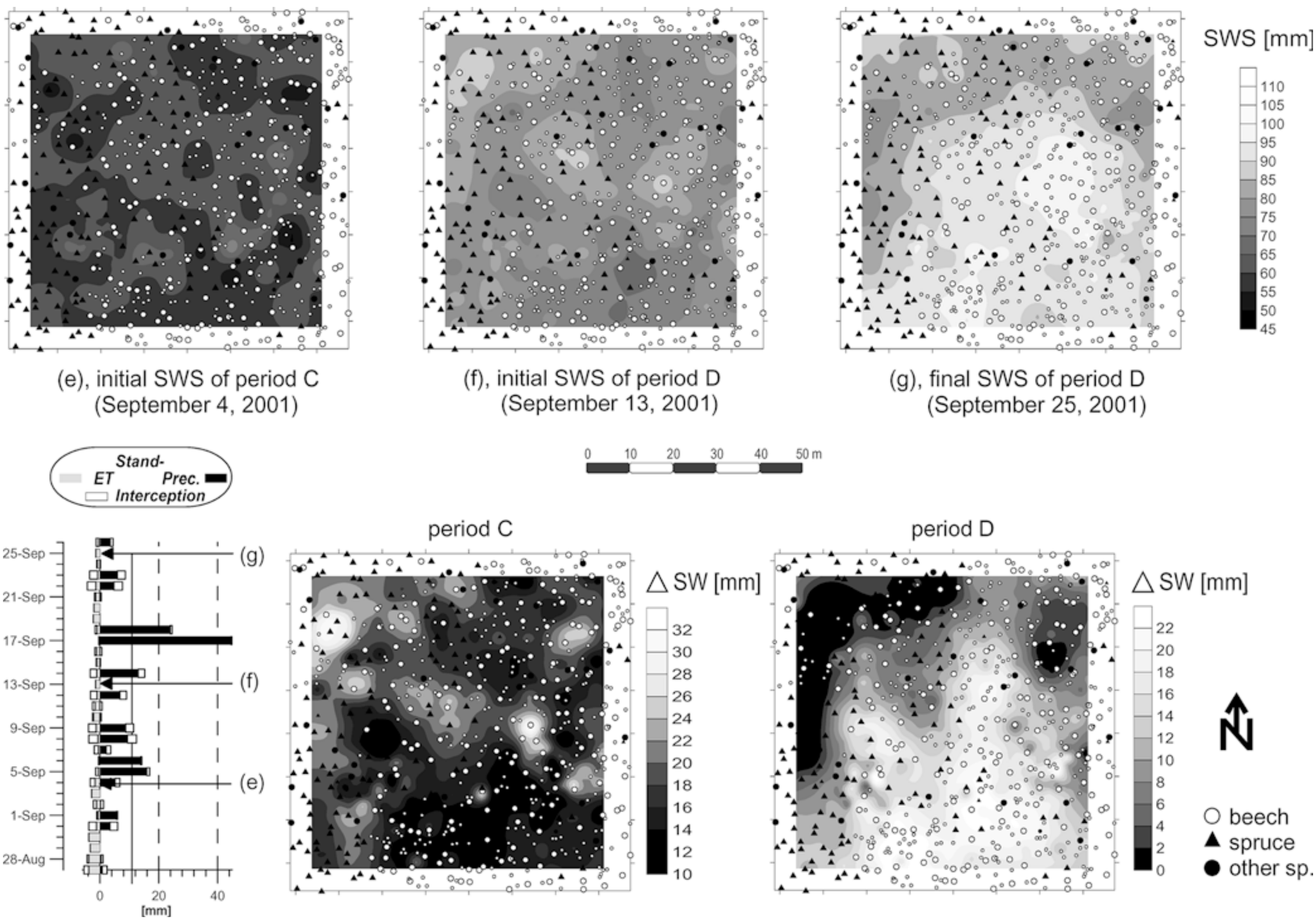


Fig. 6 Interpolations of subsoil SWS at three consecutive dates during a rainy period in autumn 2001 (**e**–**g**). *Below* Interpolation plots show the changes of subsoil water-storage (ΔSW) between the measuring dates *e*, *f* and *f*, *g*, respectively. *Left* Precipitation, interception and evapotranspiration in the considered period

tion under beech. This difference became very striking in period B. Differing water repellency of humic A-horizons under spruce versus beech might, to a certain extent, explain the insufficient rewetting of the mineral soil under spruce in period B. Particularly when dry, spruce litter exhibits hydrophobic properties and thus hinders water infiltration (Luef 1997). Repellency of A-horizons increases surface runoff in sloping terrain (Ritsema and Dekker 2000). Higher seepage rates of rain-event water under spruce are somewhat unlikely in view of the similar pore volumes and soil water-contents in all stands.

Recharge patterns in the topsoil of the mixed stand after the first period of heavy rainfall (period C) were largely congruent with tree species distribution. The increasing sill in the variogram for topsoil SWS and the unchanged nugget after period C (Fig. 3f) underline the fact that a major part of the change in spatial variation can be attributed to tree species effects. Primarily this is stem flow along beech, which contributed about 15% to total stand precipitation on a seasonal basis (Schume et al 2004). Stem-flow, a negligible factor in spruce stands, results in a concentrated water infiltration at the stem base of beech trees. Erratic subsoil recharge patterns in association with heavy rainfall can be attributed to preferential flow paths, such as animal burrows, old root channels and, judging from the initial subsoil, water content. To a certain extent, shrinkage cracks may also contribute to this pattern.

Given the high amount of precipitation (100.8 mm), soil water recharge in period D was very low. The high initial water content (close to field capacity) left only a small pore volume for long-term water storage and hence for buffering runoff (e.g. Ruprecht and Stoneman 1993; Nichols and Verry 2001). When effective rainfall exceeds field capacity, the excess of rainfall leads to a temporary increase in soil water content and initializes internal runoff in the form of interflow and/or percolation (e.g. Germann 1986; Grayson et al. 1997; Zehe and Flühler 2001). Hewlett and Nutter (1970) report a link between initially high soil water content and runoff generation. Analyses of the extraordinary floods of the years 1997 and 2002 in Central Europe pointed out the importance of antecedent SWS for runoff processes. In both cases, the soil water storage had been drastically increased by a storm prior to the one directly causing the flood (Seibert and Formayer 2002). This is analogous to our field observation in September 2001 (Fig. 5), where only a small change in SWS was observed at the end of the heavy rainfall period D, due to the increased soil water storage caused by prior period C.

After approximately 1 or 2 days, when most of the large pores have drained, field capacity is reached again (Warrick 2002). As field capacity is an upper boundary for lasting water storage, the topsoil recharge pattern of period D (Fig. 5) shows the progression of already high SWS towards field capacity. A significant decline in the sill of the variogram for topsoil SWS (Fig. 3f, g) denotes a loss of spatial variability following precipitation (Fig. 3f, g) and emphasizes the role of field capacity in regulating SWS (which is also visible in Fig. 5g). A similarly low spatial variation was found only at extremely dry situations close to the permanent wilting point (Schume et al. 2003).

Conclusions

The horizontal and vertical distribution of soil water recharge in heavy clay soils is strongly dependent upon antecedent soil water content. Given intermediate initial soil water content, moderate rainfall, both in terms of quantity and intensity, mainly leads to topsoil recharge. Furthermore, spatial patterns of soil water recharge are dependent upon the tree species present. Higher interception of spruce results in lower soil water recharge when compared to beech. The mixed subarea behaves similarly to the pure beech subarea. Low soil water-content prior to moderate rewetting causes higher water recharge in the subsoil and more heterogeneous recharge patterns. Reasons for this can be found in the opening of shrinkage cracks of the clayey soils that form a (variable) macropore system, which conducts water into deeper soil regions and over large distances in space. Field capacity acts as an upper boundary at which persistent recharge, and thus runoff buffering via an increase in soil water storage, can occur. Wetting beyond field capacity causes a spatial leveling of SWS, resulting in a relatively homogeneous soil water content throughout the stand.

This study focused on water recharges that were observed at least 1 day after the last precipitation in a rewetting period and, therefore, reflects the dynamic response of a swelling and shrinking soil matrix. Little can be said about the processes at shorter time scales, such as macropore flow velocities and drainage times of larger pores. This will be the subject of further investigation.

References

Augusto L, Ranger J, Binkley D, Rothe A (2002) Impact of several common tree species of European temperate forests on soil fertility. Ann For Sci 59:233–253

Benecke P (1984) Der Wasserumsatz eines Buchen- und eines Fichtenwaldökosystems im Hochsolling, vol 77. Schriften aus der Forstlichen Fakultät der Universität Göttingen und der Niedersächsischen Forstlichen Versuchsanstalt, Göttingen

Bosch JM, Hewlett JD (1982) A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. J Hydrol 55:3–23

Bruckner A, Kandeler E, Kampichler C (1999) Plot-scale spatial pattern of soil water content, pH, substrate-induced respiration and N mineralisation in a temperate coniferous forest. Geoderma 93:207–223

Chang M (2002) Forest hydrology. CRC Press, Boca Raton

Dekker LW, Ritsema CJ (2000) Wetting patterns and moisture variability in water repellent Dutch soils. J Hydrol 231–232:148–164

Deutsch CV, Journel AG (1997) GSLIB: Geostatistical software library and user's guide, 2nd edn. Oxford University Press, New York

Germann PF (1986) Rapid drainage response to precipitation. J Hydrol Process 1:1–13

Goovaerts P (1997) Geostatistics for natural resources evaluation. Oxford University Press, New York

Grayson RB, Western AW, Chiew FHS, Blöschl G (1997) Preferred states in spatial soil moisture patterns: local and nonlocal controls. Water Resour Res 33:2897–2908

Grayson RB, Blöschl G, Western AW, McMahon TA (2002) Advances in the use of observed spatial patterns of catchment hydrological response. Adv Water Resour 25:1313–1334

Helms JA (Ed) (1998) The dictionary of forestry. The Society of American Foresters and CABI Publishing, Bethesda

Hewlett JD, Nutter WL (1970) The varying source area of streamflow from upland basins. In: Proc Symp Interdisciplinary Aspects of Watershed Management, American Society of Civil Engineering, New York, pp 65–83

Hietz P, Offenthaler I, Schume H, Richter H (2000) Transpiration and canopy conductance in a spruce stand and a spruce–beech stand. In: Hasenauer H (ed), Proc Int Conf Forest Ecosystem Restoration, 10–12 April 2000, University of Agricultural Science, Vienna, pp 126–132

Hornbeck JW, Adams MB, Corbett ES, Verry ES, Lynch JA (1993) Long-term impacts of forest treatment on water yield: a summary for northeastern USA. J Hydrol 150:323–344

Huber A, Iroumé A (2001) Variability of annual rainfall partitioning for different sites and forest covers in Chile. J Hydrol 248:78–92

Luef S (1997) Interzeption der Streuschicht von Fichte und Buche. Diploma Thesis, BOKU—University of Natural Resources and Applied Life Sciences, Vienna, 89 pp

Nichols DS, Verry ES (2001) Stream flow and ground water recharge from small forested watersheds in northern central Minnesota. J Hydrol 245:89–103

Peck A, Mayer H (1996) Einfluß von Bestandesparametern auf die Verdunstung von Wäldern. Forstw Centralbl 115:1–9

Ridolfi L, D'Odorico P, Porporato A, Rodriguez-Iturbe I (2003) Stochastic soil moisture dynamics along a hillslope. J Hydrol 272:264–275

Ritsema CJ, Dekker LW (2000) Preferential flow in water repellent sandy soils: principles and modeling implications. J Hydrol 231–232:308–319

Ruprecht JK, Stoneman GL (1993) Water yield issues in the Jarrah forest of south-western Australia. J Hydrol 150:369–391

Schmid I (2002) The influence of soil type and interspecific competition on the fine root system of Norway spruce and European beech. Basic Appl Ecol 3(4):339–346

Schume H, Jost G, Katzensteiner K (2003) Spatio-temporal analysis of the soil water content in a mixed Norway spruce [*Picea abies* (L.) Karst.]–European beech (*Fagus sylvatica* L.) stand. Geoderma 112:273–287

Schume H, Jost G, Hager H (2004) Soil water depletion and recharge patterns in mixed and pure forest stands of European beech and Norway spruce. J Hydrol (in press)

Seibert P and Formayer H (2002) Ereignismanagement und Prävention. In: Habersack H and Moser A (Eds) Plattform Hochwasser: Ereignisdokumentation Hochwasser August 2002. Bundesministerium für Land und Forstwirtschaft Umwelt und Wasserwirtschaft, Wien

Smith M (1988) Calculation procedures of modified Penman equation for computers and calculators. FAO, Land and Water Development Division, Rome

Stednick JD (1996) Monitoring the effects of timber harvest on annual water yield. J Hydrol 176:79–95

Sumner ME (2000) Handbook of soil science. CRC Press, Boca Raton

Topp GC, Davis JL, Annan AP (1980) Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour Res 16:574–582

Villholth KG, Jensen KH, Fredericia J (1998) Flow and processes in a macroporous subsurface-drained glacial till soil I: field investigations. J Hydrol 207:98–120

Warrick AW (2002) Soil physics companion. CRC Press, Boca Raton

Zehe E, Flühler H (2001) Preferential transport of isoproturon at a plot scale and a field scale tile-drained site. J Hydrol 247:100–115