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Assessment of multi-frequency electromagnetic induction for determining soil moisture patterns at the hillslope scale

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SUMMARY

Hillslopes are fundamental landscape units, yet represent a difficult scale for measurements as they are well-beyond our traditional point-scale techniques. Here we present an assessment of electromagnetic induction (EM) as a potential rapid and non-invasive method to map soil moisture patterns at the hillslope scale. We test the new multi-frequency GEM-300 for spatially distributed soil moisture measurements at the well-instrumented Panola hillslope. EM-based apparent conductivity measurements were linearly related to soil moisture measured with the Aqua-pro capacitance sensor below a threshold conductivity and represented the temporal patterns in soil moisture well. During spring rainfall events that wetted only the surface soil layers the apparent conductivity measurements explained the soil moisture dynamics at depth better than the surface soil moisture dynamics. All four EM frequencies (7.290, 9.090, 11.250, and 14.010 kHz) were highly correlated and linearly related to each other and could be used to predict soil moisture. This limited our ability to use the four different EM frequencies to obtain a soil moisture profile with depth. The apparent conductivity patterns represented the observed spatial soil moisture patterns well when the individually fitted relationships between measured soil moisture and apparent conductivity were used for each measurement point. However, when the same (master) relationship was used for all measurement locations, the soil moisture patterns were smoothed and did not resemble the observed soil moisture patterns very well. In addition the range in calculated soil moisture values was reduced compared to observed soil moisture. Part of the smoothing was likely due to the much larger measurement area of the GEM-300 compared to the soil moisture measurements.

Introduction

Progress in hillslope hydrology is hampered by the fact that our soil moisture measurements are made at the point scale, whereas our measurement needs are at the whole-hillslope scale (Topp, 2003). Since the introduction of the neutron probe (Holmes, 1956), soil moisture measurement methods have focused on accuracy and precision at the point scale. They have remained highly invasive and often focused on particular depths. In addition, the traditional measurements have integrated only over a very small area or volume, which has been problematic for scaling up soil moisture measurements to understand how internal state behavior regulates whole-hillslope rainfall–runoff response. There has been recent debate on the relative merits of high precision and high accuracy point-scale measurements at a few measurement sites compared to a large number of measurements over a large area with lower precision and lower accuracy (McDonnell et al., 2007). Several calls have been made for pattern comparisons to enable more definitive tests of model performance and to improve confidence in model structures (Grayson and Blöschl, 2000; Seibert and McDonnell, 2002). As yet, few studies have begun to assess techniques that could be used to describe patterns of soil moisture at the hillslope scale.

For forested hillslopes in many headwater catchments, satellite-based remote sensing using passive or active microwave is not possible due to coarse satellite resolution, forest interference and limited penetration depth (Lakshmi, 2004). Ground-based electromagnetic induction (EM) has been cited as a potential alternative method to map soil moisture patterns at the hillslope to catchment scale quickly. EM measures the depth weighted average of the electric conductivity of a column of material to a specific depth, termed the apparent conductivity and expressed in milliSiemens per meter (mS/m). A transmitter coil produces an electromagnetic field that induces current to flow through the subsurface. This current sets up a secondary electromagnetic field in the soil. By comparing differences in the magnitude and phase of these electromagnetic fields, an EM device measures the apparent conductivity. The profile weighted apparent electrical conductivity of

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the soil is influenced by the types and concentration of ions in solution, the amount and types of clay minerals, the volumetric water content, temperature and the phase of soil water (McNeill, 1980). Ambient conditions such as air temperature, humidity and atmospheric electricity (spherics) can also influence apparent conductivity measurements. The depth of penetration of the electromagnetic current is influenced by the instrument's coil orientation, the coil separation, the measurement frequency and the conductivity of the soil. A higher conductivity results in a shallower depth of penetration. Lower frequencies penetrate to greater depth. To date, only single frequency EM measurements have been used for soil moisture measurements.

Previous benchmark EM studies by Kachanoski et al. (1988, 1990) and Sheets and Hendrickx (1995) have shown that electromagnetic measurements can potentially be used for soil moisture mapping. Notwithstanding, EM work to date has focused largely on soil salinity assessments (e.g. Rhoades et al, 1990; Hendrickx et al., 1992; Lesch et al., 1995, 1998; Vaughan et al., 1995; Doolittle et al., 2001), detection of buried objects (e.g. Bevan, 1983), soil type mapping (e.g. Doolittle et al., 2002), soil depth assessment (e.g. Bork et al., 1998), permafrost mapping (e.g. Hauck et al., 2001), detection of polluted plumes (e.g. Sweeney, 1984) and water table mapping (e.g. Sherlock and McDonnell, 2003). For investigations of spatial patterns of soil moisture, most work to date has been in flat, easily accessible and relatively homogeneous agricultural areas and sites where the EM can be mounted on a tractor or vehicle for data collection. No studies that we are aware of have attempted to assess spatial patterns of soil moisture using EM or other non-invasive techniques in upland forested terrain or headwater catchments – the source areas for much of the flow downstream. Kachanoski et al. (1988) studied the relationships among the spatial variations of soil moisture content, soil texture and the electrical conductivity of the soil solution using the EM38 (Geonics Ltd., Mississauga, ON, Canada). They showed that apparent conductivity could explain 96% of the variation in soil moisture. The locations of their sampling sites were selected to obtain the maximum variation in soil moisture content and soil texture across the site. They found a curvilinear relationship between volumetric soil moisture content and apparent conductivity and significant correlation among the soil variables studied. Another study by Kachanoski et al. (1990) found that approximately 50–60% of the variation in soil moisture content was explained by variation in apparent conductivity. Sheets and Hendrickx (1995) found that the temperature corrected apparent conductivity measured with the EM31 (Geonics Ltd., Mississauga, ON, Canada) could explain between 58% and 64% of the temporal soil moisture variation in the upper 1.5 m of the soil profile along a transect. Hanson and Kaita (1997) found during the drying of an irrigated field in California that the EM38 could explain between 76% and 95% of the observed soil moisture variations in the upper 1.2 m of the soil profile, depending on the salinity level of the field. Sherlock and McDonnell (2003) found for a hillslope in New York that the EM38 could explain over 70% of the gravimetrically determined soil moisture variance in the upper 0.20 m on one measurement date. They could not check the robustness of the method and found a poor relationship between raw apparent conductivity data and the volumetric soil moisture content at 10, 50 and 130 cm depth estimated from a moisture release curve and tensiometer data.

Here we present a qualitative study on the use of EM in the headwaters of a forested catchment to assess its use for quantifying the temporal and spatial patterns of soil moisture. Our philosophy in this work is that lower precision and lower accuracy measurements of soil moisture but in a fully spatially explicit grid over a large area may be more important than precise, highly accurate point-scale measurements for inferring whole-hillslope behavior. We examine several issues in relation to this first test of the multi-frequency EM approach in an upland forested catchment and examine the applicability of EM measurements for hillslope hydrological investigations: can EM be used for soil moisture measurements in areas with shallow soils? Can EM represent the temporal and spatial patterns of soil moisture throughout the year? And can multiple frequencies be used to extract additional information content from the EM approach and explain the depth profile of moisture? This study makes use of the new multi-frequency GEM-300 (Geophysical Survey Systems Inc., North Salem, NH, USA) to test if certain frequencies are better suited for soil moisture measurements than other frequencies and to determine if it is possible to obtain information about the depth distribution of soil moisture.

Site description

The Panola Mountain Research Watershed (PMRW) is located within the Panola Mountain State Conservation Park southeast of Atlanta, Georgia (84°10′W, 33°37′N). The climate at PMRW is classified as humid subtropical. The mean annual temperature is 16.3 °C. Mean annual precipitation is 1240 mm and is distributed relatively uniform throughout the year. Rainfall tends to be of longer duration and lower intensity associated with the passage of fronts in the winter, and of shorter duration but higher intensity associated with thunderstorms in the summer. Streamflow at PMRW has a seasonal pattern with the highest flow occurring during the November through March dormant season. Bedrock at PMRW is dominated by the Panola Granite (granodiorite composition), described as a biotite-oligioclase-quartz-microcline granite (Crawford et al., 1999).

The experimental hillslope is located approximately 30 m upslope from an ephemeral stream. A 20 m wide trench to bedrock forms the lower boundary of the hillslope and a small bedrock outcrop forms the upper boundary of the hillslope. The forested hillslope is dominated by hickory (*Carya* sp.) and oak (*Quercus* sp.) trees. Soils on the experimental hillslope are best described as a light colored sandy loam with little textural differences except for a 0.15 m humus rich upper horizon. No large differences in soil texture or soil type are observed across the hillslope. The average soil depth of the experimental hillslope is 0.63 m and ranges from 0 to 1.8 m (McDonnell et al., 1996; Freer et al., 2002). In general soils on the lower slope (<25 m upslope from the trench) are deeper than soils on the upper slope (>25 m upslope from the trench). The average soil depth of the lower- and upper- slope is 0.80 and 0.51 m, respectively. The surface topography is relatively planar while the bedrock topography is very irregular (McDonnell et al., 1996; Freer et al., 1997). The average slope is 13°.

Methods

Soil moisture measurements

Soil moisture measurements were made during February–August 2002. Soil moisture was measured using the Aqua-pro (Aqua-pro Sensors, Reno NV) capacitance sensor. Sixty-four polycarbonate access tubes were installed on a 4 by 4 m grid across the hillslope and a 4 by 2 m grid on the lower 6 m of the hillslope. The fixed tube locations ensured repeatability for EM calibration. The Aqua-pro sensor is a capacitance (radio-frequency) sensor that measures soil moisture on a percent scale between 0 (in air or air dried soil) and 100 (in water or saturated soil). The relation between the Aqua-pro soil moisture values and gravimetrically determined volumetric soil moisture content is linear (J. Selker, Oregon State University, Personal Communication):

$$\theta_{vol} = \frac{Ap}{a} + b \qquad (1)$$

where θ_{vol} is the volumetric soil moisture content (%) determined by the gravimetric approach, *Ap* is the Aqua-pro measurement value ($\%_{\text{Aqua-pro}}$) and *a* and *b* are constants that depend on the soil type.

Soil moisture was measured at 5 cm depth intervals between the soil surface and 30 cm, and at 10 cm depth intervals between 30 cm below the soil surface and the depth of the soil–bedrock interface (i.e. refusal). Profile average soil moisture was calculated by multiplying the Aqua-pro soil moisture values at the different measurement depths by the distance between the measurement depths and dividing this by the total soil depth. Hillslope average soil moisture was calculated by averaging profile average soil moisture of all 64 measurement locations. Hillslope average soil moisture at a certain depth was calculated by averaging all soil moisture measurements at that depth. The field capacity of the soil on the study hillslope is ~70$\%_{\text{Aqua-pro}}$ (Tromp-van Meerveld and McDonnell, 2006a). More information about the soil moisture measurements and the observed spatio-temporal soil moisture patterns can be found in (Tromp-van Meerveld and McDonnell, 2006a).

Electromagnetic measurements

Hillslope surveys were made with the GEM-300 over the course of a 10 month period (83 separate surveys between November 2001 and August 2002). This period represented the late wetting-up, wet, drying and dry part of the hydrological year. Measurements were made on average twice to three times per week during the winter and early spring and once every 2 weeks during the late spring and summer. Measurements were made at 130 locations on an approximately 2 by 2 m grid across the hillslope. A complete hillslope survey took ~55 min to complete. We determined the relation between apparent conductivity from the EM measurements and soil moisture using only the measurements that were made on the same day (57 occasions) and at the same location (64 locations) as the Aqua-pro soil moisture measurements. Hillslope average apparent conductivity was calculated by averaging the apparent conductivity of all 64 measurement locations that corresponded with the soil moisture measurements. Apparent conductivity values from measurements with the GEM-300 were relative to the calibration standard.

The vertical dipole at hip height (~0.85 m above the soil surface) configuration was used because this configuration was the most practical and fastest configuration for EM data acquisition. Sheets and Hendrickx (1995) showed that there were negligible differences between different dipole configurations for the EM31. We assumed that this would apply to the GEM-300 measurements as well. Special care was given to assure the same position, height and direction of the instrument during each measurement. Four frequencies were recorded simultaneously: 7.290, 9.090, 11.250 and 14.010 kHz. The frequencies of the widely reported EM31 and EM38 are 9.800 and 14.600 kHz, respectively. The lateral resolution of the EM measurements (i.e. the horizontal EM coverage) is approximately equal to the inter-coil spacing, which is 1.3 m for

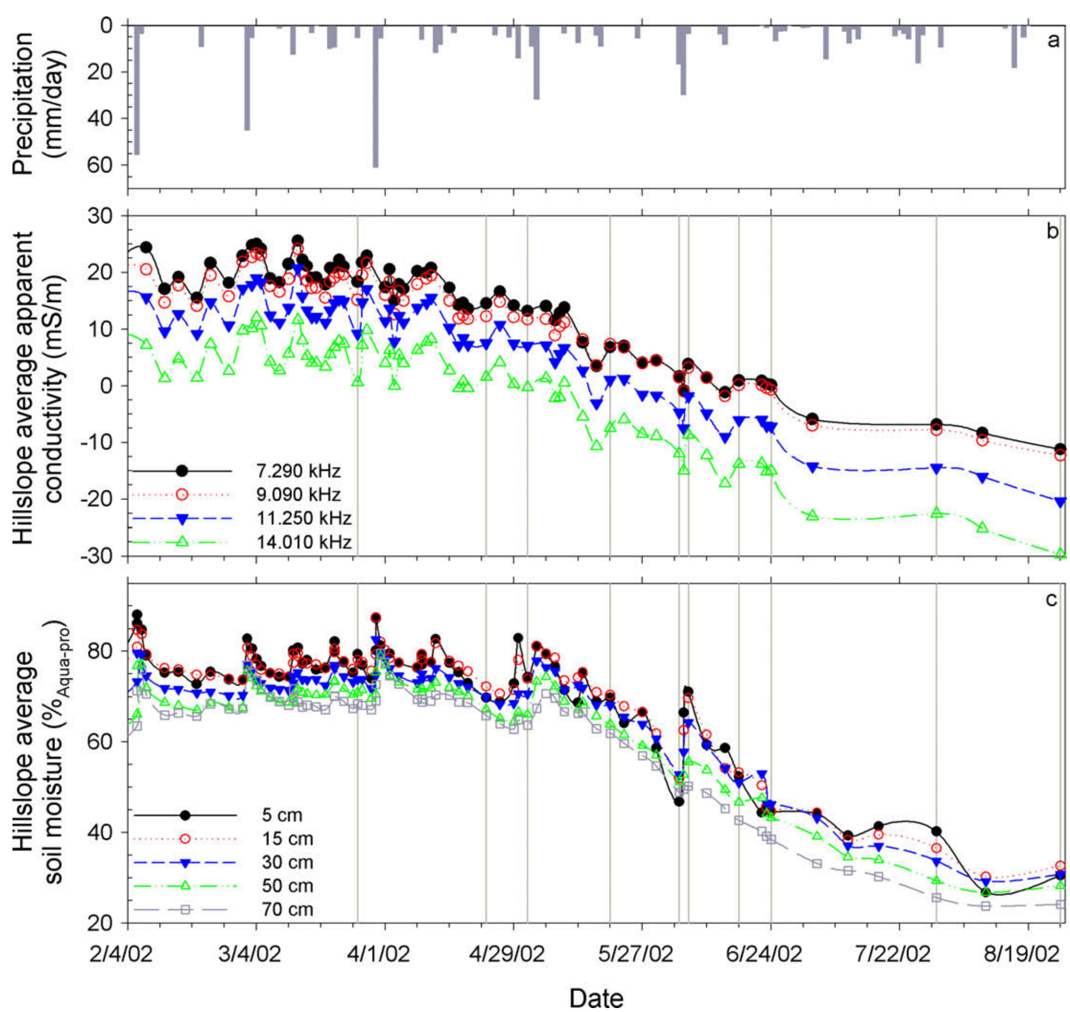

Fig. 1. Time series of daily precipitation (a), hillslope average apparent conductivity measured by the four frequencies (b), and hillslope average soil moisture at different depths below the surface (c). The vertical gray lines represent the times of the spatial soil moisture maps shown in Fig. 6.

the GEM-300. In theory, the depth of penetration for all four frequencies, which depends on the measurement frequency and the conductivity of the soil, was deeper than the soil depth at the hillslope. However, previous studies have shown that the actual depth of observation (i.e. the depth that contributes the largest part to the total EM response) is much shallower than the theoretical depth of penetration (Roy and Apparao, 1971). Also, surface and shallow soil layers contribute more to the overall response than deeper layers. Thus we assumed that even though the theoretical depth of penetration was deeper than the soil depth, the conductivity response would contain enough information from the shallow soil layers that these frequencies could be used to measure soil moisture on the hillslope.

External influences on EM response

On six measurement dates in this study, the measured apparent conductivity values were anomalously high compared to the other measured apparent conductivity values. These occasions occurred after or during rain events and were omitted from the analyses.

Apparent conductivity measurements can vary due to changes in soil temperature (Slavich and Petterson, 1990). We therefore standardized the field measured apparent conductivity values to an equivalent conductivity at a reference temperature of 25 °C using soil temperature measured next to the study hillslope at 40 cm below the soil surface and a conversion function given by Sheets and Hendrickx (1995) and Reedy and Scanlon (2003):

$$EC_{25} = EC_a\left(0.4779 + 1.3801e^{\left(\frac{-T}{25.654}\right)}\right) \quad (2)$$

where EC_{25} is the temperature corrected apparent conductivity (mS/m), EC_a is the measured apparent conductivity (mS/m), and T is the measured soil temperature (°C).

EM measurements can be influenced by (thermal) drift (Robinson et al., 2004). The GEM-300 was usually left outside to thermally equilibrate for at least 30 min before the measurements

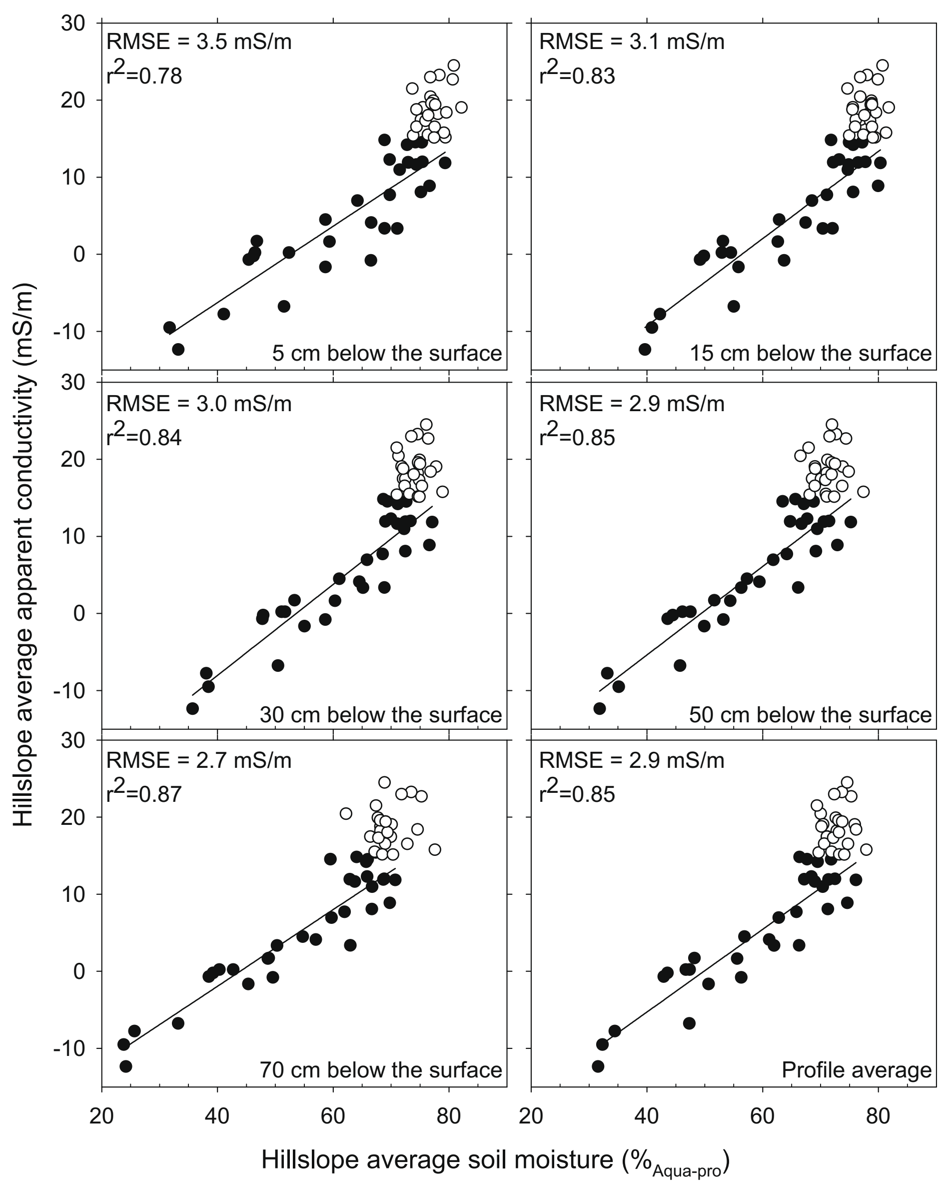

Fig. 2. The linear relation between hillslope average apparent conductivity (9.090 kHz) below the threshold (15 mS/m for 9.090 kHz) and hillslope average soil moisture at different depths below the surface. Conductivity values below the threshold are shown with solid circles while the conductivity values above the threshold are shown with open symbols. Relationships for the 7.290, 11.250, 14.010 kHz frequencies are similar to the results shown here for the 9.090 kHz frequency.

were made on each recording session. Because of the short time to complete the measurements on the hillslope, we initially assumed that drift would be minimal. However, we observed a linear relationship between station number and apparent conductivity on seven measurement dates (mostly during the winter). While there may have been drift or insufficient time to thermally equilibrate the GEM-300 on these measurements dates, we can not determine if this was indeed the case and did not correct these measurements for possible drift.

On one occasion we kept the GEM-300 stationary and took measurements at one location for 5 h, during which the air temperature increased from 11 to 21 °C and the apparent conductivity changed by 7 mS/m. Unfortunately, we do not have soil temperature data for this period. If we assume that the soil temperature did not change during this period, this corresponds to a calculated change in soil moisture of $11\%_{\text{Aqua-pro}}$ (see further in the text for this conversion). An increase in soil temperature during this period would decrease this difference. The relationship between air temperature and apparent conductivity was non-linear during this drift experiment. Sudduth et al. (2001) found for the EM38 that drift in apparent conductivity may not be caused by temperature variations, but that drift may merely be a function of instrument instability integrated over time. In their tests drift per time was relatively constant within a test but varied from day to day. They concluded that the causative factors of drift in apparent conductivity appear to be complex, and are not readily compensated for with additional readily obtained measurements, such as ambient air temperature. We do not have data to correct for drift and thus did not correct for any possible drift.

Other measurements

Lateral subsurface flow was measured in the 20 m long trench at the downslope end of the study hillslope using tipping buckets. The trench and the flow-collection system are described in McDonnell et al. (1996), Freer et al. (1997, 2002) and Tromp-van Meerveld and McDonnell (2006b). Transient saturation at the soil–bedrock interface was measured with capacitance rods (Trutrack, Christchurch, New Zealand) in 29 PVC wells across the hillslope (see Tromp-van Meerveld and McDonnell (2006c) for details).

The hillslope was surveyed on a 2 m grid. Depth to bedrock was measured on the same survey grid network using a soil corer or small hand auger (Zumbuhl, 1998; Freer et al., 1997, 2002). The multidirectional flow algorithm of Quinn et al. (1991) was used to calculate the drainage area for both the soil–bedrock interface and the soil surface. The topographic index (Kirkby, 1975) was calculated for both the surface topography and bedrock topography (Freer et al., 1997).

Results

Temporal patterns

The temporal response of hillslope average apparent conductivity was very similar for the four measured frequencies (Fig. 1b) and followed that of the observed soil moisture response (Fig. 1c). In general, apparent conductivity was high (positive relative to the calibration standard) during the winter months and low during the summer months.

The relationship between hillslope average soil moisture at a certain depth and hillslope average apparent conductivity was linear below a threshold apparent conductivity (Fig. 2). This threshold was ~15 mS/m for 7.290 and 9.090 kHz, ~10 mS/m for 11.250 kHz and ~1 mS/m for 14.010 kHz. These thresholds corresponded to a soil moisture content of ~70–80%$_{\text{Aqua-pro}}$ (depending on soil depth), which is approximately the moisture content at field capacity. Above these thresholds differences in hillslope average apparent conductivity were not explained by differences in hillslope average soil moisture. All of the EM readings above the apparent conductivity threshold occurred in March-early April, the time when the watershed was wettest. The relation between hillslope average soil moisture and hillslope average apparent conductivity below the threshold was good for all depths and all frequencies and was only slightly better for the deeper soil layers than for the shallow soil layers (Figs. 2 and 3), e.g. for the 9.090 kHz frequency the square of the Pearson product moment correlation coefficient (r^2) was 0.85 for soil moisture at 70 cm below the soil surface while it was 0.78 for soil moisture at 5 cm below the soil surface. The root mean square error (RMSE) was 2.7 and

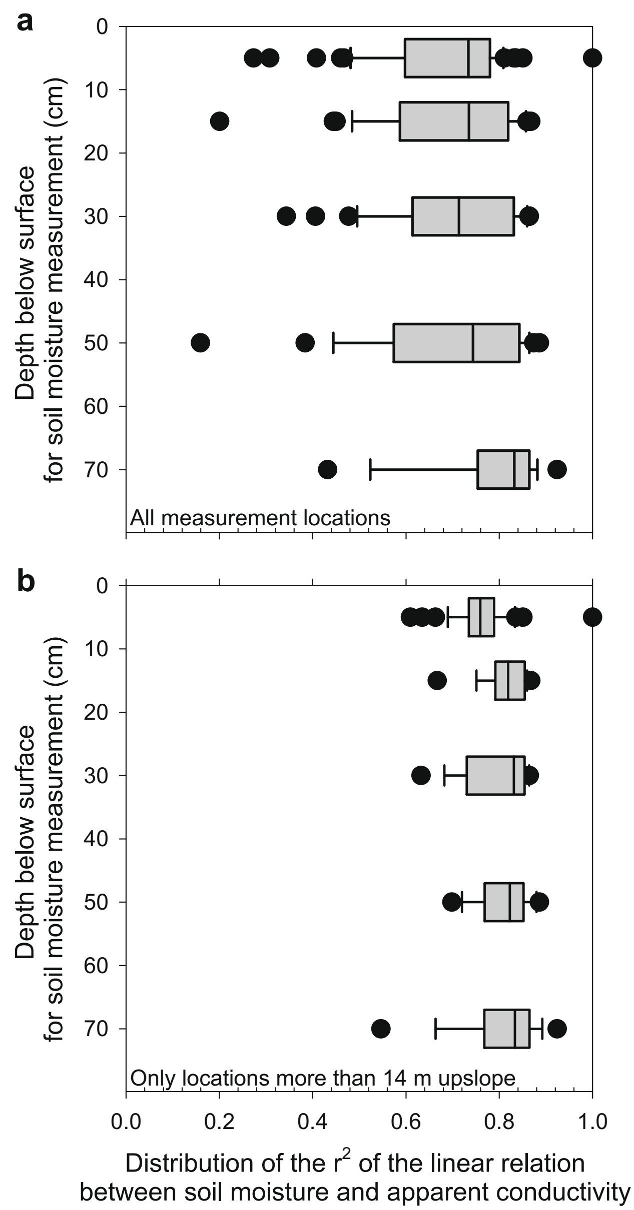

Fig. 3. The distribution of the r^2 of the linear relation between soil moisture and apparent conductivity (9.090 kHz) below the apparent conductivity threshold (i.e. 15 mS/m for 9.090 kHz) as a function of depth below the soil surface for all measurement sites (a) and only the measurement sites located more than 14 m upslope from the trench (b). The lines represent the 25th, 50th and 75th percentile, the whiskers represent the 10th and 90th percentile and the dots represent all outliers. Results for the 7.290, 11.250 and 14.010 kHz frequency are similar to the results shown for the 9.090 kHz frequency.

3.5 mS/m for hillslope average soil moisture at 70 and 5 cm below the soil surface, respectively. This corresponded to a RMSE for calculated soil moisture of 4.4% and 5.8%$_{\text{Aqua-pro}}$, respectively.

Measured soil moisture at the individual measurement locations was also linearly related to apparent conductivity below the threshold at that location (Table 1). These relationships were strong for most measurement locations (Fig. 3). The relation between soil moisture and apparent conductivity was not as strong for some locations on the lower 14 m of the hillslope. The low r^2 for these locations was caused by several outliers occurring during artificial water applications on the lower 14 m of the hillslope between June 18 and August 20, 2002 (Tromp-van Meerveld et al., 2007). Soil moisture was increased artificially during these experiments but the measured apparent conductivity remained nearly constant (this was partly due to soil temperature differences due to the water applications (see Discussion)). When the soil moisture measurements that were influenced by the artificial water applications were excluded from the analysis, the r^2 of the linear part of the relation between apparent conductivity and observed soil moisture increased to larger than 0.75 for 94% of the measurement locations. There was no relation between the r^2 and any of the computed topographic variables (up-slope distance, along-slope distance, surface elevation, bedrock elevation, accumulated area or topographic index for the surface or bedrock topography, soil depth). The slope and intercept of the linear part of the relation between apparent conductivity and observed soil moisture (Table 2) were also not related to any of the topographic variables. There was also no spatial pattern in the r^2, slope or intercept.

We used the linear relation between soil moisture and apparent conductivity to convert the measured apparent conductivity values to calculated soil moisture values. We did this by (1) using the best fitted linear relation between measured soil moisture and measured apparent conductivity for each individual measurement location (i.e. applying a different relationship to each measurement location) and (2) by using the same linear relation between soil moisture and apparent conductivity for all measurement locations (i.e. applying a master relationship to all measurements). Values above the threshold apparent conductivity (i.e. 15 mS/m for 9.090 kHz) were excluded from the conversion of apparent conductivity values to soil moisture.

The temporal patterns of calculated soil moisture (from the apparent conductivity measurements) represented the temporal patterns of measured hillslope average soil moisture at the different depths well (Fig. 4). Both methods represented the average hillslope soil moisture response equally well. Especially the general dry down after late April (when full leaf out occurred) was well represented. The EM signal also showed the wetting and drying of the soil in response to the measured rainfall events. However, the calculated increase in shallow soil moisture after the 50 mm rainfall event on June 4–6, 2002 was less than observed (Figs. 4 and 5). During this period the EM signal represented soil moisture at depth better than shallow soil moisture.

Table 2
Statistics of the slope and intercept of the linear relations between profile average soil moisture and the measured apparent conductivity below the threshold conductivity for each measurement location on the study hillslope.

		Minimum	Maximum	Average	Standard deviation
7.290 kHz	Slope	0.8	2.4	1.6	0.4
	Intercept	28.8	63.0	50.0	7.1
9.090 kHz	Slope	0.7	2.4	1.6	0.4
	Intercept	30.7	63.7	51.0	7.0
11.250 kHz	Slope	0.9	2.7	1.8	0.4
	Intercept	35.4	66.3	54.6	6.6
14.010 kHz	Slope	0.8	3.4	2.1	0.6
	Intercept	44.5	77.3	63.1	7.1

Depth distribution

The temporal response of hillslope average apparent conductivity was very similar for the four measured frequencies (Fig. 1b). In fact, there was a strong linear relation between the apparent conductivities measured with the four frequencies (Table 3). Measured soil moisture at the different depths was also highly correlated to each other (Table 4, Fig. 1c). Soil moisture stratification with depth occurred only directly after storms during the late spring and summer when rainfall did not penetrate to depth but only increased soil moisture near the surface ((e.g. the 50 mm June 4–6, 2002 event, Figs. 1c and 5). During these storms the EM response represented the soil moisture change at depth (>30 cm) better than the shallow soil moisture response (Figs. 4 and 5). The higher frequencies (11.250 and 14.010 kHz) represented the wetting-up during these events only slightly better than the lower frequencies (7.290 and 9.090 kHz) (Fig. 5).

Spatial patterns

The spatial patterns of measured and calculated profile average soil moisture are shown in Fig. 6. There was limited spatial variability in soil moisture across the hillslope. Soil moisture calculated from the apparent conductivity measurements represented the seasonal drying down well. However, the drying was a bit slower than observed and the re-wetting during the 50 mm June 4–6, 2002 rainfall event was not as complete as observed.

Table 1
The median and the range of the r^2 values of the linear relation between the apparent conductivity below the threshold conductivity value and soil moisture at different depths below the soil surface.

Depth (cm)	Frequency Threshold conductivity	7.290 kHz 15 mS/m	9.090 kHz 15 mS/m	11.250 kHz 10 mS/m	14.010 kHz 1 mS/m
5	Median	0.64	0.68	0.65	0.47
	Range	0.31–1.00	0.27–1.00	0.26–1.00	0.12–1.00
15	Median	0.66	0.69	0.64	0.39
	Range	0.31–0.86	0.20–0.87	0.24–0.86	0.09–0.77
30	Median	0.66	0.69	0.65	0.42
	Range	0.33–0.85	0.34–0.86	0.35–0.88	0.10–0.74
50	Median	0.68	0.69	0.63	0.39
	Range	0.17–0.86	0.16–0.89	0.16–0.88	0.04–0.75
70	Median	0.77	0.78	0.72	0.45
	Range	0.47–0.90	0.42–0.92	0.43–0.88	0.05–0.81
Profile average	Median	0.71	0.74	0.68	0.44
	Range	0.37–1.00	0.29–1.00	0.31–1.00	0.08–1.00

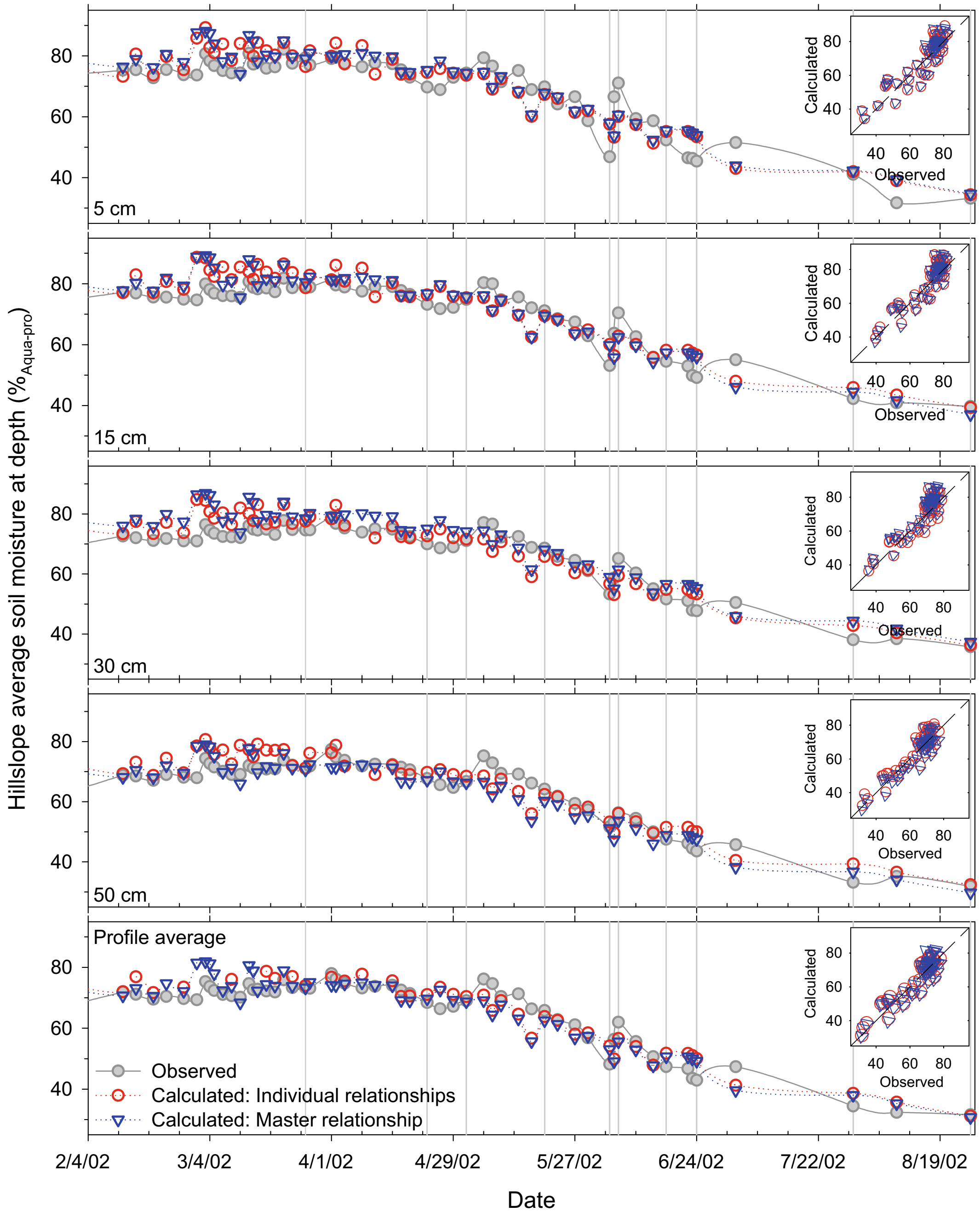

Fig. 4. Time series of hillslope average measured soil moisture (closed circles), hillslope average soil moisture calculated using the individual relationships between apparent conductivity and soil moisture for each measurement location (open circles), and hillslope average soil moisture calculated using the same relation between soil moisture and apparent conductivity (i.e. master relation) for all measurement locations (open triangles). The insert graphs show the relationship between observed and calculated soil moisture (in$\%_{Aqua\text{-}pro}$). The vertical gray lines represent the times of the spatial soil moisture maps shown in Fig. 6. Results for the 7.290, 11.250 and 14.010 kHz frequencies are similar to the results shown here for the 9.090 kHz frequency.

The spatial soil moisture pattern during the drying down period was well represented when the individual relationships between soil moisture and apparent conductivity were used for the conversion of apparent conductivity values to soil moisture values (Fig. 6b). However, the spatial soil moisture pattern was smoothed and more uniform when the master relationship between soil moisture and apparent conductivity was used (Fig. 6c). In addition, there appeared to be no response to the artificial wetting of the soil on the lower 14 m of the hillslope during the June 18–August 20, 2002 period when the master relationship was used. Calculated soil moisture was consistently wetter or drier than measured for some measurement locations but there was no spatial pattern in the difference between observed and calculated soil moisture, nor was the difference related to any of the calculated topographic variables.

The calculated profile average soil moisture pattern represented up to 85% of the observed spatial soil moisture pattern on a measurement day when the individual relationships between soil moisture and apparent conductivity were used. The measured apparent conductivity patterns represented more of the observed spatial patterns in soil moisture at deeper depths than at shallower depths (Table 5). The measured apparent conductivity pattern also represented more of the observed pattern in soil moisture during the spring months compared to other time periods (Table 5). When

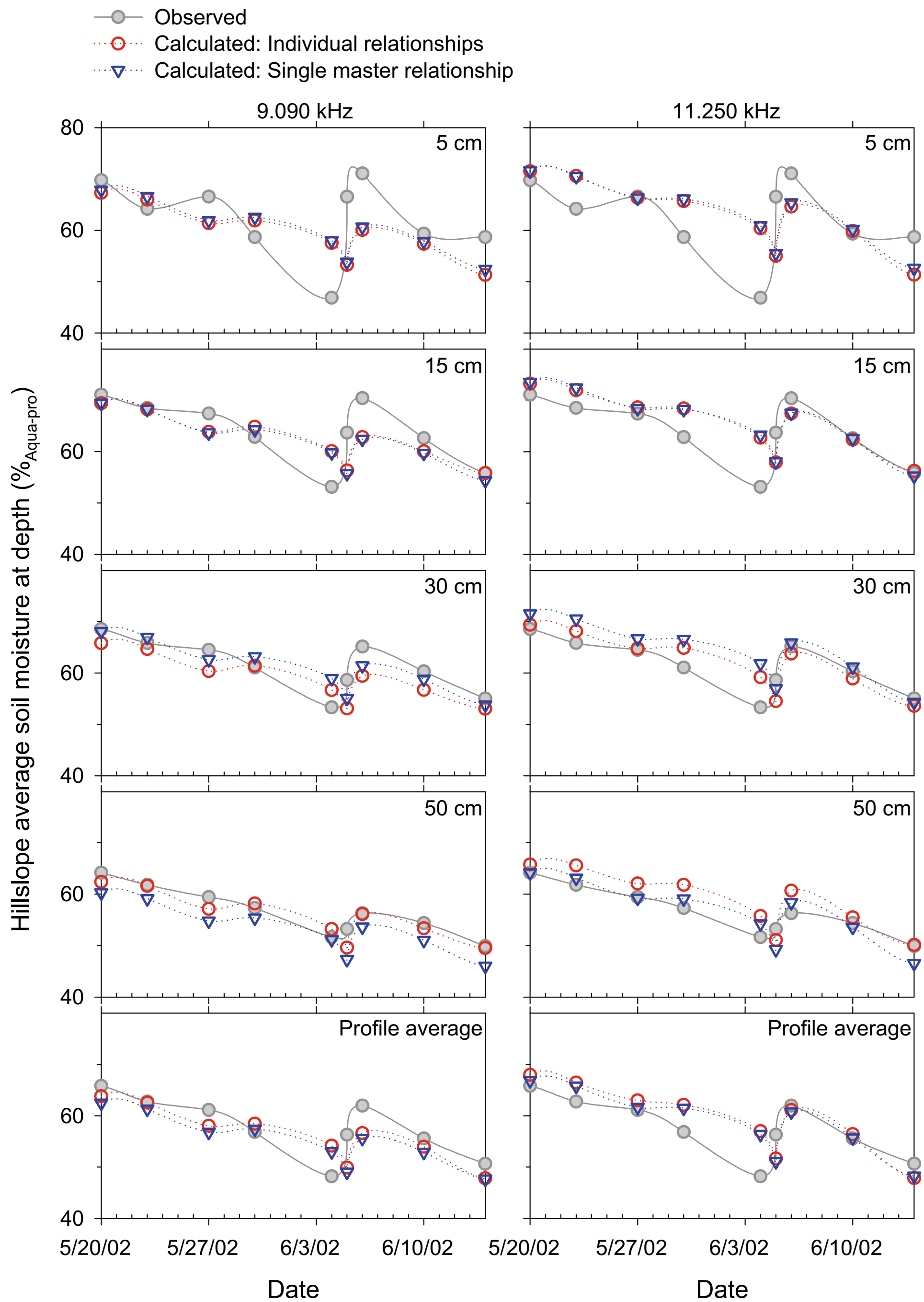

Fig. 5. Time series of hillslope average measured soil moisture (closed circles), hillslope average soil moisture calculated using the individual relationship between apparent conductivity and soil moisture for each measurement location (open circles), and hillslope average soil moisture calculated using the same relation between soil moisture and apparent conductivity (i.e. master relation) for all measurement locations (open triangles) during the 50 mm June 4–6, 2002 rainfall event for the 9.090 and 11.250 kHz frequencies.

Table 3
The average (in the upper part of the matrix) and the range (*in the lower part of the matrix*) of the r^2 of the linear relations between the apparent conductivities measured by the four frequencies for each measurement location on the hillslope.

Frequency (kHz)	7.290	9.090	11.250	14.010
7.290	–	0.99	0.98	0.96
9.090	*0.92–1.00*	–	0.99	0.97
11.250	*0.85–1.00*	*0.94–1.00*	–	0.99
14.010	*0.76–0.99*	*0.80–1.00*	*0.89–1.00*	–

Table 4
The r^2 of the linear relation between hillslope average soil moisture measured at different depths (upper part of the matrix) and the slope of the linear relation between hillslope average soil moisture measured at different depths (*lower part of the matrix*).

	5 cm	15 cm	30 cm	50 cm	70 cm	Profile average
5 cm	–	0.97	0.95	0.91	0.89	0.96
15 cm	*1.09*	–	0.99	0.96	0.93	0.99
30 cm	*1.14*	*1.06*	–	0.98	0.96	0.99
50 cm	*1.08*	*1.00*	*0.95*	–	0.98	0.98
70 cm	*0.91*	*0.84*	*0.80*	*0.85*	–	0.96
Profile average	*1.04*	*0.96*	*0.90*	*0.94*	*1.08*	–

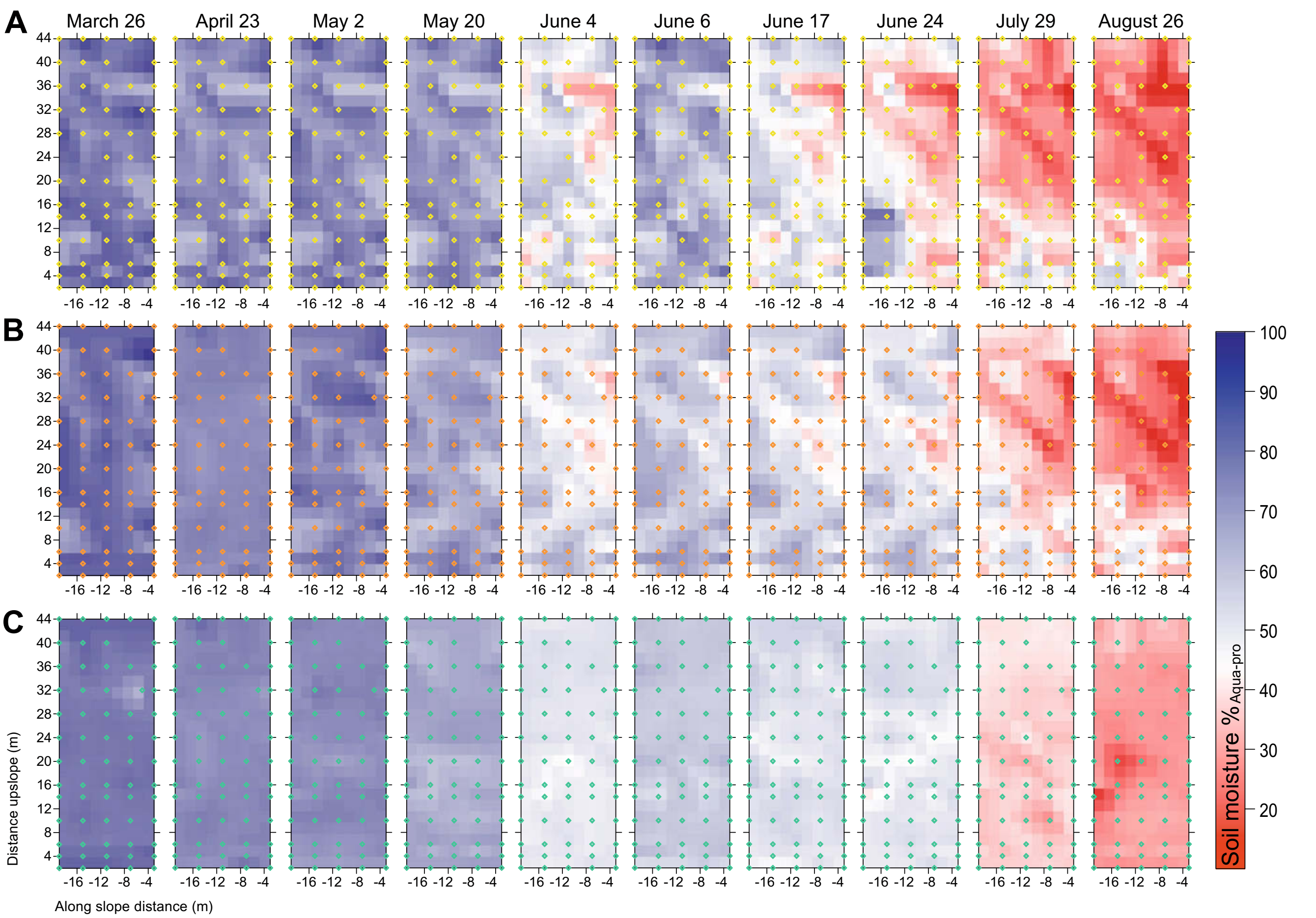

Fig. 6. Maps of measured profile average soil moisture (a), profile average soil moisture calculated using the individual relationships between the apparent conductivity and soil moisture for each measurement location (b), and profile average soil moisture calculated using the same relation between soil moisture and apparent conductivity (i.e. master relation) for all measurement locations (c). The maps were created using linear triangulation. The diamonds represent the locations of the soil moisture and EM measurements. Results shown here are for the 9.090 kHz frequency. Results for the 7.290, 11.250 and 14.010 kHz frequencies are similar to the results shown here for the 9.090 kHz frequency. Soil moisture on the lower 14 m of the hillslope was influenced by artificial water applications between June 18 and August 20, 2002 (see text).

the master relationship was used to convert the measured apparent conductivity patterns to soil moisture patterns, the calculated soil moisture patterns did not represent the observed soil moisture patterns well (Table 5) as the calculated pattern was much smoother than observed and the range of calculated soil moisture values was much smaller than the range in observed soil moisture values (Fig. 6).

Discussion

Representing the temporal variability of soil moisture

The relationship between hillslope average soil moisture at a certain depth and hillslope average apparent conductivity was linear below a threshold apparent conductivity (∼15 mS/m for 7.290 and 9.090 kHz, ∼10 mS/m for 11.250 kHz and ∼1 mS/m for 14.010 kHz). These linear relationships could explain the temporal soil moisture dynamics at all depths, especially the seasonal dry down, very well. However, the apparent conductivity measurements explained the deeper soil moisture dynamics during the spring rainfall events better than the shallower soil moisture dynamics (Figs. 4 and 5). The higher frequencies, which have a shallower depth of penetration, were able to represent the re-wetting of the soil during spring rainfall events only slightly better than the lower frequencies (Fig. 5)

The range of conductivity values at high soil moisture contents (i.e. above the threshold conductivity values/field capacity) could be caused by differences in the water table depth or moisture content of the bedrock. Except for the February 22 and February 26, 2002 measurements, all of these high apparent conductivity measurements occurred when subsurface flow was observed in the trench at the downslope end of the hillslope and water tables were observed in the deepest wells on the hillslope. The apparent conductivity readings were in general higher when subsurface flow and water tables were highest but these relationships were not very consistent. The influence of bedrock wetness and transient water tables at the soil–bedrock interface on the EM signal thus requires further study.

During the artificial water applications a small area (approximately 12 by 5.5 m) was brought to near saturation while the neighboring soil was dry. The area of wet soil was larger than the theoretical lateral resolution of the GEM-300 (1.3 m). However, when a single master relationship was used to convert the apparent conductivity values to calculated soil moisture values, the GEM-300 was not able to detect that this area of the hillslope was wetter than the surrounding soil (e.g. June 24 in Fig. 6). We assumed that soil temperature was relatively constant across the hillslope and thus did not lead to spatial variability in the apparent conductivity readings. However, the artificial water applications likely changed the soil temperature in the area of the artificial water applications. Artificial water applications on another site in

Table 5
Median of the r^2 between the soil moisture patterns calculated from the 9.090 kHz EM measurements and the observed soil moisture patterns during different periods.

Period	February–March	April–May	June–August
Number of measurements	16	21	13
Using the individual relation between soil moisture and apparent conductivity for each measurement location			
5 cm	0.10	0.20	0.17
15 cm	0.26	0.19	0.15
30 cm	0.43	0.22	0.11
50 cm	0.42	0.43	0.18
70 cm	0.24	0.39	0.45
Profile average	0.77	0.77	0.50
Using the master relationship between soil moisture and apparent conductivity for all measurement locations			
5 cm	0.05	0.01	0.01
15 cm	0.01	0.05	0.01
30 cm	0.01	0.01	0.02
50 cm	0.02	0.01	0.01
70 cm	0.08	0.09	0.02
Profile average	0.01	0.02	0.02

the PMRW changed soil temperature at 40 cm depth by ~8 °C. Unfortunately, we do not have spatially distributed soil temperature data to analyze the effect of spatially variable soil temperature on the apparent conductivity readings. However if we assume that the same temperature change occurred in response to the water applications at the study hillslope, differences in soil temperature can explain a large part of the lack of observed soil moisture change during the sprinkling experiments.

The increase in soil moisture during the artificial water applications was detected when individual relationships between soil moisture and apparent conductivity were used to convert the GEM-300 readings to soil moisture values. This is mainly because the measurements that were influenced by the artificial water applications were included in the calculation of the slope and intercept of the individual relationships between apparent conductivity and observed soil moisture for these sites.

Representing the spatial variability of soil moisture

When individual relationships between soil moisture and apparent conductivity were used for each measurement location, the calculated soil moisture patterns and frequency distributions resembled the observed soil moisture patterns and frequency distributions well. However, when a single (master) relationship was used for all measurement locations, the soil moisture patterns were smoothed and did not resemble the observed spatial soil moisture patterns and the range in soil moisture values was reduced compared to observed soil moisture (Fig. 6). However, the observed spatial variability in soil moisture across the hillslope was also relatively small.

We believe that a large part of the smoothing of the calculated soil moisture pattern compared to the observed soil moisture pattern was due to the much larger measurement area of the GEM-300 compared to the Aqua-pro measurements. The lateral resolution of an EM measurement is approximately equal to the inter-coil spacing (1.3 m for the GEM-300) while the measurement volume of the Aqua-pro sensor is approximately 5×10^{-5} m^3. In addition, some of the Aqua-pro measurements could be influenced by roots, rocks or gaps/air pockets next to the access tubes. This would influence the soil moisture measurements made with the Aqua-pro sensor and lead to a persistent underestimation (or overestimation) of the actual soil moisture content. It would also lead to a different calibration relationship between soil moisture and apparent conductivity at these measurement locations compared to other measurement locations. Using the individual relationships between soil moisture and apparent conductivity incorporates these effects into the calculated soil moisture values and thus leads to a larger range of calculated soil moisture values and a calculated soil moisture pattern that explains more of the observed soil moisture pattern. Notwithstanding, this pattern might be largely influenced by small scale soil moisture variations and may not represent the real spatial soil moisture pattern very well. When the same (master) relationship is used to convert the apparent conductivity values to soil moisture values for all measurement sites, these effects are not included in the calculated soil moisture values, resulting in a smaller range of calculated soil moisture values and a smoothed soil moisture pattern.

There was no pattern in the difference between the calculated and measured soil moisture values. This also indicates that the differences between calculated and observed soil moisture patterns were not due to differences in texture, clay mineralogy or solute concentrations across the hillslope but were rather due to small- and local-scale features. The smoothing of soil moisture may therefore not be due to the inability of the GEM-300 to detect differences in soil moisture, but rather due to the difference in the area-of-influence of the measurements.

Representing the depth variability of soil moisture

All four frequencies could be used to predict soil moisture at the Panola hillslope. All four frequencies were linearly related to each other (Table 3). This limited our ability to use the four different frequencies to obtain a soil moisture profile with depth. This situation could be due to the high correlation between measured soil moisture at the different depths at this study site (Table 4). However, when a depth distribution in soil moisture was observed after the June 4–6, 2002 rainfall event the changes in apparent conductivity values for the four frequencies were still relatively similar. This suggests that either all frequencies had the same depth of observation (the depth that contributes the largest part to the total EM response) or that the shallow soil depth influenced the measurements. Doolittle et al. (2001) found during a comparison of the GEM-300 and the EM38 for a salinity appraisal study that although each instrument and frequency had a different theoretical depth of penetration, the instruments and frequencies had similar depths of observation. They concluded that the close similarity in the data collected at different frequencies indicated that the sensitivity of the GEM-300 to variations in conductivity with increasing depth was diminished by the high conductivity of the upper part of the soil profile at their study site. At Panola, there were no high conductivity soil layers, but still, the multi-frequency EM was not usable to resolve a soil moisture profile with depth.

Conclusions

EM appears to be a useful tool for gathering spatially distributed soil moisture information in shallow soils. The relationship between soil moisture at different depths below the soil surface and apparent conductivity was good for all four frequencies tested using the GEM-300. It was not possible to obtain a depth distribution of soil moisture with the different frequencies of the instrument because the four frequencies were themselves highly correlated. Nevertheless, at the Panola study hillslope, measured soil moisture at different depths was also correlated, except directly after storms in spring and summer. The relationship between apparent conductivity and soil moisture was good for all depths but when spring rainfall events wetted only the surface soil layers (e.g. the June 4–6, 2002 event) the EM measurements could explain the soil moisture dynamics at depth (>0.30 m) better than the surface soil moisture dynamics. A wide range of apparent conductivity values was observed at high soil moisture (i.e. above field capacity). Further research should determine if and how this relates to water table depth or bedrock moisture content.

When only one relationship between soil moisture and apparent conductivity was used (our so called master relation) to convert the apparent conductivity values at all locations to soil moisture values, the spatial patterns in soil moisture were not represented very well. The calculated soil moisture pattern was smoothed compared to the observed soil moisture pattern. We believe that this is at least in part due to the difference in measurement volume between the soil moisture measurements made with the GEM-300 and the Aqua-pro sensor. However, the spatial variability in observed soil moisture was relatively small at our site as well. There is thus still a need to test the GEM-300 at a site with a larger spatial variability in observed soil moisture.

Although soil moisture information obtained with EM is not as precise and accurate as point measurements with TDR and while the EM is more susceptible to external influences (e.g. the unexplained decrease in calculated soil moisture on May 17, 2002 (Fig. 4)), the possibility of obtaining spatial soil moisture data relatively quickly over a large area and a measurement that integrates over a larger area (and is thus less susceptible to local disturbances around the probe) makes EM useful in catchment or hillslope studies. We believe that apparent conductivity data together with a few soil moisture measurements (to obtain the relationship between soil moisture and apparent conductivity) is a potential way forward for obtaining spatially distributed data for the calibration of spatially distributed models.

Further research is needed to better understand how the underlying bedrock influences the EM signal and the depth of observation, and to quantify all (external) sources of error. Notwithstanding these needs, we believe that EM measurements can be useful in hillslope hydrology where the temporal changes in soil moisture or the spatial patterns of soil moisture may prove more important than the absolute volumetric soil moisture content values at a point for conceptualizing processes and structuring and testing hillslope models.

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